at least upon one of said detected operating conditions of the engine related to air flow, said actual air flow status being different from said detected intake manifold pressure;

means for calculating a throttle angle which achieves said target torque from the detected operating conditions and the estimated value of actual air flow status; and

means for controlling the engine throttle based upon the calculated throttle angle.

27. An engine control system comprising:

means for detecting operating conditions of the engine, including intake manifold pressure;

means for calculating a value of target torque based upon detected operating conditions of the engine;

means for calculating a target air mass flow rate at the inlet port from the target torque;

means for calculating a throttle angle which achieves the target torque, based on the detected intake manifold pressure and said target air mass flow rate at the inlet port; and

means for controlling the engine throttle based upon the calculated throttle angle.

28. An engine control method comprising:

a step of detecting operating conditions of the engine, including a condition related to air flow;

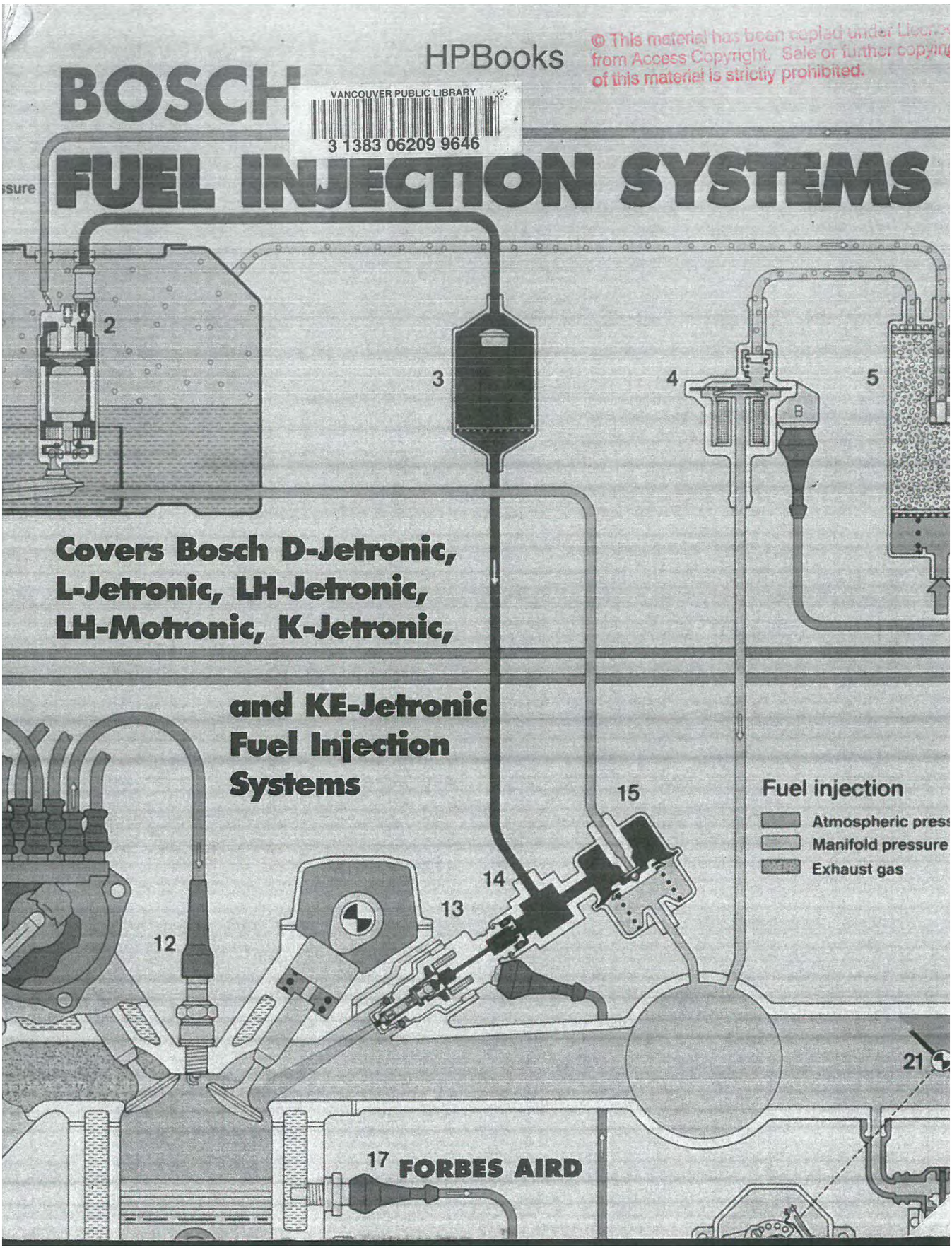
a step of calculating a target torque, based upon the detected operating conditions of the engine;

a step of estimating a value of actual air flow status inside the intake manifold, through an air flow model using at least one of the detected operating conditions of the engine in connection with an air flow;

a step of calculating a throttle angle which achieves the calculated target torque, based on the calculated target torque and said estimated value of actual air flow status; and

a step of controlling the throttle based upon the calculated throttle angle.

* * * * *



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BOSCH FUEL INJECTION SYSTEMS

Forbes Aird

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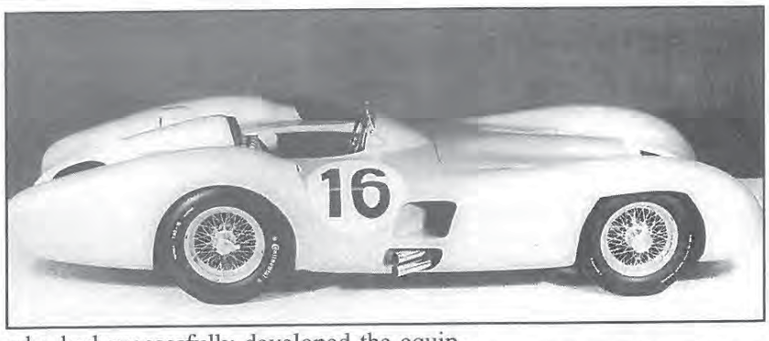
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2 FUEL INJECTION: THEN AND NOW

Despite the fact that there were a thousand and one other problems to be dealt with in the early days of the automobile, auto pioneers were quick to focus attention on the shortcomings of carburetors. The drawbacks included the possibility of ice forming within the venturi in cold, damp air, and a tendency to vapor lock in hot weather when volatile fuels were used. Conversely, carburetors were unsuitable for use with fuels that did not readily vaporize (remember, the automobile came first—gasoline followed, almost anything that would burn was used as a fuel at one time or another in the earliest days). Also, the venturi restricts airflow, and thus power. Because fuel delivery depends on the level in the float bowl, a carburetor is sensitive to the inclination of the car, such as when climbing hills. In addition, there was some dawning awareness of the problems of feeding multiple cylinders from a single "central mixer," as described in the previous chapter. Accordingly, some of the critics set about designing an alternative, specifically what we now call fuel injection.

Early Production FI Systems

Although there were even earlier experiments, perhaps the first production application of FI was by the German company, Deutz, who built about 300 fuel-injected stationary engines around the turn of the century. Hampered by a lack of precision manufacturing facilities, Deutz abandoned the scheme soon after. (Deutz is still in the business of manufacturing industrial and marine diesel engines.) Perhaps aware of Deutz's work, Robert Bosch began experiments with fuel injection in 1912. In 1927, Bosch bought the Acro company, and the patent rights of an Acro employee, Franz Lang, who had successfully developed the equipment needed for high-pressure fuel injection. Shortly afterward, Bosch began manufacturing diesel injection equipment of a pattern that has changed little in the 70-odd years since (see sidebar "The Real Jerk").



The straight eight engine of Mercedes Benz's first post-war Formula One race car—this streamlined W196—injected fuel directly into each cylinder, a system developed from Diesel injection principles. (Mercedes Benz).

The adaptation of this system to gasoline-fuelled engines began in the 1930s, initially for use in aircraft. In this application, three advantages of fuel injection over carburetors stand out: freedom from problems of vapor lock, no risk of icing, and a complete indifference to the attitude of the vehicle. Vapor lock is a significant problem at high altitudes, because the reduced atmospheric pressure there makes it so easy for the fuel to evaporate that it is inclined to boil, forming bubbles of vapor in all sorts of awkward places that can effectively prevent any fuel from getting to the engine. Carburetor icing, while merely an annoyance in an automobile, can be potentially fatal in an aircraft. And a fuel system that can keep the engine running no matter what the attitude of the aircraft becomes a matter of first importance during extreme maneuvers, such as inverted flight. Most, if not all, Daimler Benz engines fitted to German aircraft during World War II enjoyed this advantage over their Allied opponents.

Early Racing FI Systems

If we substitute severe cornering for

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THE REAL JERK

In a diesel, the cylinder at the end of the compression stroke is filled with nothing but air; combustion cannot begin until the fuel is injected. Thus, the moment of introduction of the fuel is equivalent to the ignition timing on a spark-ignition gasoline engine. For that reason, control is needed over not just the quantity of fuel injected, but also the timing of that injection.

Because the fuel has to be kept separate from the air until the correct instant for ignition, the fuel is injected directly into the combustion chamber—the injector nozzle lies inside the cylinder. As a result of that, the injector is exposed to full cylinder pressure during the power stroke. To prevent combustion pressure from blowing the fuel backward through the fuel lines, the injector is fitted with a very stiff spring-loaded check valve. This check valve also performs a number of other important functions. It prevents fuel from dribbling out of the injectors between timed squirts, and ensures that the start and end of each injection is clearly defined. Without this valve, the fuel spray would taper off gradually toward the end of each injection. The check valve, in conjunction with similar check valves at the pump outlets, also ensures that the fuel lines leading from the injection pump remain filled with fuel at full pressure, to ensure that the pressure pulse from the pump is transmitted immediately to the injector nozzle. To overcome the resistance of these check valves, the entire system has to operate at a very high pressure—as much as 3000psi!

The design of the classic diesel injection pump, and the gasoline injection pumps directly derived from that design, follows from the three requirements: to control the quantity of the fuel delivery, and its timing, and to provide a very high pressure output. In construction, it consists of an approximately rectangular body, bored with a number of small cylinders—one for each engine cylinder—each of which is lined with a cylindrical sleeve. The whole thing thus roughly resembles a miniature engine block, a similarity that extends to the "bottom end" of the pump, which has a shaft running lengthwise through it, analogous to an engine's crankshaft. Instead of crank throws, however, this shaft has a number of individual cams, one for each cylinder. Each cylinder in the pump contains a piston-like plunger that is driven up its sleeve by the corresponding cam lobe as the pump shaft rotates, driven by the engine at half crank speed, like an ordinary ignition distributor.

The mechanical drive thus provides the timing and the necessary pressure, leaving the problem of control of fuel quantity. To achieve this, each sleeve has a "spill" port drilled through its side, while the upper edge of each plunger has its side cut away to form a sort of spiral ramp. The sleeve fits in its bore with a very slight clearance, and so is free to rotate. Rotation of the sleeve in its bore thus covers or exposes the spill port, according to the angular position of the sleeve relative to the spiral cutaway on the plunger. With the sleeve rotated so that the spill port is covered even when the plunger is at the bottom of its stroke, the only route out of the cylinder is through a hole at the top, where the fuel lines to the injectors connect. A single stroke of the piston will thus expel the entire volume of fuel held in the cylinder; this represents the maximum capacity of the pump and thus corresponds to full power.

At anything less than wide-open throttle, a lesser amount of fuel per revolution is obviously needed, and this reduction is achieved by rotating the sleeve around, relative to the plunger, so that the spill port lies some distance above the plunger's spirally formed top edge. Upward movement of the plunger thus initially causes fuel to be discharged from this port, from where it is fed back to the tank, until the plunger rises far enough to close off the port, and injection commences.

The rotation of the sleeve(s) is accomplished by a toothed rack that meshes with gear teeth cut onto the outside of each sleeve. The rack is connected directly to the throttle linkage, so moving the pedal rotates the sleeves within the pump, thus controlling the quantity of fuel delivered with each stroke of the plunger.

Although such a mechanical injection pump is, in fact, quite a simple device, and contains few parts—just two per engine cylinder served, plus the camshaft and rack—the quantity of fuel delivered per stroke is very small, so all those parts have to be made with extreme precision, involving much hardening, grinding and precision gaug-

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ing. Accordingly, mechanical injection pumps—known widely and for fairly obvious reasons as "jerk" pumps—are mighty expensive. When adapted for use with gasoline, rather than the kerosene used in diesels, there is the additional problem that gasoline is a "dry" fuel, lacking the lubricating properties of diesel fuel, thus demanding the use of extremely hard, wear-resistant alloys, which further adds to the machining difficulty and expense.

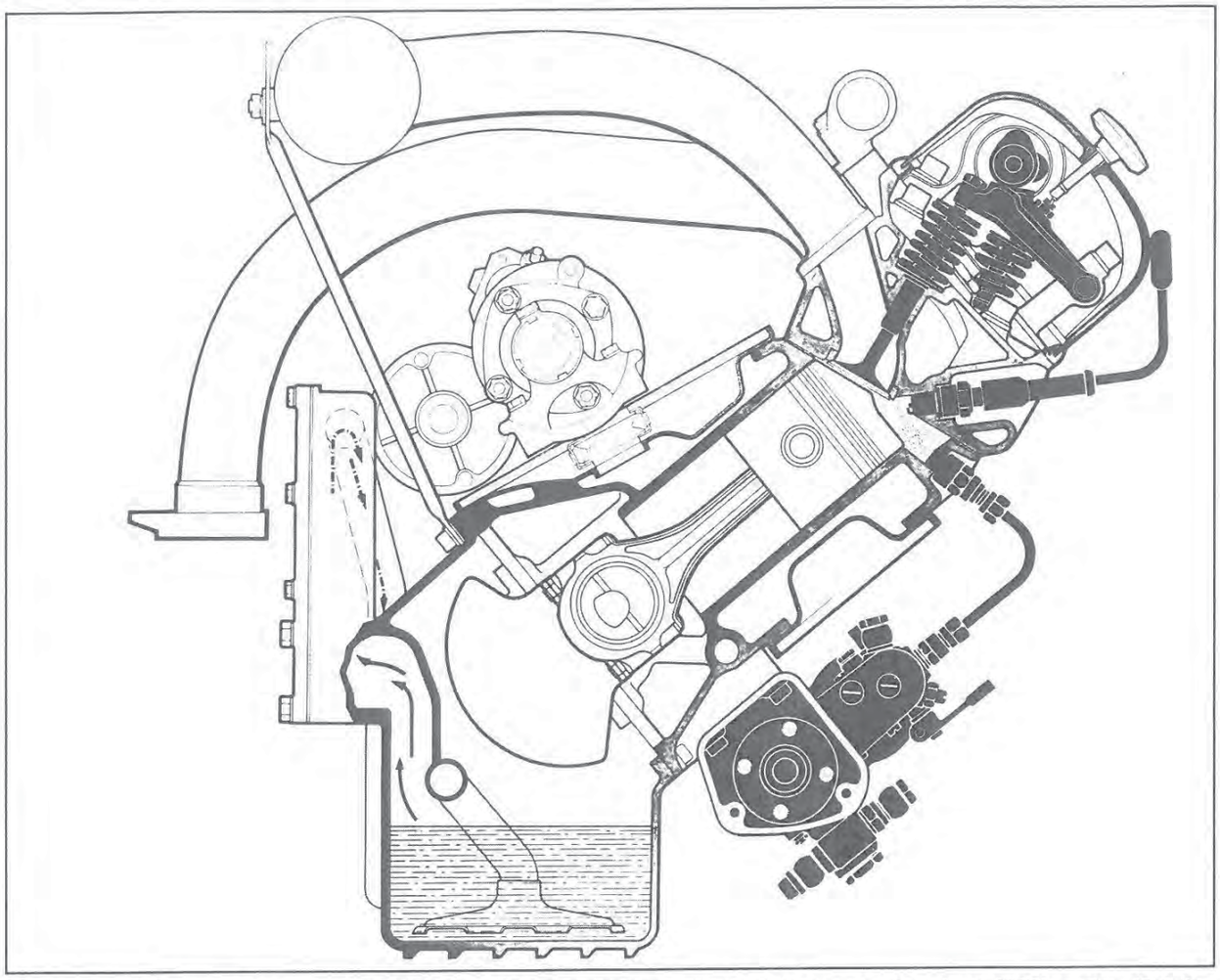


The famous Mercedes 300SL "gull-wing" coupe introduced fuel injection to the street. Like the W196, a system of direct injection was used. (Mercedes Benz).

inverted flight, most of the advantages listed are also highly applicable to race cars. Accordingly, by 1937 Mercedes Benz had tested a single cylinder mockup for a racing engine, using high-pressure injection of fuel directly into the combustion chamber. In the meantime, a handful of European makers of small, two-stroke engined passenger cars had introduced this "direct" fuel injection, in an attempt to tame the notorious thirst of two-strokes that results from something like one quarter of the air/fuel mixture whistling straight out the exhaust ports during the intake/exhaust event, when both inlet ("transfer") and exhaust ports are open together. Because these engines were two-strokes, the injection pump had to run at crank speed, rather than half-speed, as for a four-stroke. This provided Bosch with valuable lessons in running their injection equipment at high pump rpm. Mercedes's first post-war Formula One race engine made direct use of the experience so gained, both their own and that of Bosch.

In both the M196 Formula One engine that appeared in 1952 and in the engine for the famous 300SL "gull-wing" sports car, first exhibited in New York in 1954, Mercedes retained the direct (into the combustion chamber) injection scheme used in

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The location of the injector—screwed right into the cylinder head—is apparent in this cross-section of the 300SL engine. (Daimler-Chrysler Archive)

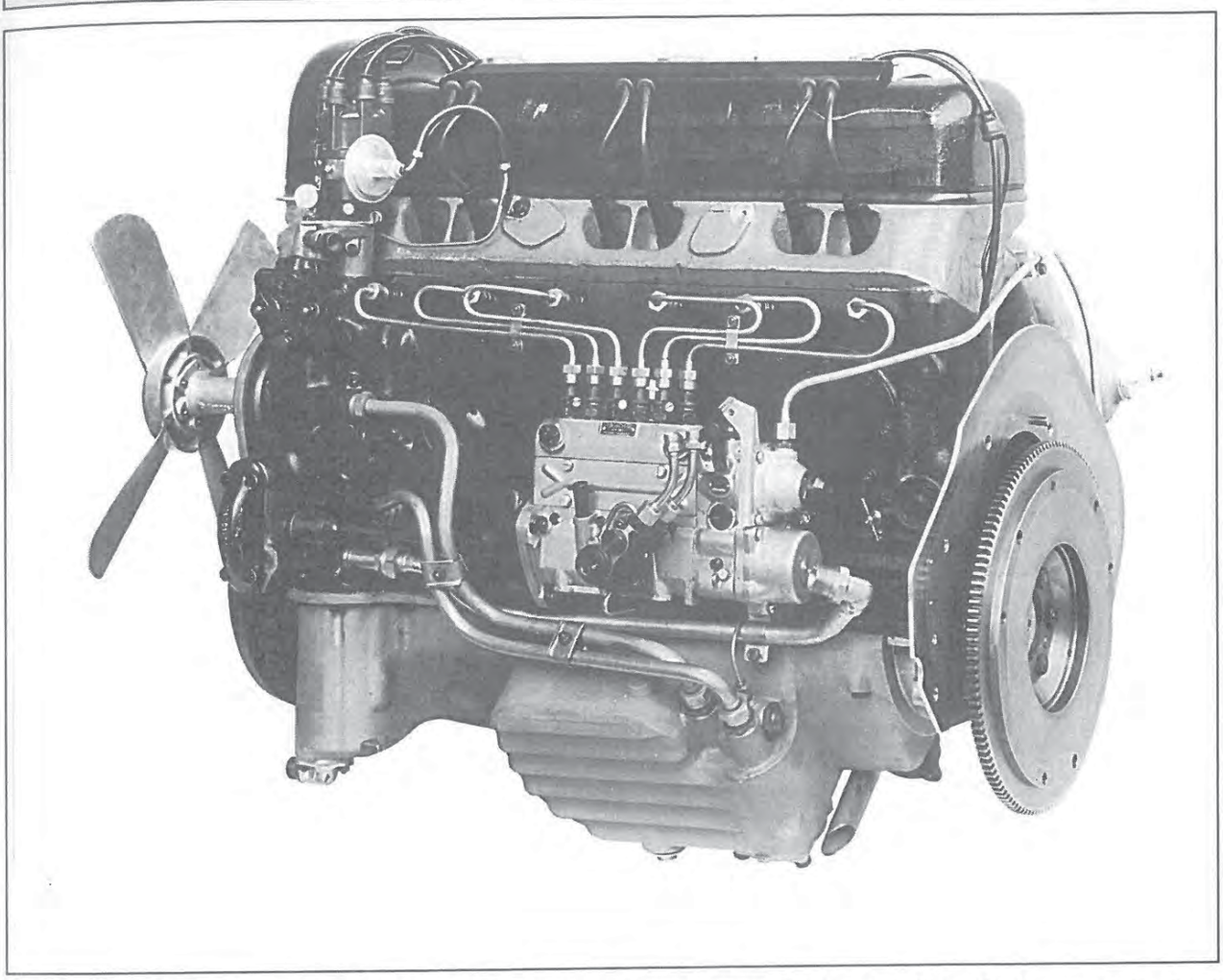
diesels and in the earlier experiments with gasoline fuel. Combined with suitable injection timing, this allowed radical valve timing and experiments with "tuned" intake pipes, without introducing the problem of poor fuel economy from portions of the intake charge being lost out the exhaust. Until injection occurred, after the exhaust valve had closed, the engine was inhaling only air.

Diesel Jerk Pump

Given the existence of an established technology for injecting fuel, it is hardly surprising that the diesel "jerk" pump was adapted in this way for gasoline injection. The adaptation, however, required hurdling a major difficulty—the problem of regulating the quantity of fuel delivered throughout the full range of engine operating speeds and loads.

Unlike gasoline engines where power is controlled by closing off ("throttling") the air supply, yet where a very narrow range of air/fuel ratios must be maintained, on a diesel there is no "throttle" as such. At any given speed, the engine inhales the same full load of fresh air no matter what the position of the gas pedal; varying the power is sim-

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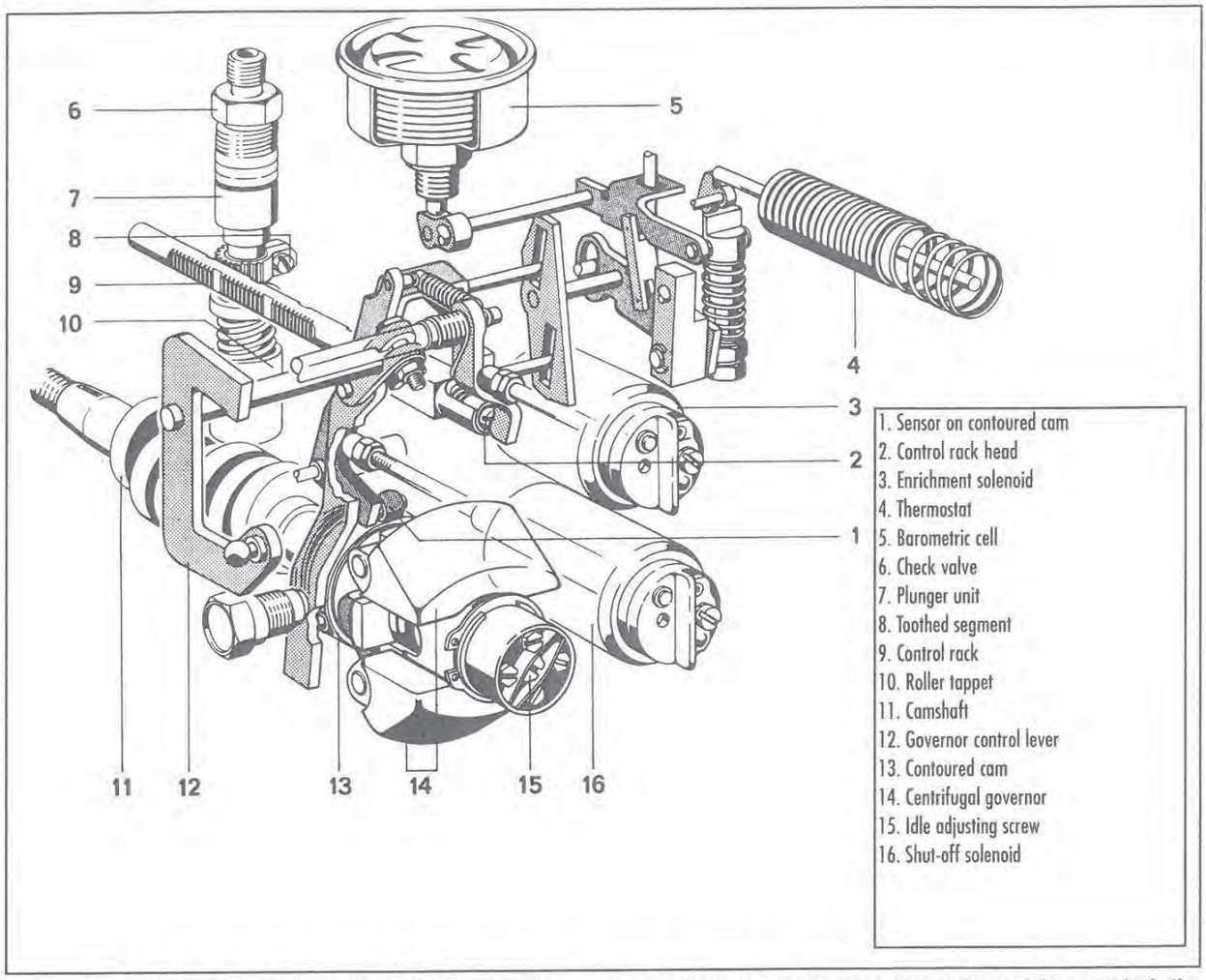


The resemblance to Diesel engine practice is clear in this exterior shot of the 300SL engine. Gasoline's lower lubricity, compared to diesel fuel, compelled the use of expensive, wear-resistant alloys in the injection pump. (Daimler-Chrysler Archive)

ply a mater of injecting more or less fuel. Power is regulated, in other words, by adjusting the mixture strength. In the simpler diesel systems, at least, this is directly controlled by the driver's right foot—the engine runs extremely lean at light throttle, and rich to the point that it visibly smokes when maximum power is demanded. In fact, it is the smoky exhaust that sets the limit for the rated power of a diesel engine; more power would be available simply by injecting yet more fuel—if we were prepared to put up with the smoke. (Even at full power, the amount of fuel injected falls short of a stoichiometric mixture—diesels are always running "lean," which is one reason they can never produce as much power as a gasoline engine of the same displacement.)

The inefficient breathing of any piston engine, gas or diesel, at speeds well away from the rpm at which torque peaks means that the mass of air inhaled per revolution, at any given throttle setting, will most definitely not be constant across the speed range. Because of the gasoline engine's finicky appetite, the amount of fuel mixed in with that air also has to be varied on the basis of the quantity of air inhaled, and not just

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The complexity of the mechanical controls for the Bosch system used on the 300SL is mind-boggling. Fuel delivery of the pump (only the camshaft is shown, 11) is controlled by the rack (9). The position of the rack is governed by engine speed, via the centrifugal weights (14) acting on a contoured cam (13), and by throttle position. Other factors are accounted for by a barometric capsule (5) and a temperature sensitive device (4). (Robert Bosch Corporation)

according to speed and throttle position.

Adapting to Gas Engines—To adapt a diesel jerk pump to gasoline operation, then, means that the rack (see sidebar, page 20) cannot simply be directly hooked up to the loud pedal; the relationship between the two has to be modulated by some other control(s). The usual way this is done is by adding a set of centrifugal weights, somewhat like those in a traditional ignition distributor, to provide a signal proportional to engine speed, plus a diaphragm that "reads" manifold vacuum, a fairly close approximation of engine load. These additional control devices are connected to the linkage controlling the rack via a system of cams and links, with the shape of the cams tailored according to the idiosyncrasies of the engine's breathing.

The monkey motion of these additional levels of control added even more to the substantial cost of the pump itself, demanded meticulous adjustment, and its complexity mocked the essential simplicity of the

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basic pump. Indeed, one observer at the time mused aloud that if all engines had worn fuel injection all along, then someone invented the carburetor, he would have been hailed as a genius.

Injector Location—Apart from the mechanical complexity of the "add-on" speed- and load-sensing mechanisms at the pump, another problem confronted this adaptation from diesel to gasoline—that of shielding the injector nozzles from the heat and fury of combustion. Surprising as it may seem, gasoline combustion chambers see higher peak temperatures than diesels. On their M196 Formula One engine, Mercedes dealt with this by fitting the injector into the side of the cylinder, where it was masked by the piston at TDC and thus shielded from the worst of the inferno.

Certainly, timed direct injection deals with the potential issue of fuel consumption, especially with radical valve timing, and the high pressure spray of these systems is favorable for atomization, but against these advantages were set the problems noted above, plus the issue of the power required to drive a pump that has enough grunt to blow open the stiff check valves in the injectors and at the pump outlets, used respectively to prevent combustion pressure from blowing back through the injection lines and to keep the lines fully charged. Nevertheless, the fact that engines operate quite happily on carburetors made it clear from the outset that there was no absolute need for precision timing of the fuel delivery in a spark-ignition engine.

Granted, a carbureted engine would probably make a little less power than a similar one with direct injection, but some part of this might be attributed to the fact that a separate injector for each cylinder eliminates the problems of a central mixer, rather than to the timing. Of course, the same thing can be achieved with carburetors if a separate carb is provided for each cylinder. That, however, would be heavier, probably more expensive and arguably even more complex, depending on the number of cylinders. Thus, while a handful of other Formula One teams and upmarket European sports car manufacturers also used Bosch gasoline injection, to the best of this writer's knowledge, all these others left the injector just outside the combustion chamber, aimed at, and spraying against, the head of the intake valve.

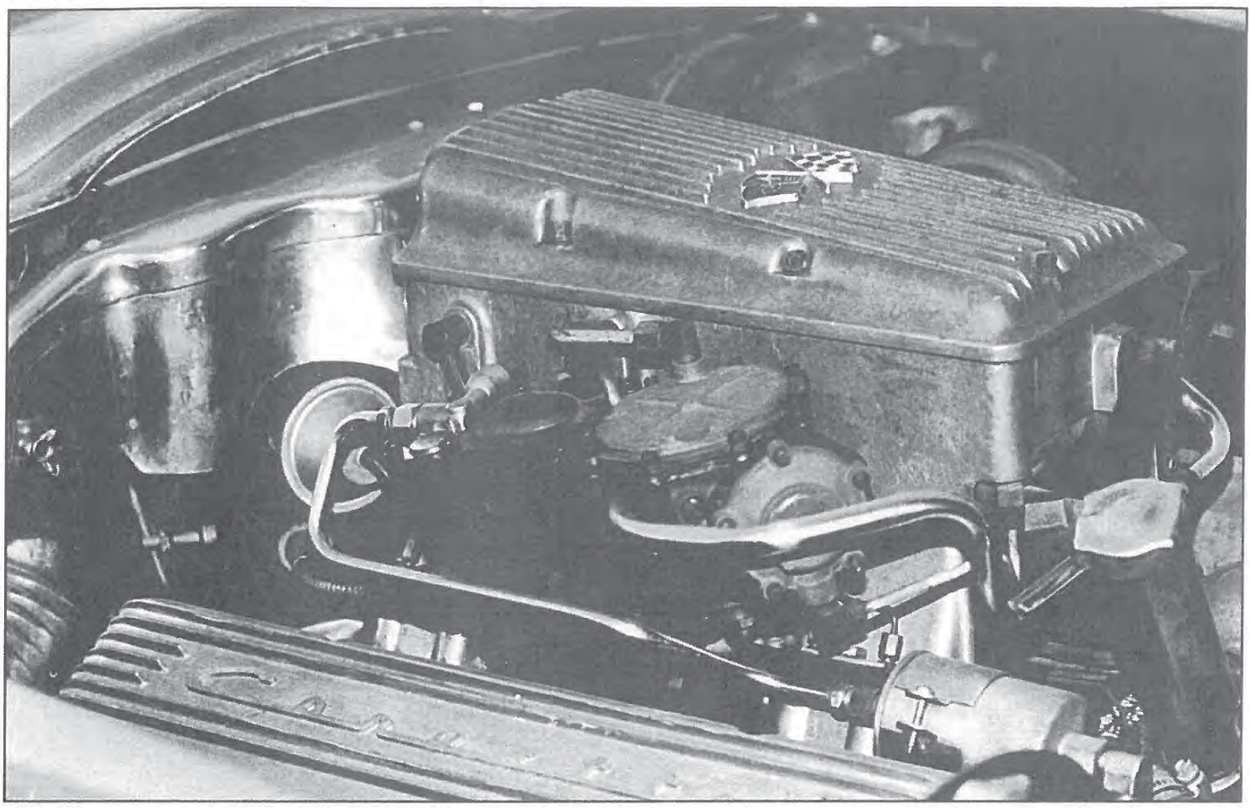
But if you decide to locate the injectors outside the combustion chamber, then you don't need to fight combustion pressure, so you don't need a very high pressure pump. Also, if the injector lies outside the cylinder, then you don't need to time the injection so it occurs with both valves closed. In that case, why bother to time it at all? And if the timing of discrete squirts is not crucial, then why does the fuel have to be delivered in individual pulses?

Early Continuous Injection Systems

These questions had occurred to a good many people, and an alternate form of fuel injection came into being. In these, fuel is injected continuously, rather than in pulses, and at very much lower pressure than a "jerk" pump provides, though still much higher than the small pressure difference that exists between a carburetor venturi and the atmosphere.

The Wright brothers used a primitive form of this continuous injection, as the arrangement is called, on the engine of their first successful aircraft. An engine-driven pump of the "positive displacement" type—one which supplies a fixed quantity of fuel at each revolution—was used, to continuously spray fuel directly into the engine air intake. It should be clear that while a satisfactory mixture strength might be arranged at full throttle—presumably after some tinkering with the size and/or drive ratio for the pump—with no means to reduce the pump output the mixture must have become hopelessly rich at anything less than full throttle.

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Although Stu Hilborn had proved, years earlier, that such a system could work on the track, Rochester were the first to demonstrate the practicality of the simpler, continuous flow fuel injection system, as on this early "fuelie" Corvette. (Dave Emanuel)

But then the Wrights' had no immediate interest in operation at part throttle!

Winfield's FI System—About the same time that Bosch and Mercedes were beginning their experiments with timed, high-pressure, direct gasoline injection in the mid-1930s, Ed Winfield developed a low pressure, continuous injection system, intended for Indy cars. Winfield's design had provision for varying the fuel flow with throttle position, but a lack of interest from potential customers forced him to eventually abandon the scheme, and he allowed his patents to lapse. It was not until fifty years after the Wrights that racers had access to a continuous injection system that dealt with the part-throttle problem.

Hilborn Injection—Stu Hilborn achieved this by incorporating a controllable spill valve, connected to the throttle linkage, that tapped off (and returned to the tank) some portion of the pump's output, according to how wide the throttle was opened.

On the face of it, this might appear to fill the bill, but the assumption built-in here is that an engine, at any given throttle setting, needs a fixed quantity of fuel per crank revolution, and we have already seen that this is mistaken, because of the way an engine's ability to take a full breath varies across its speed range. As a result, gasoline FI systems that use just engine speed and throttle position to determine fuel quantity can be arranged to provide a suitable mixture strength only under very limited circumstances, and must inevitably miss the mark by a large margin under others.

Still, schemes such as Hilborn's have a long and honorable history when used with methanol fuel. As discussed in more detail

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in Chapter 8, methanol will tolerate wide variations in mixture strength with little effect on power output, which helps mask the inherent shortcomings of such a simple system. In this case, rpm and throttle position alone provide a sufficiently accurate measure of fuel flow requirements, so it is not necessary to measure the rate of airflow at all. Since there is no need to measure it, there is no need for the restriction of a venturi or any other airflow sensor stuck in the airstream. This improves engine breathing and so promises more power just for that reason alone.

Rochester FI System

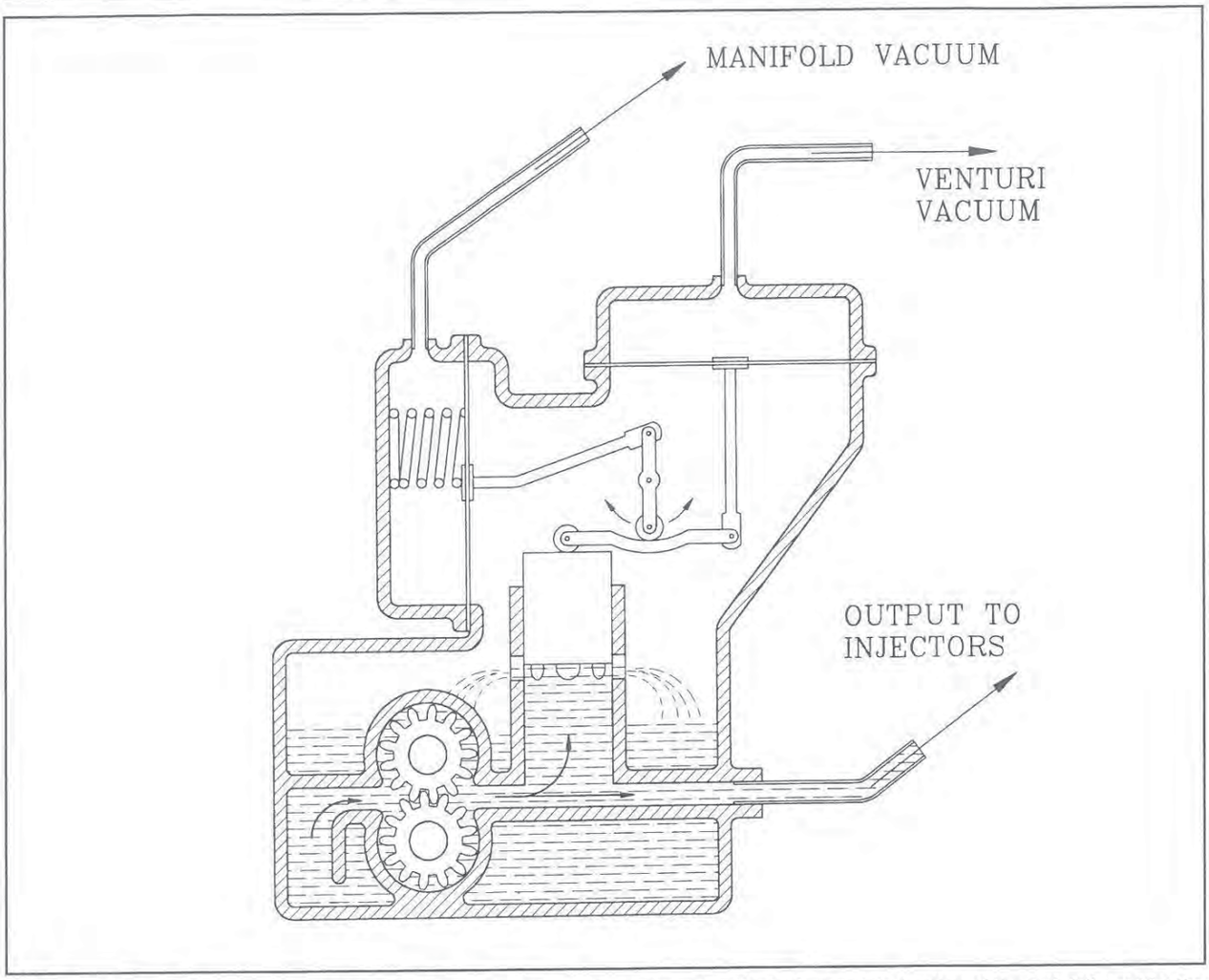
For a street engine running on gasoline, however, any purely mechanical system, whether injecting continuously or in a series of pulses, needs to somehow measure or compute the rate of airflow into the engine, and to use that information to modulate the delivery of fuel so as to keep the air/fuel ratio appropriate to the circumstances. We have discussed how this can be achieved with a jerk pump, but what about a continuous gasoline injection system?

There have been many such systems throughout automotive history; one of the more recent and more widely used of these is the Bosch K-Jetronic system, described in Chapter 6. Nevertheless, the example most of us remember best is likely the Rochester system used on "fuelie" Corvettes from 1957 to 1965. The heart of the Rochester system is a spill valve that serves as a regulator of fuel quantity—indeed, it is the only mixture control element in the whole system. Fuel is fed to the spill valve by an engine-driven gear-type pump that simply serves as a source of fuel at medium-high pressure (200psi at maximum), with the pressure tending to rise with increasing rpm. The spill valve consists of a sleeve with a number of ports arranged radially in its side, plus a plunger that covers or exposes these ports, according to its position. The position of the plunger, in turn, depends on a balance between the fuel pressure and a force applied to the top of the plunger by a mixture control mechanism.

Increasing fuel pressure tends to raise the plunger, thus uncovering the sleeve ports and so bleeding off some of the pressure. The mixture control device, shown schematically in the following illustration, amounts to a simple mechanical computer that applies a spring force to the top of the plunger, modified by the forces acting on two diaphragms—one connected to the intake manifold, and one to a venturi through which all the air entering the engine has to pass. The eight individual port injectors downstream of the spill valve thus see a fuel pressure that depends on a balance between the supply pressure and the forces acting on the diaphragms, and their output varies accordingly.

The Rochester system is strikingly simple, especially when compared to a jerk pump having the controls needed for street use on gasoline, and none of its parts require exceptional precision or expensive materials for their manufacture. Although the injectors themselves had to be individually calibrated and installed as a matched set, given sufficiently large production numbers it seems likely that the system overall would have been little (if any) more expensive to make than a pair of four barrel carburetors. Nevertheless, it remained a somewhat rare and costly performance option, and justified its price premium by offering more power. Partly this was because the near-elimination of cylinder-to-cylinder variations in mixture strength permitted a higher compression ratio (CR) than was safe with carburetors, but an advantage still showed even when the CR was unchanged. We might attribute this to three sources: nearly identical air/fuel ratios at each cylinder, elimination of manifold heating, and a reduction in the breathing restriction imposed by the venturi, compared with a carburetor. Although a venturi

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The heart of the Rochester system's control unit was a spill valve that returned to the tank a certain fraction of the fuel delivered by the gear-type pump. The position of the piston in the spill valve was determined by two diaphragms—one hooked to a manifold vacuum, one to a single large metering venturi that fed the air box. A system of links and rollers linked movement of the diaphragms to the spill valve piston.

was needed to measure air quantity, the amount of pressure drop needed to provide a useful signal to the mixture control unit was much less than that required to lift gasoline out of a carburetor's discharge tube.

In its day, the Rochester FI was regarded by the auto industry and the public alike as very much a high-tech piece, and possibly the final word in fuel delivery. Ironically, at about the same time that GM was introducing this system, another completely different form of fuel injection was being unveiled, to much less public acclaim, yet this one would eventually sweep away not only the carburetor, but most other forms of fuel injection as well.

The First Use of Solenoid Valves

The basis of this little-hailed breakthrough was the use of an electrically operated solenoid valve as a fuel injector. Supplied with fuel at a modest constant pressure, it squirts at a constant rate as long as an electric current is applied to the solenoid windings, and stops when the current is turned off. Thus, the quantity of fuel injected depends simply

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on how long the juice is turned on. If one electrical pulse is delivered every second revolution of the crankshaft (for a four-stroke engine), then the air/fuel ratio of the mixture delivered to the engine can be controlled simply by varying the length of each pulse.

The idea of using a solenoid valve as a fuel injector is a surprisingly old one. Such a scheme had been developed by an engineer named Kennedy at the Atlas Imperial diesel Engine Co, in 1932, and an installation appeared on a marine engine exhibited at the New York Motor Boat Show in 1933, around the same time that Bosch and Mercedes in Germany, and Winfield in the U.S. were beginning their experiments. Given the primitive state of the electrical sciences back then, it is mildly astonishing that the thing worked at all, yet in 1934 a similar but smaller engine was installed in a truck and driven successfully from Los Angeles to New York and back.

The "Electrojector"—A quarter century later, A.H. Winkler and R.W. Sutton of the Eclipse Machine Division, Bendix Aviation Corporation, announced the fruits of four years' work at Bendix to develop anπ FI system for gasoline-fuelled automobiles using such a solenoid-controlled valve as an injector, in conjunction with an electronic control unit, or (as they termed it) "brain box." They described this combination of components as "electronic fuel injection"—surely the first time this phrase was ever used. The resulting "Bendix Electrojector" comprised a separate port injector for each cylinder, each supplied with fuel from a common rail at a regulated 20 psi. Sensors responsive to manifold pressure, engine speed, atmospheric pressure, and air and coolant temperature fed their various outputs to the "brain box"—the electronic control unit (ECU)—which then calculated the instantaneous fuel requirements of the engine. On the basis of that calculation, the ECU delivered a pulse of current to a rotary distributor which fed that current pulse to each solenoid valve in turn, causing each successively to open and supply fuel to the cylinder it served. The quantity of fuel delivered by each injection was simply a matter of the duration of the pulse—as long as it was "on," the injector would deliver fuel at a constant rate. At idle, the pulses were of very short duration; at maximum load, the injectors were open for as much as 150 crankshaft degrees.

At the beginning of the development of the Electrojector, about 1951 or 1952, the triggering signal for the ECU was provided by a mechanical commutator—a simple wiper making intermittent contact with a segmented brass ring, as the engine-driven ring swept past. That soon gave way to triggering by an extra set of contact points in a housing sandwiched under the ignition distributor. In at least the three earliest versions, the working bits in the ECU were . . . vacuum tubes! One such unit was installed on the V8 engine of a 1953 Buick, and used to demonstrate the system to the auto industry.

By 1957, when it became available to the public in very limited numbers, the electronics were, thankfully, all transistorized. This eliminated the need to wait for the tubes to warm up before the system became functional, shrank the size of the ECU and substantially reduced the electrical power required to run it, and doubtless greatly improved the system reliability—vacuum tubes do not take kindly to be rattled around! The Electrojector was listed by American Motors as an option for the 1957 Rambler Rebel, but very few cars so equipped were ever sold. A year later, Chrysler offered it on the 300D and DeSoto Adventurer, and several hundred with the option were manufactured in 1958 and 1959.

Despite occasional problems from external electrical fields causing the brain box to go haywire, and a degree of unreliability of the injectors themselves, on the whole the system worked satisfactorily and matched Bendix's claims of modest (5 percent)

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improvements in both fuel economy and power, compared to a similar engine fitted with a pair of four-barrel carburetors. The teething troubles were eventually worked out, and by 1965 Bendix had a fully developed production version ready to go.

At this point, rather than try to produce and market the Electrojector themselves, Bendix decided instead to enter into an agreement with the Robert Bosch Co., which gave Bosch access to the Bendix patents. From a business point of view, this made a good deal of sense. In view of their reputation in the auto industry as an established OEM supplier—one with wide experience both in fuel injection and in electrical and electronic equipment—Bosch was clearly in a better position to exploit the potential market. And fuel prices in Europe were many times what they were in the U.S. of the 1950s, justifying a much higher initial cost there, in exchange for the fuel economy benefits alone.

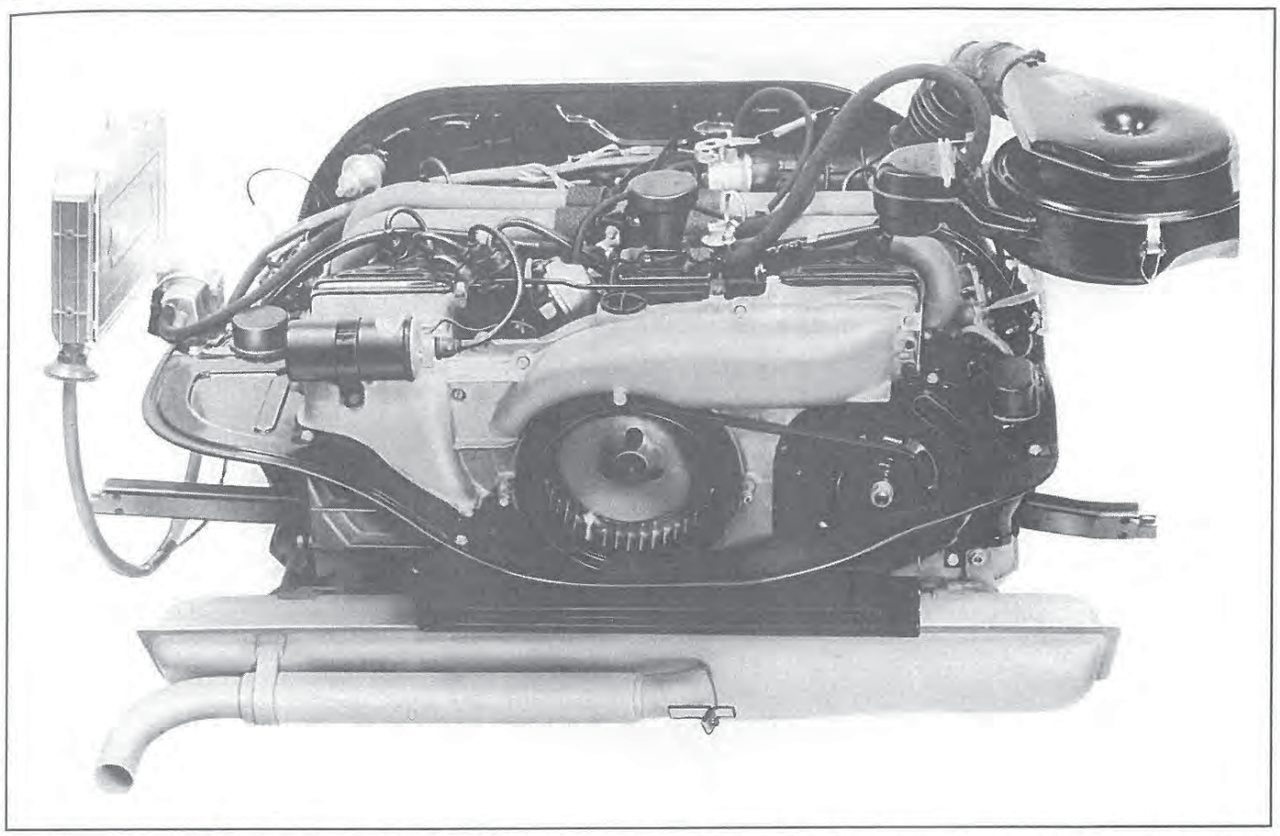
Bosch Jetronic FI

In most respects, the Bosch "Jetronic" FI that first appeared on the 1967 Volkswagen 1600, was functionally identical to the Electrojector system described by Winkler and Sutton ten years earlier. Apart from taking advantage of advances in electronics to produce a more compact ECU, this system—since identified as D-Jetronic, to distinguish it from later Jetronic versions—differed from the Bendix prototype in one respect. In the Electrojector, the housing that was piggybacked onto the ignition distributor and which contained the triggering contact points also contained a rotor, just like an ignition rotor; this distributed the timed pulse to each injector sequentially. In the D-Jetronic as applied to the four cylinder VW, there was no rotor, but there were two sets of triggering contacts, one for each pair of cylinders. Each set of contact points drove two injectors simultaneously, timed so that one cylinder received its injection while its intake valve was open; for the other cylinder, the injection occurred with valves closed. Fuel thus accumulated in the port, awaiting that cylinder's next intake stroke.

We have mentioned earlier that the mere fact that a carbureted engine will function in a satisfactory way should make it obvious that injection timing is, to say the least, not critical, and the power gains realized with a few continuous injection systems tended to confirm this view. The matter was pretty much clinched in 1959, when Mercedes successfully used a Bosch jerk pump with just two plungers, each feeding three engine cylinders, on its six cylinder 220SE. This must all have improved the comfort level of the Bosch and VW engineers who adopted the hop-skip timing used on the D-Jetronic, an arrangement that allowed eliminating the rotor used in the Electrojector.

The Electrojector-based, intermittent injection "Jetronic" systems from Bosch have undergone successive improvements and refinements over the years since the D-Jetronic's introduction. Apart from the electronic innards of the control unit gaining computing power while shrinking ever further in size and weight, and the use of all-electronic triggering (rather than contact points), the major differences between one variant and another have been in the way the quantity of air supplied to the engine is measured. These basic differences between systems are reflected in the nomenclature used: L-Jetronic, LH-Jetronic, etc. In addition, most later systems accept inputs from additional sensors, most notably an oxygen sensor, also called an O_2 sensor or lambda sensor. As mentioned in the previous chapter, this is a device fitted to the exhaust system that "sniffs" the exhaust gas to gauge its oxygen content, thereby providing a direct measure of what the air/fuel ratio actually is at any given moment, rather than obliging the system to depend totally on a set of pre-programmed "maps" or "look-up tables" that predict what the ratio should be for a

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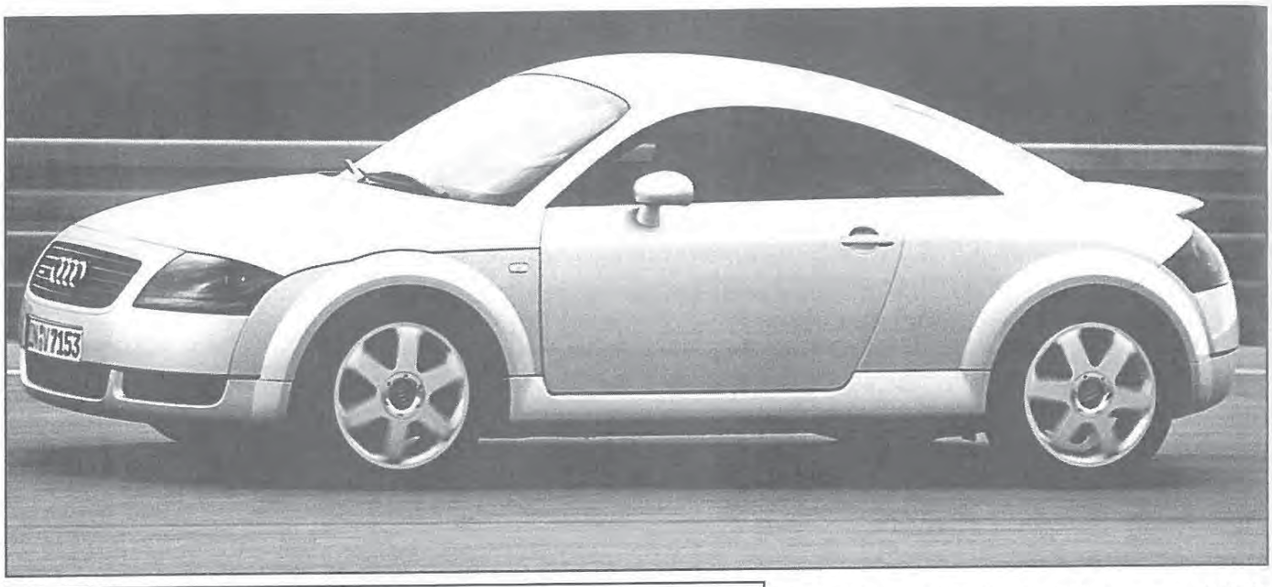
With the rear-mounted "pancake" engine nestled under the apparent floor of the trunk, earlier carburetted versions of the VW 1500/1600 were notorious for vapor lock problems. This is the later 1600 engine with Bosch D-Jetronic injection. The ECU is visible at the far left. (VW Canada).

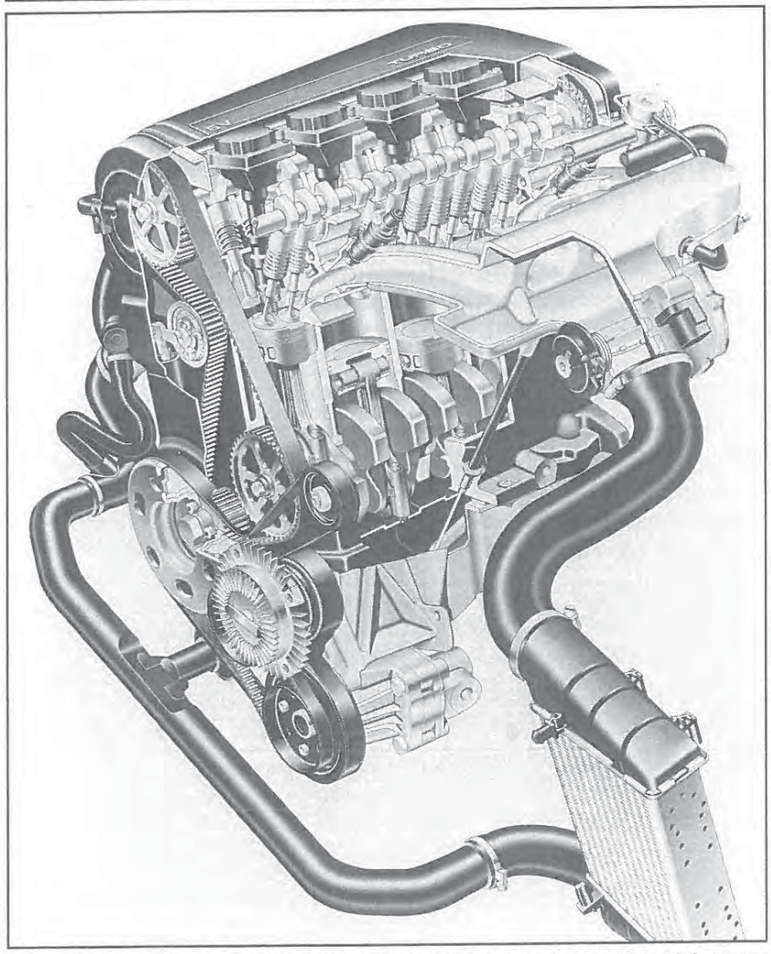
given set of operating conditions. (See also the sidebar "The Oxygen Battery.")

In many cases, control over ignition timing has been integrated into the ECU of these systems, in which case they are termed "Motronic," again with variants according to the method of air metering. Over time, an increasing number of functions have been combined into the Motronic system, including integrated control over automatic transmission shift points and torque converter lockup, the waste-gate on some turbocharger-equipped cars, selection among different length intake ports on some others, and authority over the variable valve lift and/or timing found on a few vehicles. We discuss these Motronic systems in some detail in Chapter 4.

K-Jetronic—At the start of the new millenium, the principle of intermittent injection using electronically controlled, electrically powered solenoid injectors is now universal on domestic passenger cars, and near-universal on models imported from Europe and Asia. Yet not everyone was an immediate convert to this plan. It seems ironic now that even after the pulsed (intermittent) Jetronic system was commonplace, Bosch felt obliged to introduce a continuous injection system, the K-Jetronic (The "K" stands for *kontinuierlich*, German for continuous). Early versions of this were purely mechanical; in response to ever-tightening emissions standards, later ones—such as KE-Jetronic and corresponding Motronic versions—added a degree of electronic control. In part this apparent preference for an all-mechanical system may have been due to a powerful conservative

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Intermittent electronic fuel injection allows modern cars to combine high power with driveability, economy, and low emissions. (VW Canada).

streak among some manufacturers and their engineers. In part, too, it may have been a matter of economics—the intermittent systems may have been more expensive at the OEM level. Although there were a few holdouts until the early 1990s, most of the various K-Jetronic systems were history by the mid 1980s. These now-superseded (not to say obsolete) systems are dealt with in Chapter 6.

We will not be dealing with a handful of sub-variants of Jetronic and Motronic FI that are used on vehicles not imported into North America.

To summarize, then, the essential difference between carburetors and fuel injection systems is that a carburetor uses the pressure drop within its venturi both to measure the airflow and as the means to propel the fuel into the intake air stream, whereas FI mechanically forces the fuel into the intake air in an amount usually determined by a separate airflow or manifold pressure sensor, acting on an electronic or mechanical system that actually controls the quantity of fuel injected.

Basic Types of Fuel Injection

All fuel injection systems can be divided up into two basic types: those that inject fuel

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continuously and those that inject intermittently, in a series of pulses. Again, in either case control over how much fuel is injected can be achieved either mechanically or electronically. In the present context, only the old, diesel-type jerk pump uses mechanical control over intermittent injection; all Bosch intermittent systems use electronic control. Bosch K-Jetronic continuous injection systems—sometimes called CIS—may use purely mechanical control, as in the original K-Jetronic, or may include some degree of electronic fine-tuning on top of the basic mechanical computation.

Many FI applications, especially in newer cars and in older high-performance ones, use a separate injector for each cylinder. This greatly reduces the quantity of liquid fuel laying on the walls of the ports. If the injectors are located very close to the intake valves and the intermittent injections are sequential, the possibility of maldistribution of the mixture between one cylinder and another is essentially eliminated.

Many others, though, are of the "throttle body" type, in which the fuel is sprayed into and mixed with the air in one centralized location, then conducted to the cylinders through a thus "wet" manifold, just like that of a carbureted engine. This would seem to put it on the same footing as a single carb in terms of mixture distribution, but the fact that the fuel is injected under pressure means that it emerges from the injector nozzles as a very fine spray, with droplets so small that they have a much better chance of evaporating than is often the case with the lumpy soup coming from a carburetor. While a TBI system is thus likely to be better in this regard than a carb, an individual injector at each intake port can do even better.

One of the further advantages sometimes argued for FI is that it achieves the maximum possible engine power because it does away with the venturi. That is not quite true, because it is a basic principle of science that you cannot measure something without affecting the thing you are measuring. Certainly a venturi measures airflow, and in the process it also restricts that flow, but electronic fuel injection (EFI) systems that use a spring-loaded flap valve or a "hot wire" airflow sensor (the current needed to keep the wire at a constant temperature is used as the air-quantity signal) both offer at least some restriction to flow, too, although a hot wire (or hot film) sensor will impede airflow much less than any carburetor venturi.

The ultimate sophistication is to provide an oxygen sensor (O_2 sensor, lambda sensor) in the exhaust pipe and to correct the mixture strength from moment to moment, based on that information; an excess of O_2 calls for a richer mixture, and vice versa. For all these reasons, EFI with an injector for each cylinder is unarguably the state-of-the-art for fuel-air mixing and delivery.

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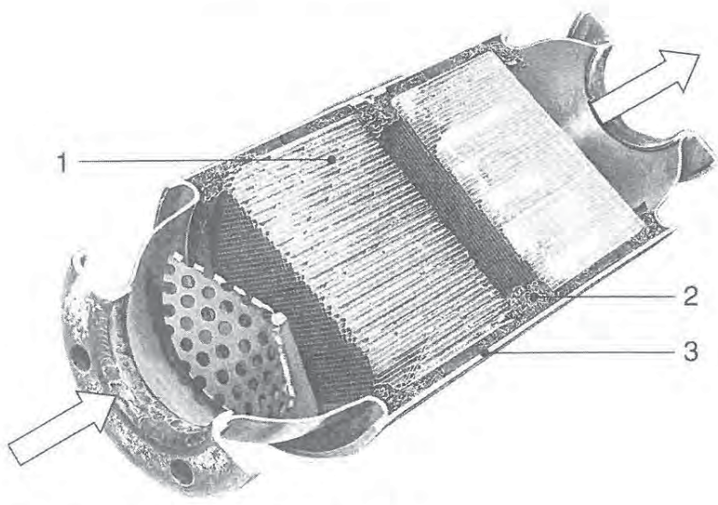
THE OXYGEN BATTERY

Rich mixtures, we explained in Chapter 1, mean that some of the hydrocarbon molecules in the fuel entering the engine pass out into the exhaust unreacted—there simply aren't enough oxygen molecules available for them to combine with. These unburned hydrocarbons are a source of air pollution, and legislation severely limits the quantity of them that is allowed to escape into the atmosphere. The shortage of oxygen also means that the reaction with the hydrocarbons that do burn is chemically incomplete—instead of the hydrocarbon-oxygen pairings forming CO_2 and H_2O, many of them wind up as CO—carbon monoxide. Emissions of carbon monoxide are also strictly controlled by law.

Lean mixtures would keep down the CO levels, and as long as they were just a little lean, the HC levels, too. Ironically, excessively lean mixtures actually raise HC levels above those found with a stoichiometric mixture, because as the mixture approaches the "lean limit"—the air/fuel ratio at which the mixture simply won't ignite—some cylinders misfire, so all of the HC in that particular cylinderful goes straight out the exhaust unburned.

But even mixtures just lean enough to minimize CO and HC create high combustion temperatures. Too-hot combustion encourages some of the nitrogen (N) in the air, normally thought of as inert, to combine with some of the excess oxygen, to form various oxides of nitrogen—NOx. NOx is also a pollutant—it is the principle source of photochemical "smog"—so the amount of it, too, is limited by law. (Damned if you do; damned if you don't!) A compromise setting won't work, either. Anything lean enough to meet HC and CO limits would bust the NOx limit, and anything rich enough to avoid excessive NOx would lead to illegal levels of HC and CO. (Damned even if you sit on the fence!)

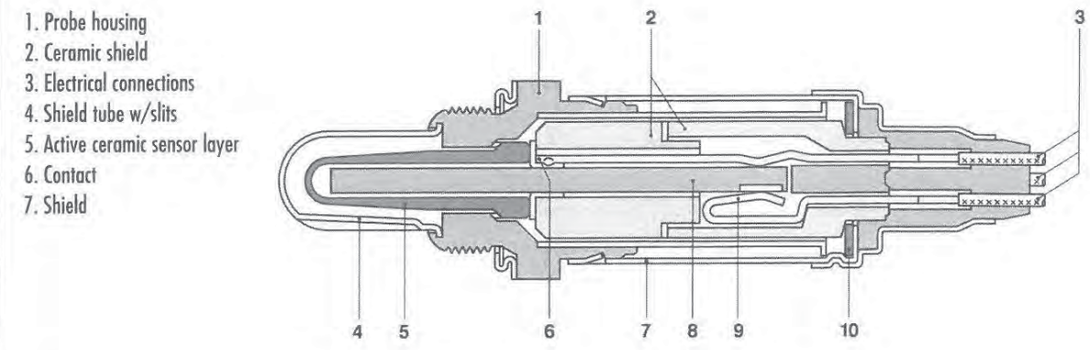
The solution arrived at by auto makers, beginning about 1975, has been the "three-way catalytic converter." In essence, this device splits the oxygen from the NOx and helps it combine with the CO to make CO_2, and with the HC to make H_2O, and more CO_2. This works well enough to satisfy the G-men . . . provided that the mixture was neither too rich nor too lean in the first place. And the three-way catalytic converter is mighty fussy indeed about just how close to the stoichiometric ideal the ingoing mixture has to be; mixtures that are less than one percent either



1. Ceramic material with catalytically active substances
2. Steel wool retainer
3. Housing

Construction of a three-way catalytic convertor. Convertors are essential to meet current emissions limits, but can only do their job if the air/fuel mixture fed to the engine is held very close to the chemically correct ratio. And to achieve that, a lambda (oxygen) sensor is essential. (Robert Bosch Corporation).

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Lambda sensors have a voltage output that rises from near zero in the absence of oxygen in the engine exhaust to a bit less than one volt when small traces of it are present. This characteristic enables an electronic fuel injection system to control fuel delivery on the basis of the sensor's reading of the exhaust gas. The sensor only works when hot, however. To reduce the time between engine start-up from cold and the sensor reaching its operating temperature, some versions are electrically heated. (Robert Bosch Corporation).

side of the chemical ideal render the converter next to useless.

No fuel injection system yet developed (and certainly no carburetor!) can hope to control the mixture strength that closely, based simply on a set of values derived from the characteristics of some similar engine in a test lab. The device that enables EFI to "know" just what the mixture strength needs to be at any instant for any particular engine out in the real world is the "lambda sensor."

In construction, the lambda sensor consists of a hollow ceramic bulb, with both inner and outer surfaces covered with a microthin layer of platinum. For protection, the outer surface is surrounded by a shield. This bulb is inserted into the exhaust system so that its exterior surface is washed by the exhaust gas stream, while its hollow interior is exposed to the atmosphere. In operation, the lambda sensor acts like an oxygen-powered battery: a difference in the oxygen level of the gasses surrounding the two surfaces of the sensor causes it to generate a small voltage.

As you might expect, there is very little oxygen in the exhaust of an engine running on a stoichiometric mixture, yet there is some—about 0.5 percent. Surprisingly, even with a mixture that is about five percent rich, there is still about 0.2 percent oxygen. Equally surprising, a mixture that is five percent lean will only contain about one percent oxygen. A particularly useful feature of the lambda sensor is that its output voltage changes very dramatically right around the point of stoichiometry; very small changes (a few tenths of one percent) in oxygen content lead to large changes in the sensor output. While the sensor will put out about 900 millivolts (0.9v)

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when the exhaust oxygen content corresponds to a lambda of about 1.2 (that is, the mixture is about twenty percent lean—an air/fuel ratio of a bit less than 12:1), and while its output drops to near zero at about lambda=0.8 (an air/fuel ratio of near 18:1), almost all of that voltage change occurs within one percent of stoichiometry. The voltage output of the sensor is fed back to the ECU, which slightly reduces or increases the duration of the on time for the injectors, according to whether the sensor reports the mixture is richer or leaner than stoichiometric. This "closed-loop" control maintains the air/fuel ratio within 0.1 percent of the chemical ideal, thus allowing the converter to do its job.

In practice, an output from the sensor of 450mv is used by the ECU as the threshold of the lean limit and 500mv as the rich limit. This means that the air/fuel ratio actually oscillates back and forth (though always within 0.1 percent of stoichiometry) as the ECU responds to the voltage signal from the sensor. The time required for the sensor output voltage to vary between these limits depends on its temperature. At idle, when the gas temperatures are low—say 300° C (about 570° F)—that time interval might be as much as a couple of seconds; under typical road loads, the exhaust temperature is more like 600° C (1100° F), and the "cycle time" is reduced to less than 50 milliseconds (1/20 second).

The sensor is essentially inoperative at temperatures below 300° C, so during engine startup and initial warm-up the ECU ignores the sensor voltage and falls back on a set of internal "maps," until such time as the signals it is getting from the sensor make sense. Accordingly, emissions are inevitably increased during this warm-up period, so to reduce the wait for the sensor to reach operating temperature, some sensors have an internal heating element to bring it on-line as quickly as possible.

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(12) **United States Patent**
Melchior et al.

(10) **Patent No.: US 6,209,519 B1**
(45) **Date of Patent: Apr. 3, 2001**

(54) **METHOD AND ARRANGEMENT FOR CONTROLLING THE QUIET RUNNING OF AN INTERNAL COMBUSTION ENGINE**

(75) Inventors: **Gerard Melchior**, Schwieberdingen; **Klaus Ries-Müller**, Bad Rappenau, both of (DE)

(73) Assignee: **Robert Bosch GmbH**, Stuttgart (DE)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/466,978**

(22) Filed: **Dec. 17, 1999**

(30) **Foreign Application Priority Data**

Dec. 21, 1998 (DE) 198 59 074

(51) **Int. Cl.**[7] **F02P 5/15**
(52) **U.S. Cl.** **123/406.24**; 123/436; 701/111
(58) **Field of Search** 123/435, 406.24, 123/403.26, 406.27, 436; 701/111

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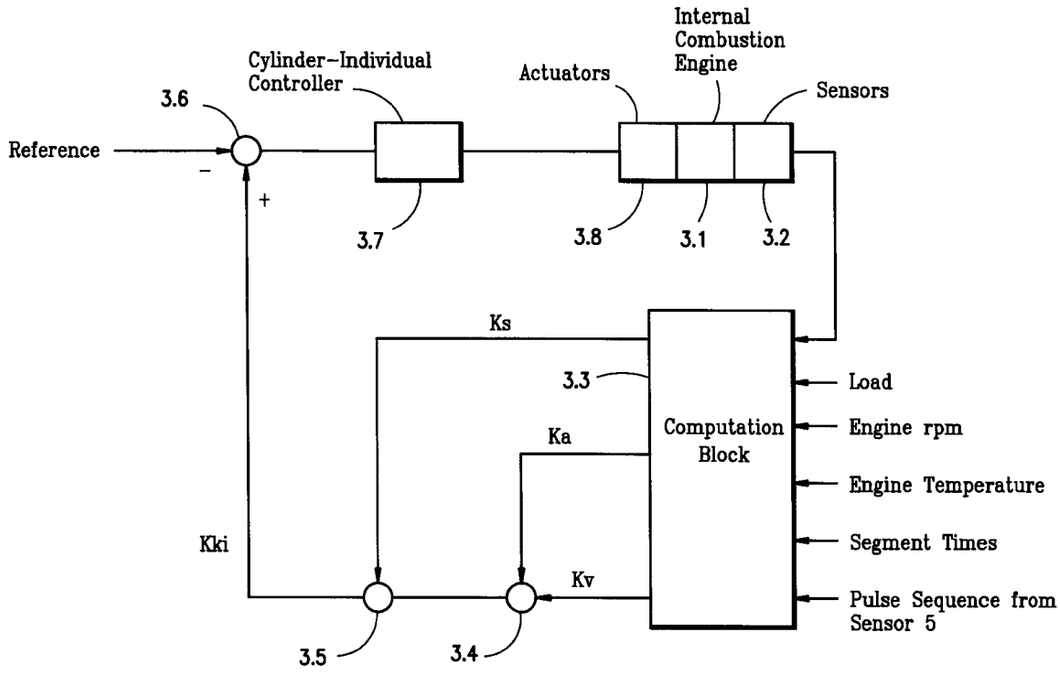
* cited by examiner

Primary Examiner—Erick Solis
(74) *Attorney, Agent, or Firm*—Walter Ottesen

(57) **ABSTRACT**

The invention is directed to a method and an arrangement for equalizing torque contributions of different cylinders of an internal combustion engine to the total torque of the engine. The engine can operate in an overrun mode and in a fired mode. First quantities (Ka) are provided of a rough running of the engine in the overrun mode and second quantities (Kvi) are provided in the fired mode. Third quantities (Ksi) for a rough-running component based on torsion vibrations are also provided. Cylinder-individual fourth quantities (Kki) for the rough running are formed from the first, second and third quantities with the fourth quantities being independent of the rough running in the overrun mode and independent of the rough-running component based on the torsion vibrations. The torque contributions are equalized on the basis of the fourth quantity.

9 Claims, 3 Drawing Sheets



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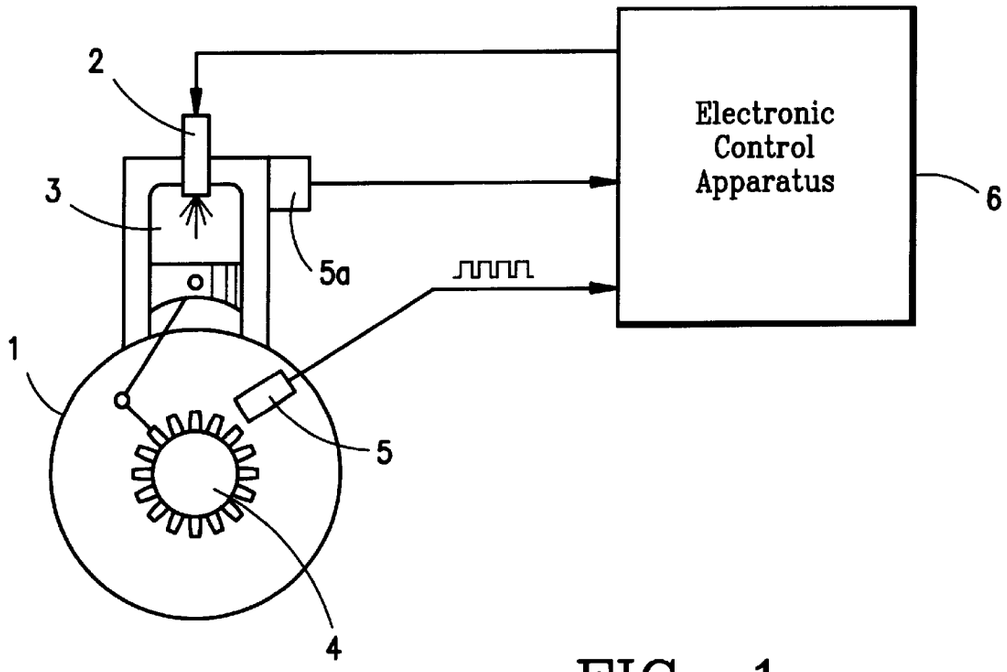


FIG. 1

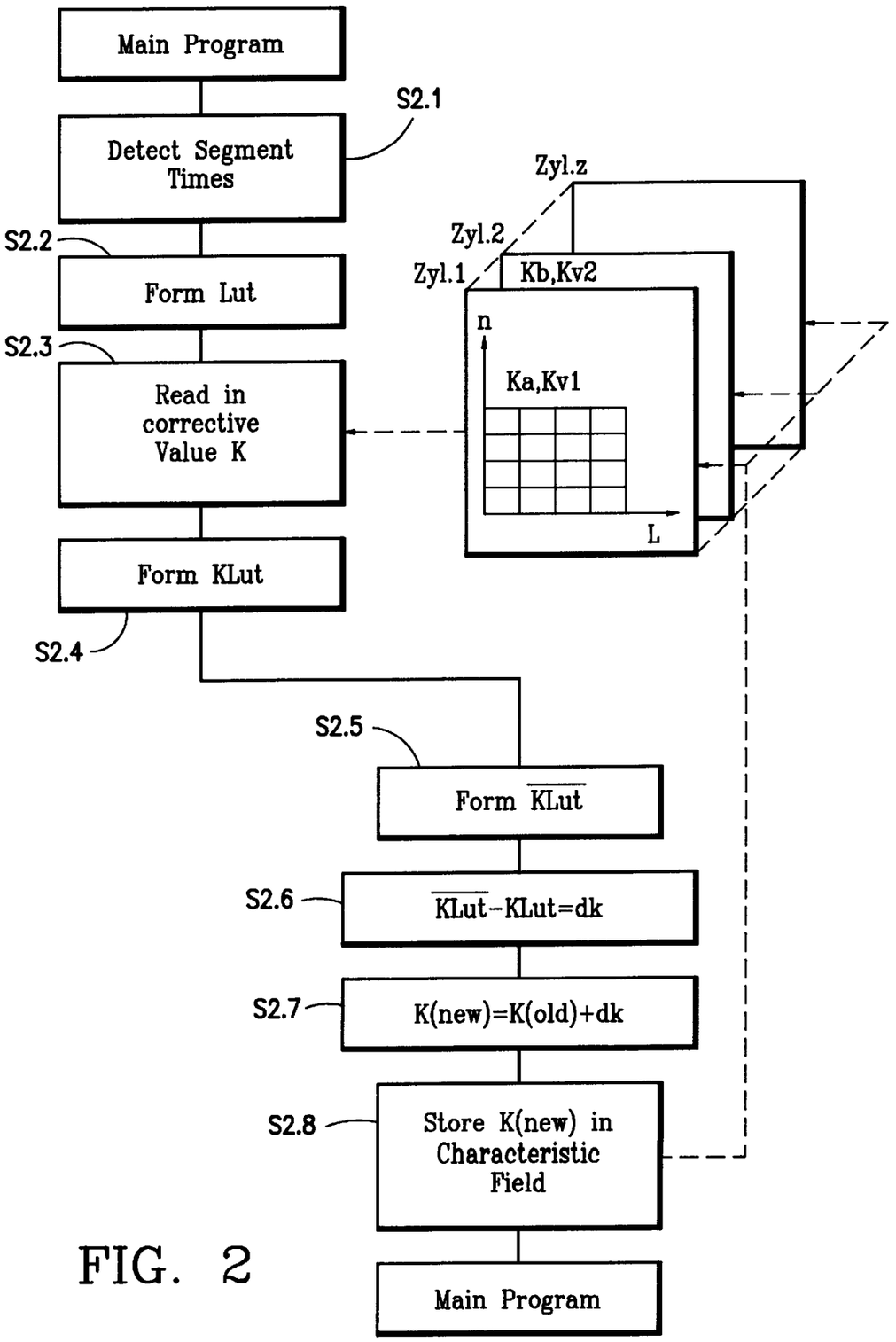

Main Program
S2.1
Detect Segment Times
S2.2
Form Lut
S2.3
Read in corrective Value K
Form KLut
S2.4
Zyl.z
Zyl.2
Zyl.1
Kb,Kv2
n
Ka,Kv1
L
S2.5
Form $\overline{KLut}$
S2.6
$\overline{KLut}$-KLut=dk
S2.7
K(new)=K(old)+dk
S2.8
Store K(new) in Characteristic Field
Main Program

FIG. 2

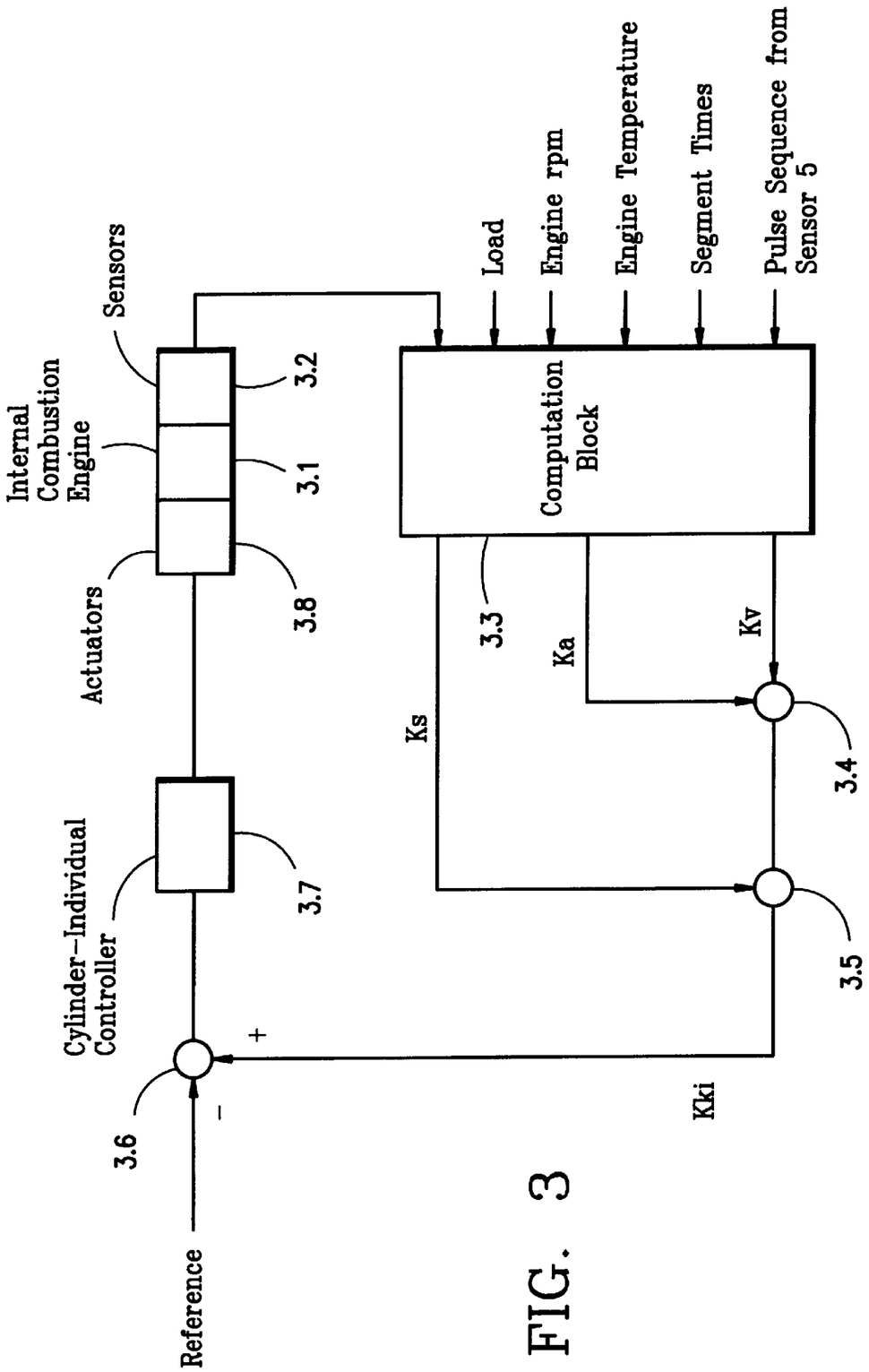

Sensors
Load
Engine rpm
Engine Temperature
Segment Times
Pulse Sequence from Sensor 5
Internal Combustion Engine
Computation Block
3.2
3.1
3.8
Actuators
3.3
Ka
Kv
Ks
3.4
3.7
Cylinder–Individual Controller
3.5
+
–
3.6
Kki
Reference

FIG. 3

METHOD AND ARRANGEMENT FOR CONTROLLING THE QUIET RUNNING OF AN INTERNAL COMBUSTION ENGINE

BACKGROUND OF THE INVENTION

The invention relates to the improvement of the quiet running of an engine by equalizing the torque components of the individual cylinders as to the total torque of an internal combustion engine. Here, the engine can be a spark-ignition engine or a diesel engine. A detection of the actual torque of a cylinder takes place via an evaluation of the time-dependent course of the rotation of the crankshaft or of the camshaft. A torque correction takes place via an intervention on at least one of the variables: injected fuel quantity, air quantity or ignition time point in a spark-ignition engine, exhaust-gas return rate, injection position or cylinder compression. The term "injection position" relates to the angular position of an injection pulse to a reference point such as top dead center of the piston of a cylinder in a combustion stroke.

A method for cylinder equalization is disclosed in U.S. Pat. No. 4,688,535. In this method, segment times are detected to evaluate the time-dependent course of the rotational movement of the crankshaft or camshaft. Segment times are the times in which the crankshaft or camshaft passes through a predetermined angular region assigned to a specific cylinder. The more uniformly the engine runs, the lesser are the differences between the segment times of the individual cylinders. From the above-mentioned segment times, an index for the rough running of the engine can therefore be formed. In the known method, a controller is assigned to each cylinder of the engine and a rough-running actual value specific to a cylinder is supplied to the controller as an input signal. The rough-running values of several cylinders are averaged to form the desired control value. The mean value serves as the desired value. At the output end, the controller influences the cylinder-specific injection time and therefore the cylinder-individual torque contribution such that the cylinder-individual rough-running actual value approaches the desired value.

Rough-running values, which are obtained from rpm signals, are also used for detecting combustion misfires. Quotients are formed as rough-running values LUT in the method disclosed in U.S. Pat. No. 5,861,553. In the numerator of these quotients, differences of sequential segment times are present and the denominator of these quotients contains the third power of one of the participating segment times. This quotient can be weighted with additional factors as well as be provided with a dynamic correction which considers rpm changes of the entire engine. With respect to the formation of rough-running values, U.S. Pat. No. 5,861,553 is incorporated herein by reference. The sum of these rough-running values, which is formed over one camshaft rotation, is equal to zero for a constant engine rpm.

The detection of defects of the transducer wheel system as well as the detection of the component of the rough running which is based on torsion vibrations of the crank drive and on different energy releases in different cylinders, is known from U.S. Pat. No. 5,822,710.

The detected defects and the above-mentioned rough-running component serve to provide a computed correction of the rough-running values for the detection of combustion misfires. For example, in overrun operation with a six-cylinder engine, the segment times (t1, t2, t3) of the three transducer wheel segments are detected. At each segment time, a corrective value (K1, K2, K3) is formed and additively or multiplicatively coupled to the segment time (Kt1= t1*K1 or t1*K1, . . .). The corrective values are so determined that the results Kti (wherein i=1 to 3) are equal to each other. Such a correction considerably improves the quality of the detection of combustion misfires which is based on the evaluation of rpm fluctuations.

SUMMARY OF THE INVENTION

It is an object of the invention to minimize the real cylinder-individual differences in the combustion between the cylinders with a control concept. The torque components of the cylinders are then of the same magnitude. The real differences here characterize the rough-running component which is based on different combustion but not on torsion vibrations and/or transducer wheel defects.

The electronic control arrangement of the invention is for equalizing torque contributions of different cylinders of an internal combustion engine to the total torque of the engine which can operate in an overrun mode and in a fired mode. The electronic control arrangement includes: means for providing first quantities (Ka) of a rough running of the engine in the overrun mode and second quantities (Kvi) in the fired mode; means for providing third quantities (Ksi) for a rough-running component based on torsion vibrations; means for forming cylinder-individual fourth quantities (Kki) for the rough running from the first, second and third quantities with the fourth quantities being independent of the rough running in the overrun mode and independent of the rough-running component based on the torsion vibrations; and, means for equalizing the torque contributions on the basis of the fourth quantity.

Especially advantageous effects occur during idle and in the lower part-load range because these ranges exhibit especially intense smooth running effects or rough-running effects as a consequence of varying torque components of different cylinders.

The combination of the above features permits a separation of the influences of different causes of rpm fluctuations. These influences are described below as items (a) to (c).

Item (a)

Disturbances, which are caused by defects of the rpm detection system, occur synchronously with the rotation movement of the transducer wheel and are synchronous to the rotational movement thereof because of the coupling of the transducer wheel to the crankshaft. These disturbances are independent of load and can be learned during overrun operation. For example, for an eight-cylinder engine, four corrective values KA, KB, KC and KD can be formed.

Item (b)

Non-uniformities, which are based on torsion vibrations of the crank drive are mostly synchronous to the rotation movement of the camshaft and typically at specific resonance rpms. The vibration components are independent of deterioration and can be computed. The vibration components can also be determined utilizing measurements as an alternative to a computation. For an eight-cylinder engine, there are eight corrective values KS1, . . . ,KS8, which can be stored in a corrective characteristic field of the engine control apparatus.

Item (c)

Differences because of the combustion process, for example, because of varying cylinder charges, are synchro-

nous to the rotation of the camshaft and are dependent upon deterioration because of different wear of the cylinder/piston pairing. In the following, these differences are assigned eight corrective values (Kv1, . . . ,Kv8) in the example of an eight-cylinder engine.

An essential element of the invention is to intervene in the management of the engine based on the above-mentioned corrective values so that the torque components of the different cylinders are equalized.

In this context, the computed correction of the mechanical faults of the segment time detection system (transducer wheel tolerances) is especially important in the detection of the segment times during overrun operation because these would otherwise be controlled out by a controlled intervention. The consequence would be a real physical rough running which would generate a signal of perfect smooth running in combination with the mechanical defects.

According to the invention, corrective values Kvi are learned in fired operation; and, in overrun operation, corrective values Ka, Kb, . . . , et cetera are learned and are coupled to predetermined corrective values Ksi.

What is decisive in the computation of the corrective values is that the different systematic disturbance components are considered separately. What is essential in this context is especially the use of predetermined values for the torsion vibration effects because these effects cannot be separated effectively in a simple manner from the other effects neither in overrun operation nor in fired operation.

From the corrective value Kvi of a cylinder having index I, the corresponding corrective values Ksi and Ka are subtracted, that is, the corrective values Ksi, Ka, . . . concerning the same cylinder or the same crankshaft angle segment. Example: Kk1=Kv1−Ks1−Ka.

The result Kki of the subtraction corresponds to a difference between cylinder-individual rough-running values. This difference is based only on different torque components and is independent of transducer wheel inaccuracies as well as torsion vibrations. Stated otherwise, the corrective values Kki reflect torque differences based on varying energy releases in the combustion processes individual to a cylinder. The differences are compensated by corresponding control interventions of the engine management.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described with reference to the drawings wherein:

FIG. **1** shows the technical background of the electronic control arrangement for equalizing the torque components of different cylinders of an internal combustion engine to the total torque;

FIG. **2** is a flowchart showing an example of a determination of the corrective values for the detection of the engine rpm; and,

FIG. **3** is a schematic of an embodiment of the electronic control arrangement according to the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS OF THE INVENTION

Reference numeral **1** in FIG. **1** represents a spark-ignition engine having direct injection which is exemplified by a high pressure injection valve **2** which projects into the combustion chamber **3** of the engine. FIG. **1** also shows a transducer wheel **4**, sensors **5** and **5***a* and an electronic control apparatus **6**. The control apparatus **6** receives signals from the sensors **5** and **5***a* and, for example, outputs an injection pulsewidth as an actuating variable tik to a high pressure injection valve of an individual cylinder. Additional actuating variables outputted by the engine manager (that is, the electronic control apparatus **6** for balancing torque) can be the injection time point, the ignition time point, the supplied air quantity and/or the returned exhaust-gas quantity.

For the equalizing intervention, cylinder-individual rough-running values are formed in the electronic control apparatus **6** and are processed to corrective values which influence the torque via a computation into the actuating variables such as into the cylinder-individual injection times and therefore influence the time-dependent sequence of the rotation of the transducer wheel **4**.

FIG. **2** shows an example of determining the corrective values for the rpm detection.

For this purpose, ignition synchronous segment times are detected in step **S2.1** and processed to rough-running values Lut in step **S2.2**. In step **S2.3**, a corrective value for compensating the torque vibrations and similar effects is read in from a load/rpm characteristic field K(L,n). In the first runthrough of the method, it is only a plausible or neutral value which successively assumes, via repeated method runthroughs, a value which is characterized in that the corrected rough-running values of different cylinders become equal to each other. For this purpose, the rough-running values Lut are coupled to the corrective value K in step **S2.4**. Thereafter, the corrected rough-running value KLut enters into the formation of a mean value $\overline{KLut}$ in step **S2.5**. Step **S2.6** follows for determining the deviation dK of the actual value $\overline{KLut}$ from the mean value KLut. In step **S2.7**, a new corrective value K(new) is formed by addition of the deviation dK to old corrective value K(old) and is written into the characteristic field K(n,L) of the cylinder via step **S2.8**. The cylinder being that cylinder for which the rough-running value was determined.

By repeated runthroughs of the described sequence of steps, the characteristic field values K of the various cylinders become such that no deviations of the corrected rough-running values of the various cylinders occur any longer amongst each other during misfire-free normal operation. The characteristic field values K belong to an operating point.

The cylinder-individual characteristic fields can contain the corrective values Ka et cetera from the overrun operation as well as the corrective values Kv from the fired operation. The corrective values from the overrun operation are stored with the load value zero.

The described method for the corrective values Ka et cetera and Kv can be carried out repeatedly during the operation of the engine.

The corrective values Ks are, in contrast, predetermined and stored via computation or via a measuring detection ahead of or during the first time that the engine is taken into service. These corrective values Ks are not changed again during operation of the engine and can be called up in dependence upon the operating point.

FIG. **3** discloses an embodiment of the invention. A sensor **3.2** detects operating parameters of the engine **3.1**. Examples of operating parameters are: load, rpm, engine temperature, cylinder identification signal, segment times or the pulse sequences which form the basis of the segment times. The pulse sequences are from the rpm detection system made up of transducer wheel **4** and inductive pickup **5** shown in FIG. **1**.

These values are supplied to a computation block **3.3**. Block **3.3** as well as components **3.4** to **3.7** belong to the control apparatus **6**.

The corrective values are formed in block **3.3**. This can take place, for example, in correspondence to the illustration shown in FIG. **2**. In addition, block **3.3** contains the predetermined corrective values Ks for the torsion vibration effects.

Downstream of block **3.3**, the corrective values Ks, Ka, et cetera and Kv are coupled in logic elements **3.4** and **3.5** to a corrective value Kk=Kv−Ks−Ka for each cylinder. This corrective value Kk is compared to a reference value in logic element **3.6**.

As a reference value, the corrective value of one individual cylinder (for example, the corrective value of the first cylinder) can be applied, for example, in a first alternative. Stated otherwise, in this alternative, the corrective values of the individual cylinders are only corrected relative to each other, namely, referred to the reference value of the first cylinder which is assumed to be correct. In the sequence, the cylinders are equalized relative to each other. The absolute level of the idle rpm is then adjusted via a higher-ranking control, that is, via an intervention which is the same for all cylinders.

As an alternative, all cylinders, that is, their segment times, can be referred to a mean rpm region. Per cylinder, a correct value then results which is also correct with respect to its absolute value.

The signal resulting from the logic coupling in logic element **3.6** is supplied to the cylinder-individual controllers **3.7**, which form drive signals for actuators **3.8** therefrom, for example: for interventions into the fuel metering, into the quantity of supplied fresh air or recirculated exhaust gas or the ignition.

The following actuating interventions (**1**) to (**5**) can be carried out on the engine in dependence upon the occurring deviations:

1. Extending the injection time of the cylinders which supply less torque while simultaneously shortening the injection time of the cylinders which output more torque. In this way, the lengthening or shortening is so computed that the total fuel quantity is not affected; that is, the lambda value of the mixture with which the engine is driven is not changed. This concept serves, for example, for lean control at the pregiven lambda value and maximum smooth running or minimal rough running.
2. At the lean misfire limit, the difference of the actual Lut value to the Lut mean value becomes significantly larger.

For a lean misfire limit, that rough running is taken for which there are just still stable combustions, for example, in homogeneous lean operation. The lean misfire limit is detectable with the above-mentioned method and can be controllable as required. In this concept, the lambda sum changes and therefore this is not a lean control; instead, it is a cylinder individual running boundary control. Block **2.1** can be omitted in this realization.

3. The ignition angles of an engine are stored in characteristic fields in present day systems and these characteristic fields are applicable for all cylinders. The control can therefore be so designed that, at first, an attempt is made to compensate a torque which is too low by an advanced ignition angle. Example: A coking or carbonization in the direct injector causes a torque of a cylinder which is too low. This cylinder runs lean. The optimal ignition angle for this lean mixture is more advanced and can be correspondingly adjusted. Likewise, a cylinder, which causes a high torque, can be influenced by a retarded ignition angle.
4. In systems with exhaust-gas recirculation, the possibility is present to reduce the exhaust-gas rate of recirculation in the event that the measured values fluctuate greatly. Here too, a lean misfire limit control is possible with the objective of maximizing the rate of exhaust-gas recirculation.
5. For a direct-injection engine, the outputted torque can be additionally changed in stratified operation by varying the injection time point.

It is understood that the foregoing description is that of the preferred embodiments of the invention and that various changes and modifications may be made thereto without departing from the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. An electronic control arrangement for equalizing torque contributions of different cylinders of an internal combustion engine to the total torque of the engine which can operate in an overrun mode and in a fired mode, the electronic control arrangement comprising:

means for providing first quantities (Ka) of a rough running of said engine in said overrun mode and second quantities (Kvi) in said fired mode;

means for providing third quantities (Ksi) for a rough-running component based on torsion vibrations;

means for forming cylinder-individual fourth quantities (Kki) for said rough running from said first, second and third quantities with said fourth quantities being independent of the rough running in said overrun mode and independent of the rough-running component based on said torsion vibrations; and,

means for equalizing said torque contributions on the basis of said fourth quantity.

2. The electronic control arrangement of claim **1**, wherein said engine includes actuator means for operating on at least one of the following functions thereof: fuel metering to said engine, air supplied to said engine, the ignition, cylinder compression, drive of camshaft valves and drive of a swirl flap; the electronic control arrangement further comprising:

a plurality of controllers corresponding individually to respective ones of said cylinders; and,

means for conducting said fourth quantities to said controllers wherein drive signals are formed for said actuator means to thereby intervene in at least one of said functions.

3. The electronic control arrangement of claim **2**, wherein said arrangement functions to intervene individually or in combination as follows in dependence upon the deviations which occur on said engine:

extending the injection time of those ones of said cylinders which output less torque while simultaneously shortening the injection time of those ones of said cylinders which output more torque with the extending and shortening being so computed that the total quantity of fuel is unaffected and the lambda value of the mixture with which said engine is driven is not changed;

first compensating a torque which is too low by an advanced ignition angle;

with a system having exhaust-gas recirculation, reducing the rate of recirculating of the exhaust gas in the event that measured values fluctuate greatly;

with a system having variable control of the gas exchange valves, the control lines and/or the valve stroke is changed;

with a system having a charge movement flap, the position of the charge movement flap is changed;

with a system having a variable compression, the cylinder compression is changed;

with a system having a variable camshaft adjustment, the position and elevation of the inlet valve is changed; and,

with a system having a swirl flap, the position of the swirl flap is changed.

4. The electronic control arrangement of claim **1**, wherein said engine is a direct-injection spark-ignition engine or a diesel engine in stratified operation; and, the outputted torque is changed by varying the time point of injection.

5. The electronic control arrangement of claim **1**, wherein said means for providing said first quantities (Ka) and said second quantities (Kvi) are adapted to detect the torque of said engine.

6. A method for equalizing torque contributions of different cylinders of an internal combustion engine to the total torque of the engine which can operate in an overrun mode and in a fired mode, the method comprising the steps of:

providing first quantities (Ka) of a rough running of said engine in said overrun mode and second quantities (Kvi) in said fired mode;

providing third quantities (Ksi) for a rough-running component based on torsion vibrations;

forming cylinder-individual fourth quantities (Kki) for said rough running from said first, second and third quantities with said fourth quantities being independent of the rough running in said overrun mode and independent of the rough-running component based on said torsion vibrations; and,

equalizing said torque contributions on the basis of said fourth quantity.

7. The method of claim **6**, wherein said engine includes actuator means for operating on at least one of the following functions thereof: fuel metering to said engine, air supplied to said engine, the ignition, cylinder compression, drive of camshaft valves and drive of a swirl flap; and, wherein the method comprises the further steps of:

providing a plurality of controllers corresponding individually to respective ones of said cylinders; and, conducting said fourth quantities to said controllers wherein drive signals are formed for said actuator means to thereby intervene in at least one of said functions.

8. The method of claim **7**, wherein the method provides for intervening individually or in combination as follows in dependence upon the deviations which occur on said engine:

extending the injection time of those ones of said cylinders which output less torque while simultaneously shortening the injection time of those ones of said cylinders which output more torque with the extending and shortening being so computed that the total quantity of fuel is unaffected and the lambda value of the mixture with which said engine is driven is not changed;

first compensating a torque which is too low by an advanced ignition angle;

with a system having exhaust-gas recirculation, reducing the rate of recirculating of the exhaust gas in the event that measured values fluctuate greatly;

with a system having variable control of the gas exchange valves, changing the control lines and/or the valve stroke;

with a system having a charge movement flap, changing the position of the charge movement flap;

with a system having a variable compression, changing the cylinder compression;

with a system having a variable camshaft adjustment, changing the position and elevation of the inlet valve; and, with a system having a swirl flap, changing the position of the swirl flap.

9. The method of claim **6**, wherein said engine is a direct-injection spark-ignition engine or a diesel engine in stratified operation; and, the outputted torque is changed by varying the time point of injection.

* * * * *

US005692471A

United States Patent [19]

Zhang

[11] Patent Number: 5,692,471

[45] Date of Patent: Dec. 2, 1997

[54] **METHOD AND ARRANGEMENT FOR CONTROLLING A VEHICLE**

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[73] Assignee: **Robert Bosch GmbH**, Stuttgart, Germany

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§ 371 Date: **Sep. 9, 1996**

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PCT Pub. Date: **Sep. 14, 1995**

[30] **Foreign Application Priority Data**

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[51] **Int. Cl.**[6] **F02D 41/00**

[52] **U.S. Cl.** **123/350**

[58] **Field of Search** 123/350, 333; 477/110; 364/426.04

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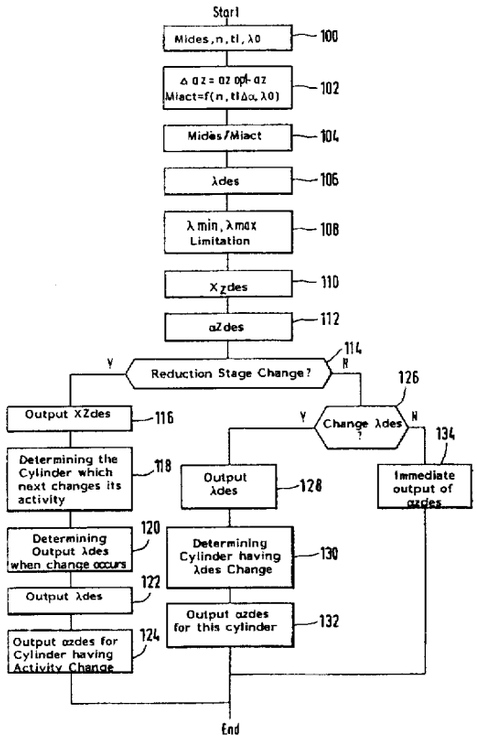
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Primary Examiner—Raymond A. Nelli
Attorney, Agent, or Firm—Walter Ottesen

[57] **ABSTRACT**

A method and an arrangement for controlling the drive power of a vehicle are suggested wherein, on the basis of a desired value for the torque to be outputted by the drive unit, the following are influenced in the sense of preparing the desired value: the ratio of the air supplied to the drive unit and of the fuel supplied as well as the ignition angle and/or the metering of fuel to the individual cylinders. The interventions into the air/fuel ratio as well as the ignition angle and/or the metering of fuel are synchronized with each other so that the torque-changing effects of the individual interventions occur essentially at the same time point especially at the same inducting cylinder.

10 Claims, 3 Drawing Sheets



VW EX1011
U.S. Patent No. 6,581,565

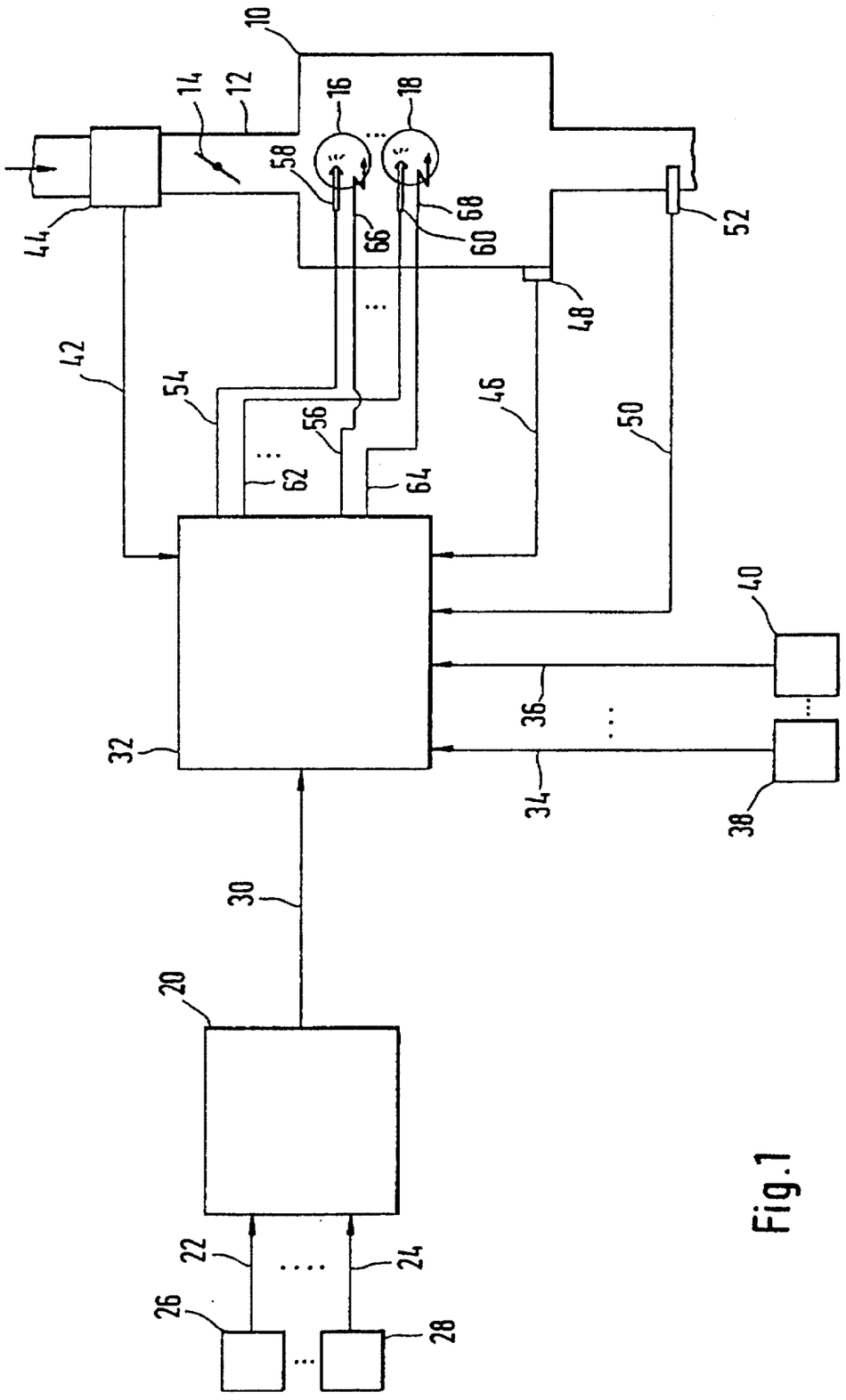

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Fig.1

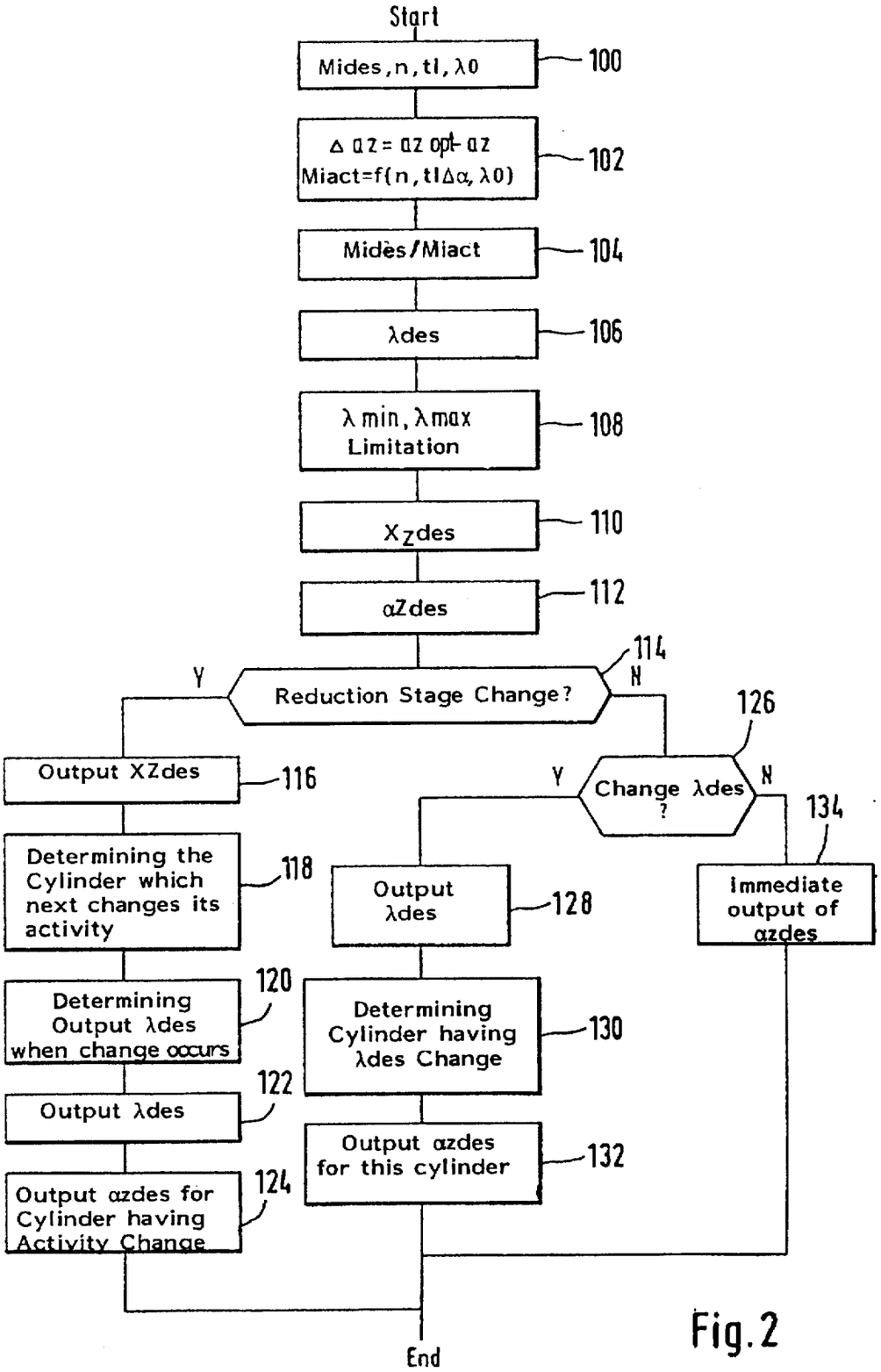
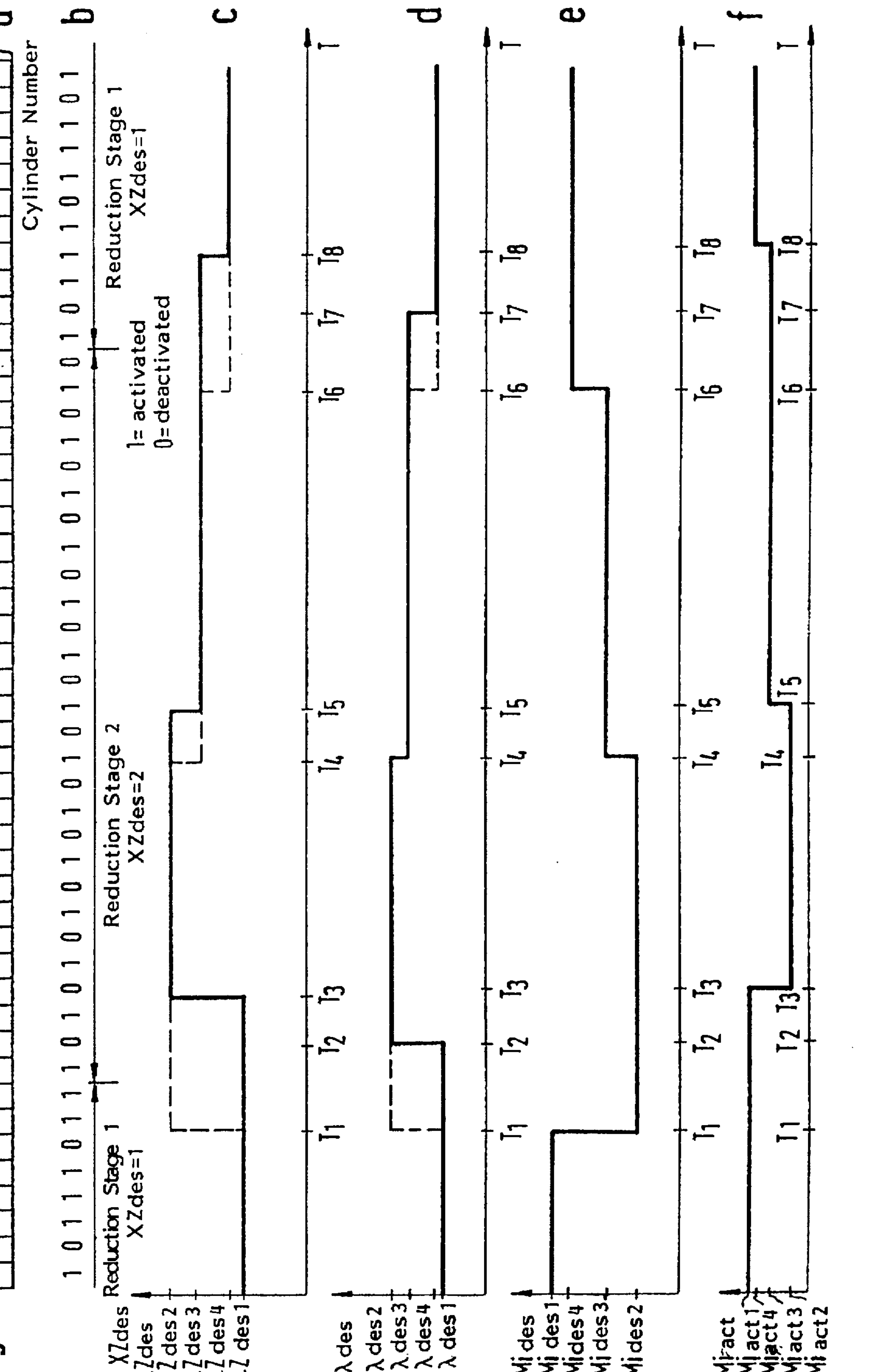

Start
Mides, n, tl, λ0
100
Δ αz = αz opt - αz
Miact=f(n, tl Δα, λ0)
102
Mides/Miact
104
λdes
106
λ min, λmax Limitation
108
Xzdes
110
αZdes
112
114
Y
Reduction Stage Change?
N
126
Output XZdes
116
Y
Change λdes ?
N
134
Determining the Cylinder which next changes its activity
118
Output λdes
128
Immediate output of αzdes
Determining Output λdes when change occurs
120
Determining Cylinder having λdes Change
130
Output λdes
122
Output αzdes for this cylinder
132
Output αzdes for Cylinder having Activity Change
124
End

Fig. 2

Fig.3


a
b
c
d
e
f
Cylinder Number
Reduction Stage 1
XZdes=1
Reduction Stage 2
XZdes=2
1= activated
0=deactivated
XZdes
αZdes
αZdes2
αZdes3
αZdes4
αZdes1
λdes
λdes2
λdes3
λdes4
λdes1
Midest
Midest1
Midest4
Midest3
Midest2
Miact
Miact1
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Miact3
Miact2
T1
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METHOD AND ARRANGEMENT FOR CONTROLLING A VEHICLE

BACKGROUND OF THE INVENTION

Such a method and such an arrangement are known from U.S. Pat. No. 5,103,928. There, to control the drive slip of a vehicle, it is suggested to determine the maximum drive torque, which can be transferred from the driven wheels, on the basis of operating variables of the vehicle and/or its drive unit and to transfer this drive torque to a central control arrangement of the internal combustion engine for adjustment. Suitable measures for processing the supplied maximum transferrable drive torque and for adjusting the torque of the drive motor in the central control arrangement are not described.

SUMMARY OF THE INVENTION

In view of the above, it is an object of the invention to provide measures for adjusting the torque of a drive motor of a vehicle by influencing power parameters of the drive motor via fuel metering, mixture composition, ignition angle and/or air supply.

The conversion of a torque desired value for a drive motor of a drive unit in an internal combustion engine is known from U.S. Pat. No. 5,558,178. This is achieved by influencing the ignition angle, by interrupting or resuming the metering of fuel to individual cylinders and/or by influencing the air supplied to the engine. A variation of the fuel/air ratio to realize a rapid torque change is not described.

According to a further aspect of the invention, measures are therefore suggested which, supplementary to other types of intervention, permit a variation of the air/fuel ratio for a spark-ignition engine to realize a rapid torque change in dependence upon a desired torque of the drive unit.

The procedure of the invention permits the realization of a torque change by changing the air/fuel ratio. The change of the air/fuel ratio for adjusting torque is used in an advantageous manner as supplement for adjusting torque via ignition angle adjustment and/or via interrupting and resuming the metering of fuel to individual cylinders (cylinder suppression).

A decisive advantage of the procedure of the invention is that the driving comfort is considerably improved by finer and more precise adjustment of the engine torque. Furthermore, an improvement of the exhaust gas emission is obtained by the change of the air/fuel ratio for fuel-injection engines compared to the exclusive use of measures for cutting off the metering of fuel. In an advantageous manner, the protection of the outlet valve, elbow and catalytic converter against overtemperature is guaranteed as a consequence of the partial avoidance of the fuel shutoff or ignition angle retard adjustment.

A continuous comfortable adjustment of the engine torque is made possible by the synchronization of the ignition intervention and/or the injection intervention with the intervention into the air/fuel ratio.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be more closely explained with respect to the embodiments shown in the drawing.

FIG. **1** shows an overview block diagram of a control arrangement for a vehicle; whereas,

FIG. **2** shows a flowchart of a preferred embodiment of the procedure of the invention; and,

FIG. **3** shows time-dependent traces of exemplary signals with respect to which the operation of the procedure of the invention is explained in greater detail.

DESCRIPTION OF THE PREFERRED EMBODIMENTS OF THE INVENTION

In FIG. **1**, an overview block diagram of an arrangement for controlling a vehicle is shown. The arrangement includes a drive unit **10** in the form of an internal combustion engine which has an air intake system **12** having a throttle flap **14** actuable by the driver. Furthermore, two cylinders **16** and **18** of the multi-cylinder internal combustion engine **10** (spark-ignition engine) are shown in FIG. **1**. The lines **22** to **24** from measuring devices **26** to **28**, respectively, are connected to a first control unit **20**. The control unit **20** includes an output line **30** which leads to a second control unit **32**. In addition, input lines **34** to **36** from respective measuring devices **38** to **40** are connected to the second control unit **32**. A line **42** from a measuring device **44** for detecting the air input to the engine **10** is connected to the control unit **32** as is a line **46** from a measuring device **48** for detecting the rpm of the engine. A line **50** from a measuring device **52** for detecting the exhaust gas composition (λ) of the engine **10** is likewise connected to the control unit **32**. Output lines **54** to **56** lead to respective injection valves **58** to **60** with an injection valve being assigned to each cylinder. Devices **66** to **68** are assigned to each cylinder and output lines **62** to **64** lead to devices **66** to **68**, respectively, for controlling the ignition time point.

The operation of the arrangement shown in FIG. **1** is described with respect to the example of the function of drive-slip control. The control unit **20** defines a drive-slip control system to which signals with respect to the rotational speed of the vehicle wheels are supplied via lines **22** to **24**. On the basis of these signal values, the control unit **20** determines a desired value for the torque of the drive motor **10** which is to be adjusted by the control unit **32**. This desired value is outputted by the control unit **20** via the line **30** to the control unit **32**. This desired value is made available by the control unit **32** while utilizing the operating variables (which are supplied to the control unit **32**) by influencing the metered fuel to individual cylinders and/or by influencing the ignition angle as well as by changing the composition of the air/fuel mixture in the sense of approximating the torque outputted by the engine **10**.

In addition to the described function of the control unit **20**, the control unit **20** can, in other advantageous embodiments, be a transmission control unit which determines the output torque to be outputted by the drive train and outputs an adjusting desired value for the torque of the drive motor via the line **30** to the control unit **32**. In another embodiment, the control unit **20** can be a higher-order control unit for the common control of at least the transmission unit and the drive motor or an arrangement for limiting the maximum torque, the road speed or engine speed in one or several operating states.

The following basic interrelationships and realizations form the basis for the conversion of the desired torque value by the control unit **32**. The torque, which is generated by the combustion operations in the individual cylinders, (the indicated torque Mi) is essentially dependent upon the engine speed Nmot, the engine load Tl (adjusted by the cylinder charge), the adjusted injection time Ti as well as the ignition angle αz. The torque desired value is prepared by influencing the air/fuel ratio, the fuel metered to individual cylinders and by adjusting the ignition angle. In this way, the injection

time is defined by the λ-value adjusted in each case for the exhaust gas composition and the so-called reduction stage XZ. This reduction stage XZ defines the number of suppressed cylinders per complete work cycle of the engine, that is, the number of cylinders to which the fuel is interrupted. The indicated engine torque can therefore be defined by the following dependency:

$$Mi=f(Nmot, T1, \alpha z, \lambda, XZ) \quad (1)$$

The indicated engine torque is thereby pregiven by the control unit **20** as the desired value. Accordingly, the task is then to compute the actual variables αz, λ and XZ. The basic consideration here is the breakdown of the dependencies according to equation (1) into individual functions according to physical viewpoints:

$$Mi=f1(Nmot, Tl)*f2(\Delta\alpha z)*f3(\lambda)*f4(XZ) \quad (2)$$

wherein:

$$\Delta\alpha z=\alpha zopt(Nmot, Tl, \lambda)-\alpha z \text{ and } f4(XZ)=1-XZ/ZZ \quad (3)$$

In equation (3), αzopt is then the optimal ignition angle determined for a maximum torque on the basis of engine rpm, engine load and exhaust gas composition and αz is the actual ignition angle adjusted on the basis of a known rpm-load characteristic field. ZZ is the maximum possible stage number for the cylinder suppression (for example, in the simplest case, for a four-cylinder engine **4**).

The components of the equation (2) have physical significance. f1 corresponds to the indicated engine torque for optimal ignition angle, λ=1 (stoichiometric ratio and fuel input to all cylinders (XZ=0). f2 corresponds to the contribution of the ignition angle deviation or ignition angle adjustment to the engine torque, that is, the contribution of the deviation of the adjusted ignition angle from the optimal ignition angle. f3 identifies the torque contribution for a changed air/fuel ratio and the function f3 for λ=1 is one. f4 identifies the torque contributions via suppression of individual cylinders. This function is 1 when no cylinder is suppressed, that is, fuel is supplied to all cylinders. The functions f1 to f4 define experimentally determined characteristic fields or characteristic lines in which the absolute torque value (f1) or the relative torque change (f2 to f4 is included in dependence upon the identified variables.

The load signal Tl is determined from the signal of a hot-wire air mass sensor or from the signal of a hot-film air mass sensor or from the signal of an intake pipe pressure sensor or an air quantity sensor while considering the engine rpm.

The desired torque is made available by adjusting the variables λdes, αzdes and XZdes. These variables can be computed in accordance to various strategies. In the following, two of these strategies are explained in greater detail and have been shown to be especially suitable in the embodiments. A first strategy imparts a higher priority to the intervention into the air/fuel ratio than to the intervention into the fuel metering (cylinder suppression) and the ignition angle adjustment; whereas, a second strategy imparts a higher priority to the cylinder suppression compared to the intervention into the air/fuel ratio and the ignition angle intervention. In other embodiments, any other possible priority distribution can be selected.

For this purpose, the adjusted torque Miact must be first determined in normal operation without intervention for λ=λ0, characteristic field ignition angle αz and reduction stage XZ 0 (no cylinder suppression) via an estimate:

$$Miact=f1(Nmot, Tl)*f2(\alpha zopt-\alpha z)*f3(\lambda 0)*f4(0) \quad (4)$$

wherein:

$$f3(\lambda 0)=1 \text{ for } \lambda 0=1 \text{ and } f4(0)=1$$

The intervention into the air/fuel ratio is necessary for adjusting the desired torque Mides and shows the priority. This intervention results while considering equation (4) by solving equation (3) as follows:

$$\lambda des=f3^{-1}\{Mides*f3(\lambda 0))/Miact\} \quad (5)$$

If the desired value for the torque of the engine then deviates from the estimated value without intervention, a desired value for the adjustment of the air/fuel ratio is determined in accordance with the above equation. This desired value at least reduces the difference between the desired value and the actual value without intervention. The desired value λdes is not permitted to depart from its permissible range which is determined via a reliable firing of the cylinders. If the desired value lies outside of this permissible range, then the desired value is limited to the minimum or maximum value.

From the value λ, which is adjusted in accordance with the desired value for the air/fuel ratio, the torque contribution of this adjustment is determined with the aid of the function f3 and equation (2) is solved to determine the number of cylinders XZ to be suppressed:

$$XZdes=\{1-Mides/(Miact*f3(\lambda)/f3(\lambda 0))\}*ZZ \quad (6)$$

If the number of reduction stages is fixed, then the possibly remaining torque difference can be compensated by changing the ignition angle on the basis of equation (2). The influence of the shift of the air/fuel ratio on the optimal ignition angle should then be considered (g(λ)). The ignition angle αzdes, which is to be adjusted, then results as a function of the adjusted reduction stage and of the torque desired value while considering the influence of the adjusted air/fuel ratio on the optimal ignition angle:

$$\alpha zdes=\alpha zopt(Nmot, Tl)*g(\lambda)-f2^{-1}\{Mides/(f1(Nmot, Tl)*f3(\lambda)*f4(XZ))\} \quad (7)$$

By sequential computation of the actuating variables, the desired torque can be adjusted by influencing the air/fuel ratio, the fuel metered to individual cylinders as well as the ignition angle to be adjusted.

If in one embodiment or in specific operating phases and operating points (such as in warm running for lower torque reduction or limiting maximum speed), no interruption of the fuel metered to individual cylinders is permitted (that is, XZdes is always 0) then, in the same manner and on the basis of the above equations, a combined intervention into the air/fuel ratio and into the ignition angle is carried out.

The actual engine torque is computed according to equation (2) from the measured or computed actual values for the ignition angle, the cylinder suppression and λ and, if required, processed.

The adjustment of the desired value for the air/fuel ratio is carried out in a preferred embodiment by correcting the injection time Ti.

In addition to the above-described basic relationships, the time-dependent performance is to be considered to realize the corresponding function. In fuel injection systems, the fuel, which is to be injected into specific cylinders, in dependence upon load and rpm, is made available, that is, the fuel is injected at a specific crankshaft angle in advance of the induction stroke of the particular cylinder forward of the intake valve. The computation of the fuel quantity to be

injected is therefore carried out a certain time in advance of the induction of this quantity. This quantity then represents the operating state, which is present during the intake operation, no longer precisely. In contrast thereto, the computation of the ignition angle is carried out so that it is very current and completed directly in advance of the mixture ignition. To improve the torque performance, the interventions into ignition and fuel quantity must therefore be synchronized in such a manner that a change of the ignition angle takes place only for that cylinder wherein a change of fuel quantity takes place (in the sense of a change of the air/fuel ratio or in the sense of an interruption or resumption of the metering of fuel). A realization for such a synchronization is shown in the flowchart of FIG. **2** with respect to the embodiment having prioritized air/fuel ratio intervention.

After the start of the subprogram, which takes place in synchronism with the crankshaft or is time synchronized, the desired value for the engine torque Mides, the engine rpm Nmot, the engine load Tl as well as the exhaust gas composition λ0 are read in in the first step **100**. Thereafter, in step **102**, the ignition angle difference Δαz between the optimal ignition angle (which is determined in dependence upon engine rpm, engine load and λ from a characteristic field) and the actual adjusted ignition angle αz is computed. Also in step **102**, the actual outputted engine torque without intervention Miact is estimated from a characteristic field in dependence upon engine rpm, engine load, exhaust gas composition λ0 and the ignition angle deviation (equation 4). In the next step **104**, the ratio between the pregiven desired torque and the estimated torque without intervention is computed and in the next step **106**, the desired value λdes for the adjustment of the air/fuel ratio is determined (equation 5). Thereafter, λdes is limited in step **108**, if required, to a minimum value or a maximum value. In the next step **110**, the reduction stage (XZdes), which is to be adjusted, is determined (equation 6) on the basis of the following: torque value without intervention, value λ for the air/fuel ratio to be adjusted and the desired torque value as shown above. In the next step **112**, the ignition angle αzdes, which is to be adjusted, is determined as a function of the following: desired torque value, torque for optimal ignition angle, value λ and the adjusted reduction stage in accordance with the above (equation 7). In the next inquiry step **114**, a check is made as to whether a change of the reduction stage compared to the previous state was computed in step **110**.

If this is the case, then, in step **116**, the desired value for the reduction stage change is outputted and, in the next step **118**, that cylinder is determined which is next to change its activity, that is, which changes its state from the switched-off into the resumed state or from the fired state into the switched-off state. Thereafter, in step **120**, the output time point for the desired value of the air/fuel ratio is determined and this is outputted at the given time point in accordance with step **122**, that is, the injection pulse, which is formed at this time point for a cylinder, is correspondingly corrected. The time point is so determined that, as a consequence of the early injection of the fuel, a change in the composition of the supplied mixture only takes place for that cylinder which, according to step **118**, changes its activity or that cylinder which follows such a cylinder. Correspondingly, in step **124**, the ignition angle desired value for the cylinder having activity change or for the next cylinder is outputted and the subprogram is ended.

If it is detected in step **114**, that no change of the reduction stage was computed, then a check is made in inquiry step **126** as to whether a change was determined in the air/fuel ratio. In this case, and in accordance with step **128**, the desired value λdes is outputted and a determination is made in the next the step **130** as to which cylinder is first to be ignited with the changed air/fuel ratio. The early injection of the fuel is primarily dependent upon engine rpm and engine load so that the time point can be determined on the basis of this operating data. The output of the desired value for the ignition angle adjustment takes place in accordance with step **132** for this cylinder. Thereafter, the subprogram is ended.

If it was detected in step **126** that no change in the air/fuel ratio was determined, then, in step **134**, the desired ignition angle is immediately outputted and the subprogram is ended.

In summary, it can be stated that the torque intervention of each actuating variable is synchronized with the other variable or other variables. This leads to the situation that the torque change, overall, takes place essentially at the same time point and therefore no unsatisfactory performance of the engine torque takes place. This would follow when each actuating variable became effective immediately and therefore the torque change, which is caused by each actuating variable, takes place at different time points.

In the embodiment of FIG. **2**, the intervention into the air/fuel ratio is provided with the highest priority. In other embodiments or in other operating phases such as in operating phases having high power requirements on the engine, it can be advantageous to assign the highest priority to the switchoff and resumption of individual cylinders. In this case (in lieu of step **106**), the desired reduction stage XZdes is determined on the basis of the ratio of the desired torque to the torque without intervention. Then, in the two next steps, λdes is determined on the basis of the following: desired torque, estimated torque without intervention and the reduction stage which is to be adjusted. λdes is then limited according to step **108**. The further program sequence with step **112** and the other steps is to be correspondingly applied.

As mentioned above, the functions f2(Δαz), f3(λ) and g(λ) are experimentally determined characteristic fields or characteristic lines in a preferred embodiment. In another mathematical description and in another advantageous embodiment, there are polynomes of the first and/or second order and/or higher orders with the constants of the polynome being dependent upon engine rpm and engine load.

In addition to the preferred description of the equations (2) and (7) as multiplication, a breakdown into functions in the form of an addition is likewise advantageous.

Typical time-dependent traces are shown in FIG. **3** to show the operative effects of the procedure of the invention.

In FIG. **3***a*, the cylinders of a four-cylinder engine are shown and, in FIG. **3***b*, the activities of these cylinders are shown. Here, the numeral **1** shows a fired cylinder and **0** shows a switched-off cylinder. FIG. **3***c* shows the time-dependent trace of the ignition angle and FIG. **3***d* shows the time-dependent trace of the air/fuel ratio. FIG. **3***e* shows the time-dependent trace of the engine desired torque and FIG. **3***f* shows the time-dependent trace of the engine torque itself. The illustration in FIG. **3** proceeds from an exemplary operating state wherein the fuel metered to one cylinder is already injected during the intake stroke of the previous cylinder. Stated otherwise, in the exemplary operating state, the early injection of the fuel takes place in advance by a half revolution of the camshaft or one revolution of the crankshaft.

Up to a time point T1, the value Mides1 is established as the desired value for the engine torque. This value is realized

by the reduction stage 1 (in which the cylinder 2 is suppressed and the other cylinders are fired) by the desired ignition angle αzdes1 and the air/fuel ratio λ1 . At time point T1, the desired engine torque value changes to the value Mides2. For realizing this desired torque Mides2, the following is computed: the reduction stage 2 (in which additionally the cylinder 4 is suppressed), the ignition angle αzdes2 and λ2 at time point T1. As a consequence of the early introduction of the fuel, the change in reduction stage is realized only at time point T3 (at which the newly suppressed cylinder 4 intakes). If the ignition angle change as well as the change of the air/fuel ratio would be carried out at time point T1, this would have a torque increasing effect as a consequence in the embodiment shown at time point T1 and at time point T2 because the change in the ignition angle and in the air/fuel ratio compensate the torque reduction which is too great by changing the reduction stage. A torque increase starting at time point T1 is unwanted so that the realization of the λ change and the ignition angle change is delayed. At time point T2, when the fuel for the newly suppressed cylinder 4 would be injected, the computed injection pulse is corrected by λdes. This has the consequence that, starting with cylinder 4 after the time point T3, an air/fuel ratio λ2 is adjusted. Ignition angle changes become immediately effective so that the change of the ignition angle to the value αzdes2 is carried out at time point T3 (at which time the newly suppressed cylinder 4 intakes). As a result, starting with time point T3, a reduction of the engine torque to the value Mi2 results in accordance with the pregiven desired value without an unwanted increase in the engine torque in advance of the time point T3. The interventions into the following are therefore synchronized: fuel metering, ignition angle and air/fuel ratio.

A further example shows a change of the engine torque without a change of the reduction range being necessary. At time point T4, the desired torque is increased from the value Mides2 to the value Mides3. Therefore, at this time point and to realize the engine torque, an ignition angle change to the value αzdes3 and the change of the air/fuel ratio to the value λ3 with torque reducing effect are computed. Since the torque change is so small that a change of the reduction stage is not necessary, the λ change can become effective at time point T4. The actual computed injection pulse is corrected. In the embodiment shown, λdes is changed at time point T4 during the intake stroke of the cylinder 1. This change becomes effective for cylinder 3. For this reason, the change of the ignition angle is delayed up to time point T5 at which the cylinder 3 inducts. The result is an increase of the engine torque at time point T5 to the value Mi3 without a torque change operating against the increase having taken place before the time point T5. The intervention into the air/fuel ratio and the ignition angle intervention are therefore synchronized.

At time point T6, a further increase of the engine desired torque value to the value Mides4 is pregiven. As with respect to time point T1, this change leads to a change of the reduction stage wherein the deactivated cylinder 4 is again activated. The effect of the reduction stage change on the engine torque takes place only at time point T8 during the induction stroke of the cylinder 4. For this reason, the changes in the air/fuel ratio and in the ignition angle are correspondingly delayed. The change in the air/fuel ratio takes place at time point T7 when the fuel provided for cylinder 4 is injected; whereas, the immediate effective ignition angle change is carried out only at time point TS. The result is a change of the torque at time point T8 to the value Mi4. Here too, the three position interventions are synchronized with each other.

In FIG. 3, the effects of the intervention into the air/fuel ratio and into the ignition angle are each shown in the same direction. In other advantageous embodiments, these work in opposite directions in that, for example, the extent of the change in the air/fuel ratio is so selected because of reasons related to the exhaust gas (for example, a jump over of regions with toxic exhaust gas components), that the engine torque is reduced too far and is compensated by corresponding torque increasing interventions into the ignition angle or vice versa. In addition to the above interventions via injection suppression, air/fuel ratio and injection angle, the realization of the desired torque is carried out by influencing the air supply, for example, via a throttle flap or a bypass valve.

I claim:

1. A method of controlling a torque of an internal combustion engine to a changeable pregiven desired value (Mides), the method comprising the steps of:

controlling at least one of the following parameters which influence said torque of said engine:

(a air/fuel ratio (λ);

(b) ignition angle (αz); and,

(c) number of deactivated cylinders (XZ);

so that said torque approaches said desired value (Mides) thereof by performing the following additional steps:

forming a desired value (λdes, αzdes, XZdes) for said at least one of said parameters (λ, αz, XZ) in dependence upon said desired value (Mides) of said torque, the engine load (tl) and the respective settings of said air/fuel ratio (λ), said ignition angle (αz) and said number of deactivated cylinders (XZ); and,

controlling said at least one of said parameters (λ, αz, XZ) to said at least one of said desired values (λdes, αzdes, XZdes) thereby causing the torque of said engine to approach said desired value (Mides).

2. The method of claim 1, wherein, based on said desired value (Mides) of said torque, a corresponding input value is computed for controlling at least one of the following: air supply, metering of fuel and ignition.

3. The method of claim 1, wherein influencing the ignition angle, metering of fuel and air/fuel ratio are so synchronized with each other that their effects on the torque of the drive unit become effective each time for the same inducting cylinder.

4. The method of claim 1, wherein the intervention into the metering of fuel is realized by suppressing the metering of fuel to individual predetermined cylinders and by adjusting the air/fuel ratio.

5. The method of claim 1, wherein: starting from the desired value for the torque, the engine rpm and the engine load, the adjusted ignition angle as well as the adjusted air/fuel ratio, first a desired value for the air/fuel ratio and then the number of deactivated cylinders and then the change of the ignition angle is determined in such a manner that the desired value for the torque is adjusted.

6. The method of claim 1, wherein: starting from the desired value for the following: the torque, the engine rpm and the engine load of the adjusted ignition angle as well as of the adjusted air/fuel ratio, first the number of deactivated cylinders and then a desired value for the air/fuel ratio and then the ignition angle change is determined in such a manner that the desired value for the torque is adjusted.

7. The method of claim 1, wherein the desired value (λdes) for the air/fuel ratio is adjusted for a spark-ignition engine by correcting the fuel quantity to be injected.

8. The method of claim 1, wherein the desired value (Mides) of said torque is outputted by a control apparatus for

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controlling drive slip in the case of an impermissibly high slip at least at one of the drive wheels, or is outputted by a transmission control unit or an arrangement for limiting the torque, rpm or road speed when a limit value is exceeded.

9. The method of claim **1**, wherein the intervention into the air/fuel ratio (λ) and the ignition angle (αz) is undertaken when the intervention into the metering of fuel to individual cylinders (cylinder deactivation) is forbidden.

10. An arrangement for controlling a toque of an internal combustion engine to a changeable pregiven desired value (Mides), the arrangement comprising:

means for controlling at one of the following parameters which influence said torque of said engine:

(a) air/fuel ratio (λ);

(b) ignition angle (αz); and

(c) number of deactivated cylinders (XZ);

means for forming a desired value (λdes, αzdes, XZdes) for said at least one of said parameters (λ, αz, XZ) in dependence upon said desired value (Mides) of said torque, the engine load (tl) and respective settings of said air/fuel ratio (λ), said ignition angle (αz) and said number of deactivated cylinders (XZ); and,

means for controlling said at least one of said parameters (λ, αz, XZ) to said at least one of said desired values (λdes, αzdes, XZdes) thereby causing the torque of said engine to approach said desired value (Mides).

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,692,471
DATED : December 2, 1997
INVENTOR(S) : Hong Zhang

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In column 3, line 31: delete "ratio" and substitute -- ratio) -- therefor.

In column 3, line 42: delete "f4" and substitute -- f4) -- therefor.

In column 7, line 64: delete "TS" and substitute -- T8 -- therefor.

In column 8, line 21: delete "(a air" and substitute -- (a) air -- therefor.

In column 9, line 9: delete "toque" and substitute -- torque -- therefor.

In column 9, line 12: between "at" and "one", insert -- least --.

Signed and Sealed this

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Foreword to the 5th Edition

The "Automotive Handbook", a reliable guide full of up-to-date and concise information, has grown over a period of six decades from a calendar supplement of 96 pages to a 960-page reference work. In that time, over a million copies have been produced worldwide and the text translated into numerous languages.

The 5th edition, in common with its predecessors, is supported by two main pillars: the expertise of the technical staff at our company and in the automotive industry. They have fully revised the contents of this manual and brought it completely up to date. Thanks are due to all those involved.

This book is intended primarily as a source of important facts and figures and as a review of present-day technology for the automotive engineer and technician, but also for anyone else with an interest in technical matters. Accordingly, the automotive technology content is restricted to passenger cars and commercial vehicles, and the remaining content to that required for practical purposes.

Within the framework of a pocketbook it is impossible to present detailed coverage of individual technical subjects. On the other hand, bearing in mind the very wide range of readers, we do not want to dispense with generally applicable topics and data. However, we have dispensed with the "Conversion Tables" as the calculator is now an everyday item of equipment and any figure required can easily be calculated using the conversion formulas provided. The chapter "Road Traffic Legislation (Germany)" has also been deleted due to the international usage of the booklet.

These deletions have made way for new and updated topics which have added an extra 70 pages to the book.

We recommend readers to scan through the "Automotive Handbook" in order to gain an overall impression before using it.

The Editors

For your information

The following topics have been updated/extended since the 4th edition:

Vibration • Acoustics • Electronics (integrated circuits, micromechanics, mechatronics, sensors) • Statistics • Reliability • Closed and open-loop control systems • Materials technology (basic principles, materials, lubricants, fuels, consumables) • Corrosion • Hardness • Calculating fuel consumption • Vehicle dynamics.

Internal-combustion engines (direct fuel injection, diesel combustion systems) • Engine cooling (cooling-module technology, thermomanagement, exhaust cooling) • Turbochargers and superchargers (multistage) • Engine management on gasoline engines (mixture control, fuel-injection systems, fuel injectors, spark plugs, ME-Motronic, exhaust gases) • Engine management on diesel engines (axial/radial-piston pumps, injectors, exhaust gases, start-assist systems).

Electric drive units • Drivetrain (transmission, traction control systems (TCS) for passenger cars and commercial vehicles) • Steering • Braking systems (ABS for passenger cars, ABS and EBS for commercial vehicles) • Bodywork, commercial vehicles • Lighting systems (stepped reflectors, Bi-Litronic, headlamps and lights).

Car radios • Park Pilot systems • Navigation systems • Vehicle information systems • Mobile phones • Safety and security systems (impact detection, interior-movement detection) • Automotive hydraulics (electric proportional control valves).

Circuit diagrams and symbols • Vehicle electrical system (batteries, battery testers, water-cooled alternators, electromagnetic compatibility (EMC))

Passenger-car specifications.

The following topics have been introduced:

Fuel filters • MED-Motronic • Natural gas operation (spark-ignition engines) • Fuel cells • EHB for passenger cars • Automatic Cruise Control (ACC) • Instrumentation • Traffic telematics • Car radios (DAB) • Connectors • Cartronic.

and the following have been dropped:

Conversion tables • Road traffic legislation (Germany).

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Quantities and units

SI units

SI denotes "Système International d'Unités" (International System of Units). The system is laid down in ISO 31 and ISO 1000 (ISO: International Organization for Standardization) and for Germany in DIN 1301 (DIN: Deutsches Institut für Normung – German Institute for Standardization).

SI units comprise the seven base SI units and coherent units derived from these base SI units using a numerical factor of 1.

Base SI units

Base quantity and symbols		Base SI unit Name	Symbol
Length	l	meter	m
Mass	m	kilogram	kg
Time	t	second	s
Electric current	I	ampere	A
Thermodynamic temperature	T	kelvin	K
Amount of substance	n	mole	mol
Luminous intensity	I	candela	cd

All other quantities and units are derived from the base quantities and base units. The international unit of force is thus obtained by applying Newton's Law:

force = mass × acceleration

$F = m \cdot a$

where m = 1 kg and a = 1 m/s², thus F = 1 kg · 1 m/s² = 1 kg · m/s² = 1 N (newton).

Definitions of the base SI units

1 meter is defined as the distance which light travels in a vacuum in 1/299,792,458 seconds (17th CGPM, 1983[1]). The meter is therefore defined using the speed of light in a vacuum, c = 299,792,458 m/s, and no longer by the wavelength of the radiation emitted by the krypton nuclide ^{86}Kr. The meter was originally defined as the forty-millionth part of a terrestrial meridian (standard meter, Paris, 1875).

1 kilogram is the mass of the international prototype kilogram (1st CGPM, 1889 and 3rd CGPM, 1901[1]).

1 second is defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of atoms of the ^{133}Cs nuclide (13th CGPM, 1967.[1])

1 ampere is defined as that constant electric current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-sections, and placed 1 meter apart in a vacuum will produce between these conductors a force equal to 2 x 10^{-7} N per meter of length (9th CGPM, 1948.[1])

1 kelvin is defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point[2]) of water (13th CGPM, 1967.[1])

1 mole is defined as the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of the carbon nuclide ^{12}C. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles (14th CGPM[1]), 1971.

1 candela is the luminous intensity in a given direction of a source which emits monochromatic radiation of frequency 540 x 1012 hertz and of which the radiant intensity in that direction is 1/683 watt per steradian (16th CGPM, 1979.[1])

Decimal multiples and fractions of SI units

Decimal multiples and fractions of SI units are denoted by prefixes before the name of the unit or prefix symbols before the unit symbol. The prefix symbol is placed immediately in front of the unit symbol to form a coherent unit, such as the milligram (mg). Multiple prefixes, such as microkilogram (µkg), may **not** be used.

---

[1]) CGPM: Conférence Générale des Poids et Mesures (General Conference on Weights and Measures).

[2]) Fixed point on the international temperature scale. The triple point is the only point at which all three phases of water (solid, liquid and gaseous) are in equilibrium (at a pressure of 1013.25 hPa). This temperature of 273.16 K is 0.01 K above the freezing point of water (273.15 K).

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Prefixes are not to be used before the units angular degree, minute and second, the time units minute, hour, day and year, and the temperature unit degree Celsius.

Prefix	Prefix symbol	Power of ten	Name
atto	a	10^{-18}	trillionth
femto	f	10^{-15}	thousand billionth
pico	p	10^{-12}	billionth
nano	n	10^{-9}	thousand millionth
micro	μ	10^{-6}	millionth
milli	m	10^{-3}	thousandth
centi	c	10^{-2}	hundredth
deci	d	10^{-1}	tenth
deca	da	10^{1}	ten
hecto	h	10^{2}	hundred
kilo	k	10^{3}	thousand
mega	M	10^{6}	million
giga	G	10^{9}	milliard[1])
tera	T	10^{12}	billion[1])
peta	P	10^{15}	thousand billion
exa	E	10^{18}	trillion

Legal units

The Law on Units in Metrology of 2 July 1969 and the related implementing order of 26 June 1970 specify the use of "Legal units" in business and official transactions in Germany.[2])

Legal units are
- the SI units,
- decimal multiples and submultiples of the SI units,
- other permitted units; see the tables on the following pages.

Legal units are used in the Bosch Automotive Handbook. In many sections, values are also given in units of the technical system of units (e.g. in parentheses) to the extent considered necessary.

[1]) In the USA: 10^9 = 1 billion, 10^{12} = 1 trillion.
[2]) Also valid: "Gesetz zur Änderung des Gesetzes über Einheiten im Meßwesen" dated 6 July 1973; "Verordnung zur Änderung der Ausführungsverordnung" dated 27 November 1973; "Zweite Verordnung zur Änderung der Ausführungsverordnung" dated 12 December 1977.

Systems of units not to be used

The physical system of units

Like the SI system of units, the physical system of units used the base quantities length, mass and time. However, the base units used for these quantities were the centimeter (cm), gram (g), and second (s) (CGS System).

The technical system of units

The technical system of units used the following base quantities and base units:

Base quantity	Base unit Name	Symbol
Length	meter	m
Force	kilopond	kp
Time	second	s

Newton's Law, $F = m \cdot a$, provides the link between the international system of units and the technical system of units, where force due to weight G is substituted for F and acceleration of free fall g is substituted for a.

In contrast to mass, acceleration of free fall and therefore force due to weight depend upon location. The standard value of acceleration of free fall is defined as g_n = 9.80665 m/s² (DIN 1305). The approximate value

g = 9.81 m/s²

is generally acceptable in technical calculations.

1 kp is the force with which a mass of 1 kg exerts pressure on the surface beneath it at a place on the earth. With

$G = m \cdot g$,

thus

1 kp = 1 kg · 9.81 m/s² = 9.81 N.

Quantities and units

Overview (from DIN 1301)

The following table gives a survey of the most important physical quantities and their standardized symbols, and includes a selection of the legal units specified for these quantities. Additional legal units can be formed by adding prefixes (see P. 13). For this reason, the column "other units" only gives the decimal multiples and submultiples of the SI units which have their own names. Units which are not to be used are given in the last column together with their conversion formulas. Page numbers refer to conversion tables.

Quantity and symbol	Legal units SI	Others	Name	Relationship	Remarks and units not to be used, incl. their conversion
1. Length, area, volume (PP. 19 ... 20)					
Length l	m		meter		1 µ (micron) = 1 µm 1 Å (ångström) = 10^{-10} m 1 X.U. (X-unit) = 10^{-13} m 1 p (typograph. point) = 0.376 mm
		nm	international nautical mile	1 nm = 1852 m	
Area A	m^2		square meter		
		a	are	1 a = 100 m^2	
		ha	hectare	1 ha = 100 a = 10^4 m^2	
Volume V	m^3		cubic meter		
		l, L	liter	1 l = 1 L = 1 dm^3	
2. Angle (P. 21)					
(Plane) angle α, β etc.	rad[1])		radian	1 rad = $\frac{1\text{ m arc}}{1\text{ m radius}}$	
		°	degree	1 rad = 180°/π = 57.296° ≈ 57.3°	1 L (right angle) = 90° = (π/2) rad = 100 gon
		′	minute	1° = 0.017453 rad	1ᵍ (centesimal degree) = 1 gon
		″	second	1° = 60′ = 3600″	1ᶜ (centesimal minute) = 1 cgon
		gon	gon	1 gon = (π/200) rad	1ᶜᶜ (centesimal second) = 0.1 mgon
Solid angle Ω	sr		steradian	1 sr = $\frac{1\text{ m}^2\text{ spherical surface}}{1\text{ m}^2\text{ sphere radius}^2}$	
3. Mass (PP. 22 ... 23)					
Mass (weight)[2]) m	kg		kilogram		1 γ (gamma) = 1µg 1 quintal = 100 kg 1 Kt (karat) = 0.2 g
		g	gram		
		t	ton	1 t = 1 Mg = 10^3 kg	

[1]) The unit rad (P. 21) can be replaced by the numeral 1 in calculations.
[2]) The term "weight" is ambiguous in everyday usage; it is used to denote mass as well as weight (DIN 1305).

Quantity and symbol	Legal units SI	Others	Name	Relationship	Remarks and units not to be used, incl. their conversion
Density ϱ	kg/m³			1 kg/dm³ = 1 kg/l = 1 g/cm³ = 1000 kg/m³	Weight per unit volume γ (kp/dm³ or p/cm³). Conversion: The numerical value of the weight per unit volume in kp/dm³ is roughly equal to the numerical value of the density in kg/dm³
		kg/dm³			
		kg/l			
		g/cm³			
Moment of inertia J (mass moment, 2nd order)	kg · m²			$J = m \cdot i^2$ i = radius of gyration	Flywheel effect $G \cdot D^2$. Conversion: Numerical value of $G \cdot D^2$ in kp · m² = 4 x numerical value of J in kg · m²

4. Time quantities (P. 28)

Time, duration, interval t	s		second[1]		In the energy industry, one year is calculated at 8760 hours
		min	minute[1]	1 min = 60 s	
		h	hour[1]	1 h = 60 min	
		d	day	1 d = 24 h	
		a	year		
Frequency f	Hz		hertz	1 Hz = 1/s	
Rotational speed (frequency of rotation) n	s⁻¹			1 s⁻¹ = 1/s	min⁻¹ and r/min (revolutions per minute) are still permissible for expressing rotational speed, but are better replaced by min⁻¹ (1 min⁻¹ = 1 r/min = 1 min⁻¹)
		min⁻¹ 1/min		1 min⁻¹ = 1/min = (1/60)s⁻¹	
Angular frequency ω $\omega = 2\pi f$	s⁻¹				
Velocity v	m/s	km/h		1 km/h = (1/3.6) m/s	
		kn	knot	1 kn = 1 nm/h = 1.852 km/h	
Acceleration a	m/s²			acceleration of free fall g P.13	
Angular velocity ω	rad/s[2]				
Angular acceleration α	rad/s²[2]				

5. Force, energy, power (PP. 24 ... 25)

Force F Force G due to weight	N N		newton	1 N = 1 kg · m/s²	1 p (pond) = 9.80665 mN 1 kp (kilopond) = 9.80665 N ≈ 10 N 1 dyn (dyne) = 10⁻⁵ N

[1]) Clock time: h, m, s written as superscripts; example: $3^h\,25^m\,6^s$.
[2]) The unit rad can be replaced by the numeral 1 in calculations.

Quantity and symbol	Legal units SI	Others	Name	Relationship	Remarks and units not to be used, incl. their conversion
Pressure, gen. p	Pa		pascal	1 Pa = 1 N/m²	1 at (techn. atmosphere) = 1 kp/cm² = 0.980665 bar ≈ 1 bar 1 atm (physical atmosphere) = 1.01325 bar[1]) 1 mm w.g. (water gauge) = 1 kp/m² = 0.0980665 hPa ≈ 0.1 hPa 1 torr = 1 mm Hg (mercury column) = 1.33322 hPa dyn/cm² = 1 µbar
Absolute pressure p_{abs} Atmospheric pressure p_{amb}		bar	bar	1 bar = 10^5 Pa = 10 N/cm² 1 µbar = 0.1 Pa 1 mbar = 1 hPa	
Gauge pressure p_e $p_e = p_{abs} - p_{amb}$	Gauge pressure etc. is no longer denoted by the unit symbol, but rather by a formula symbol. Negative pressure is given as negative gauge pressure. Examples: previously: 3 atg; 10 ata; 0.4 atu now: p_e = 2.94 bar ≈ 3 bar; p_{abs} = 9.81 bar ≈ 10 bar; p_e = −0.39 bar ≈ −0.4 bar				
Mechanical stress σ, τ	N/m²			1 N/m² = 1 Pa	1 kp/mm² = 9.81 N/mm² ≈ 10 N/mm² 1 kp/cm² ≈ 0.1 N/mm²
		N/mm²		1 N/mm² = 1 MPa	
Hardness (P. 274)	Brinell and Vickers hardness are no longer given in kp/mm². Instead, an abbreviation of the relevant hardness scale is written as the unit after the numerical value used previously (including an indication of the test force etc. where applicable).				Examples: previously: HB = 350 kp/mm² → now: 350 HB HV30 = 720 kp/mm² → 720 HV30 HRC = 60 → 60 HRC
Energy, work E, W Heat, Quantity of heat Q (P. 25)	J		joule	1 J = 1 N · m = 1 W · s = 1 kg m²/s²	1 kp · m (kilopondmeter) = 9.81 J ≈ 10J 1 HP · h (horsepower-hour) = 0.7355 kW · h ≈ 0.74 kW · h 1 erg (erg) = 10^{-7}J 1 kcal (kilocalorie) = 4.1868 kJ ≈ 4.2 kJ 1 cal (calorie) = 4.1868 J ≈ 4.2 J
		W · s	watt-second		
		kW · h	kilowatt-hour	1 kW · h = 3.6 MJ	
		eV	electron-volt	1 eV = 1.60219·10^{-19}J	
Torque M	N · m		newton-meter		1 kp · m (kilopondmeter) = 9.81 N · m ≈ 10 N · m
Power P Heat flow Q, (P. 25) Φ	W		watt	1 W = 1 J/s = 1 N · m/s	1 kp · m/s = 9.81 W ≈ 10 W 1 HP (horsepower) = 0.7355 kW ≈ 0.74 kW 1 kcal/s = 4.1868 kW ≈ 4.2 kW 1 kcal/h = 1.163 W

6. Viscosimetric quantities (P. 27)

Dynamic viscosity η	Pa · s		Pascal-second	1 Pa · s = 1 N s/m² = 1 kg/(s · m)	1 P (poise) = 0.1 Pa · s 1 cP (centipoise) = 1 mPa · s
Kinematic viscosity ν	m²/s			1 m²/s = 1 Pa · s/(kg/m³)	1 St (stokes) = 10^{-4} m²/s = 1 cm²/s 1 cSt (centistokes) = 1 mm²/s

[1]) 1.01325 bar = 1013.25 hPa = 760 mm mercury column is the standard value for atmospheric pressure.

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Quantity and symbol	Legal units SI	Others	Name	Relationship	Remarks and units not to be used, incl. their conversion
7. Temperature and heat (P. 26)					
Temperature T	K	kelvin		$t = (T - 273.15\ \mathrm{K})\ \frac{°C}{K}$	
Temperature t		°C	degree Celsius		
Temperature difference ΔT	K		kelvin	1 K = 1 °C	
Temperature difference Δt		°C	degree Celsius		
	In the case of composite units, express temperature differences in K, e.g. kJ/(m · h · K); tolerances for temperatures in degree Celsius, e.g. are written as follows: $t = (40 \pm 2)$ °C or $t = 40\ °C \pm 2\ °C$ or $t = 40\ °C \pm 2$ K.				
Refer to 5. for quantity of heat and heat flow.					
Specific heat capacity (spec. heat) c	$\frac{J}{kg \cdot K}$				1 kcal/(kg · grd) = 4.187 kJ/(kg · K) ≈ 4.2 kJ/(kg · K)
Thermal conductivity λ	$\frac{W}{m \cdot K}$				1 kcal/(m · h · grd) = 1.163 W/(m · K) ≈ 1.2 W/(m · K) 1 cal/(cm · s · grd) = 4.187 W/(cm · K) 1 W/(m · K) = 3.6 kJ/(m · h · K)
8. Electrical quantities (P. 60)					
Electric current I	A		ampere		
Electric potential U	V		volt	1 V = 1 W/A	
Electric conductance G	S		siemens	1 S = 1 A/V = 1/Ω	
Electric resistance R	Ω		ohm	1 Ω = 1/S = 1 V/A	
Quantity of electricity, electric charge Q	C		coulomb	1 C = 1 A · s	
		A · h	ampere-hour	1 A · h = 3600 C	
Electric capacitance C	F		farad	1 F = 1 C/V	
Electric flux density, displacement D	C/m^2				
Electric field strength E	V/m				

Quantity and symbol	Legal units SI	Others	Name	Relationship	Remarks and units not to be used, incl. their conversion
9. Magnetic quantities (P. 60)					
Magnetic flux Φ	Wb		weber	1 Wb = 1 V · s	1 M (maxwell) = 10^{-8} Wb
Magnetic flux density, induction B	T		tesla	1 T = 1 Wb/m²	1 G (gauss) = 10^{-4} T,
Inductance L	H		henry	1 H = 1 Wb/A	
Magnetic field strength H	A/m			1 A/m = 1 N/Wb	1 Oe (oersted) = $10^3/(4\pi)$ A/m = 79.58 A/m
10. Photometric quantities and units (P. 137)					
Luminous intensity I	cd		candela[1])		
Luminance L	cd/m²				1 sb (stilb) = 10^4 cd/m² 1 asb (apostilb) = $1/\pi$ cd/m²
Luminous flux Φ	lm		lumen	1 lm = 1 cd · sr (sr = steradian)	
Illuminance E	lx		lux	1 lx = 1 lm/m²	
11. Quantities used in atom physics and other fields					
Energy W		eV	electron-volt	1 eV= 1.60219 · 10^{-19}J 1 MeV= 10^6 eV	
Activity of a radioactive substance A	Bq		becquerel	1 Bq = 1 s^{-1}	1 Ci (curie) = 3.7 · 10^{10} Bq
Absorbed dose D	Gy		gray	1 Gy = 1 J/kg	1 rd (rad) = 10^{-2} Gy
Dose equivalent Dq	Sv		sievert	1 Sv = 1 J/kg	1 rem (rem) = 10^{-2} Sv
Absorbed dose rate $\dot{D}$				1 Gy/s = 1 W/kg	
Ion dose J	C/kg				1 R (röntgen) = 258 · 10^{-6}C/kg
Ion dose rate $\dot{J}$	A/kg				
Amount of substance n	mol		mole		

[1]) The stress is on the second syllable: the candela.

Conversion of units

Units of length

Unit		XU	pm	Å	nm	µm	mm	cm	dm	m	km
1 XU	=	1	10^{-1}	10^{-3}	10^{-4}	10^{-7}	10^{-10}	10^{-11}	10^{-12}	10^{-13}	—
1 pm	=	10	1	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	—
1 Å	=	10^{3}	10^{2}	1	10^{-1}	10^{-4}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	—
1 nm	=	10^{4}	10^{3}	10	1	10^{-3}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-12}
1 µm	=	10^{7}	10^{6}	10^{4}	10^{3}	1	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-9}
1 mm	=	10^{10}	10^{9}	10^{7}	10^{6}	10^{3}	1	10^{-1}	10^{-2}	10^{-3}	10^{-6}
1 cm	=	10^{11}	10^{10}	10^{8}	10^{7}	10^{4}	10	1	10^{-1}	10^{-2}	10^{-5}
1 dm	=	10^{12}	10^{11}	10^{9}	10^{8}	10^{5}	10^{2}	10	1	10^{-1}	10^{-4}
1 m	=	–	10^{12}	10^{10}	10^{9}	10^{6}	10^{3}	10^{2}	10	1	10^{-3}
1 km	=	–	–	–	10^{12}	10^{9}	10^{6}	10^{5}	10^{4}	10^{3}	1

Do not use XU (X-unit) and Å (ångström)

Unit		in	ft	yd	mile	n mile	mm	m	km
1 in	=	1	0.08333	0.02778	–	–	25.4	0.0254	–
1 ft	=	12	1	0.33333	–	–	304.8	0.3048	–
1 yd	=	36	3	1	–	–	914.4	0.9144	–
1 mile	=	63 360	5280	1760	1	0.86898	–	1609.34	1.609
1 n mile[1]	=	72 913	6076.1	2025.4	1.1508	1	–	1852	1.852
1 mm	=	0.03937	$3.281 \cdot 10^{-3}$	$1.094 \cdot 10^{-3}$	–	–	1	0.001	10^{-6}
1 m	=	39.3701	3.2808	1.0936	–	–	1000	1	0.001
1 km	=	39 370	3280.8	1093.6	0.62137	0.53996	10^{6}	1000	1

in = inch, ft = foot, y = yard, mile = statute mile, n mile = nautical mile

Other British and American units of length

1 µin (microinch) = 0.0254 µm,
1 mil (milliinch) = 0.0254 mm,
1 link = 201.17 mm,
1 rod = 1 pole = 1 perch = 5.5 yd = 5.0292 m,
1 chain = 22 yd = 20.1168 m,
1 furlong = 220 yd = 201.168 m,
1 fathom = 2 yd = 1.8288 m.

Astronomical units

1 l.y. (light year) = $9.46053 \cdot 10^{15}$ m (distance traveled by electromagnetic waves in 1 year),
1 AU (astronomical unit) = $1.496 \cdot 10^{11}$ m (mean distance from earth to sun),
1 pc (parsec, parallax second) = 206 265 AU = $3.0857 \cdot 10^{16}$ m (distance at which the AU subtends an angle of one second of arc).

Do not use

1 line (watch & clock making) = 2.256 mm,
1 p (typographical point) = 0.376 mm,
1 German mile = 7500 m,
1 geographical mile = 7420.4 m (≈ 4 arc minutes of equator).

[1]) 1 n mile = 1 nm = 1 international nautical mile = 1 arc minute of the degree of longitude. 1 knot = 1 n mile/h = 1.852 km/h.

Units of area

Unit		in^2	ft^2	yd^2	acre	$mile^2$	cm^2	m^2	a	ha	km^2
1 in^2	=	1	–	–	–	–	6.4516	–	–	–	–
1 ft^2	=	144	1	0.1111	–	–	929	0.0929	–	–	–
1 yd^2	=	1296	9	1	–	–	8361	0.8361	–	–	–
1 acre	=	–	–	4840	1	0.16	–	4047	40.47	0.40	–
1 $mile^2$	=	–	–	–	6.40	1	–	–	–	259	2.59
1 cm^2	=	0.155	–	–	–	–	1	0.01	–	–	–
1 m^2	=	1550	10.76	1.196	–	–	10000	1	0.01	–	–
1 a	=	–	1076	119.6	–	–	–	100	1	0.01	–
1 ha	=	–	–	–	2.47	–	–	10000	100	1	0.01
1 km^2	=	–	–	–	247	0.3861	–	–	10000	100	1

in^2 = square inch (sq in),
ft^2 = square foot (sq ft),
yd^2 = square yard (sq yd),
$mile^2$ = square mile (sq mile).

Paper sizes
(DIN 476)

Dimensions in mm

A 0	841 x 1189	**A 6**	105 x 148
A 1	594 x 841	**A 7**	74 x 105
A 2	420 x 594	**A 8**	52 x 74
A 3	297 x 420	**A 9**	37 x 52
A 4	210 x 297[1])	**A 10**	26 x 37
A 5	148 x 210		

Units of volume

Unit		in^3	ft^3	yd^3	gal (UK)	gal (US)	cm^3	dm^3(l)	m^3
1 in^3	=	1	–	–	–	–	16.3871	0.01639	–
1 ft^3	=	1728	1	0.03704	6.229	7.481	–	28.3168	0.02832
1 yd^3	=	46656	27	1	168.18	201.97	–	764.555	0.76456
1 gal (UK)	=	277.42	0.16054	–	1	1.20095	4546.09	4.54609	–
1 gal (US)	=	231	0.13368	–	0.83267	1	3785.41	3.78541	–
1 cm^3	=	0.06102	–	–	–	–	1	0.001	–
1 dm^3 (l)	=	61.0236	0.03531	0.00131	0.21997	0.26417	1000	1	0.001
1 m^3	=	61023.6	35.315	1.30795	219.969	264.172	10^6	1000	1

in^3 = cubic inch (cu in),
ft^3 = cubic foot (cu ft),
yd^3 = cubic yard (cu yd),
gal = gallon.

Other units of volume

Great Britain (UK)
1 fl oz (fluid ounce) = 0.028413 l
1 pt (pint) = 0.56826 l,
1 qt (quart) = 2 pt = 1.13652 l,
1 gal (gallon) = 4 qt = 4.5461 l,
1 bbl (barrel) = 36 gal = 163.6 l.

Units of dry measure:
1 bu (bushel) = 8 gal = 36.369 l.

[1]) Customary format in USA: 216 mm x 279 mm

United States (US)
1 fl oz (fluid ounce) = 0.029574 l
1 liq pt (liquid pint) = 0.47318 l
1 liq quart = 2 liq pt = 0.94635 l
1 gal (gallon) = 231 in^3 = 4 liq quarts = 3.7854 l
1 liq bbl (liquid barrel) = 119.24 l
1 barrel petroleum[1]) = 42 gal = 158.99 l

Units of dry measure:
1 bushel = 35.239 dm^3

Volume of ships
1 RT (register ton) = 100 ft^3 = 2.832 m^3; GRT (gross RT) = total shipping space, net register ton = cargo space of a ship.
GTI (gross tonnage index) = total volume of ship (shell) in m^3.
1 ocean ton = 40 ft^3 = 1.1327 m^3.

Units of angle

Unit[2])		°	′	″	rad	gon	cgon	mgon
1°	=	1	60	3600	0.017453	1.1111	111.11	1111.11
1′	=	0.016667	1	60	–	0.018518	1.85185	18,5185
1″	=	0.0002778	0.016667	1	–	0.0003086	0.030864	0.30864
1 rad[2])	=	57.2958	3437.75	206265	1	63.662	6366.2	63662
1 gon	=	0.9	54	3240	0.015708	1	100	1000
1 cgon	=	0.009	0.54	32.4	–	0.01	1	10
1 mgon	=	0.0009	0.054	3.24	–	0.001	0.1	1

Velocities

1 km/h = 0.27778 m/s,
1 mile/h = 1.60934 km/h,
1 kn (knot) = 1.852 km/h,
1 ft/min = 0.3048 m/min

1 m/s = 3.6 km/h,
1 km/h = 0.62137 mile/h,
1 km/h = 0.53996 kn,
1 m/min = 3.28084 ft/min,

x km/h $\triangleq \frac{60}{x}$ min/km $\triangleq \frac{3600}{x}$ s/km,

x mile/h $\triangleq \frac{37.2824}{x}$ min/km $\triangleq \frac{2236.9}{x}$ s/km.

x s/km $\triangleq \frac{3600}{x}$ km/h.

The **Mach number** Ma specifies how much faster a body travels than sound (approx. 333 m/s in air). Ma = 1.3 therefore denotes 1.3 times the speed of sound.

Fuel consumption

1 g/PS · h = 1.3596 g/kW · h,
1 lb/hp · h = 608.277 g/kW · h,
1 liq pt/hp · h = 634.545 cm^3/kW · h,
1 pt (UK)/hp · h = 762.049 cm^3/kW · h,

1 g/kW · h = 0.7355 g/PS · h,
1 g/kW · h = 0.001644 lb/hp · h,
1 cm^3/kW · h = 0.001576 liq pt/hp · h,
1 cm^3/kW · h = 0.001312 pt (UK)/hp · h,

x mile/gal (US) $\triangleq \frac{235.21}{x}$ l/100 km,

x l/100 km $\triangleq \frac{235.21}{x}$ mile/gal (US),

x mile/gal (UK) $\triangleq \frac{282.48}{x}$ l/100 km.

x l/100 km $\triangleq \frac{282.48}{x}$ mile/gal (UK).

1) For crude oil.
2) It is better to indicate angles by using only one of the units given above, i.e. not $\alpha = 33° 17' 27.6''$ but rather $\alpha = 33.291°$ or $\alpha = 1997.46'$ or $\alpha = 119847.6''$.

Units of mass

(colloquially also called "units of weight")

Avoirdupois system (commercial weights in general use in UK and US)

Unit		gr	dram	oz	lb	cwt (UK)	cwt (US)	ton (UK)	ton (US)	g	kg	t
1 gr	=	1	0.03657	0.00229	1/7000	–	–	–	–	0.064799	–	–
1 dram	=	27.344	1	0.0625	0.00391	–	–	–	–	1.77184	–	–
1 oz	=	437.5	16	1	0.0625	–	–	–	–	28.3495	–	–
1 lb	=	7000	256	16	1	0.00893	0.01	–	0.0005	453.592	0.45359	–
1 cwt (UK)[1]	=	–	–	–	112	1	1.12	0.05	–	–	50.8023	–
1 cwt (US)[2]	=	–	–	–	100	0.8929	1	0.04464	0.05	–	45.3592	–
1 ton (UK)[3]	=	–	–	–	2240	20	22.4	1	1.12	–	1016.05	1.01605
1 ton (US)[4]	=	–	–	–	2000	17.857	20	0.8929	1	–	907.185	0.90718
1 g	=	15.432	0.5644	0.03527	–	–	–	–	–	1	0.001	–
1 kg	=	–	–	35.274	2.2046	0.01968	0.02205	–	–	1000	1	0.001
1 t	=	–	–	–	2204.6	19.684	22.046	0.9842	1.1023	10^6	1000	1

Troy system (used in UK and US for precious stones and metals) and **Apothecaries' system** (used in UK and US for drugs)

Unit		gr	s ap	dwt	dr ap	oz t = oz ap	lb t = lb ap	Kt	g
1 gr	=	1	0.05	0.04167	0.01667	–	–	0.324	0.064799
1 s ap	=	20	1	0.8333	0.3333	–	–	–	1.296
1 dwt	=	24	1.2	1	0.4	0.05	–	–	1.5552
1 dr ap	=	60	3	2.5	1	0.125	–	–	3.8879
1 oz t = 1 oz ap	=	480	24	20	8	1	0.08333	–	31.1035
1 lb t = 1 lb ap	=	5760	288	240	96	12	1	–	373.24
1 Kt	=	3.086	–	–	–	–	–	1	0.2000
1 g	=	15.432	0.7716	0.643	0.2572	0.03215	0.002679	5	1

UK = United Kingdom, US = USA.
gr = grain, oz = ounce, lb = pound, cwt = hundredweight,
1 slug = 14.5939 kg = mass, accelerated at 1 ft/s² by a force of 1 lbf,
1 st (stone) = 14 lb = 6.35 kg (UK only),
1 qr (quarter) = 28 lb = 12.7006 kg (UK only, seldom used),
1 quintal = 100 lb = 1 cwt (US) = 45.3592 kg,
1 tdw (ton dead weight) = 1 ton (UK) = 1.016 t.
The tonnage of dry cargo ships (cargo + ballast + fuel + supplies) is given in tdw.
s ap = apothecaries' scruple,
dwt = pennyweight,
dr ap = apothecaries' drachm (US: apothecaries' dram),
oz t (UK: oz tr) = troy ounce,
oz ap (UK: oz apoth) = apothecaries' ounce,
lb t = troy pound,
lb ap = apothecaries' pound,
Kt = metric karat, used only for precious stones[5]).

[1]) Also "long cwt (cwt l)".
[2]) Also "short cwt (cwt sh)".
[3]) Also "long ton (tn l)".
[4]) Also "short ton (tn sh)".
[5]) The term "karat" was formerly used with a different meaning in connection with gold alloys to denote the gold content: pure gold (fine gold) = 24 karat; 14-karat gold has 14/24 = 585/1000 parts by weight of fine gold.

Mass per unit length
SI unit kg/m
1 lb/ft = 1.48816 kg/m, 1 lb/yd = 0.49605 kg/m
Units in textile industry (DIN 60905 and 60910):
1 tex = 1 g/km, 1 mtex = 1 mg/km,
1 dtex = 1 dg/km, 1 ktex = 1 kg/km
Former unit (do not use):
1 den (denier) = 1 g/9 km = 0.1111 tex, 1 tex = 9 den

Density
SI unit kg/m³
1 kg/dm³ = 1 kg/l = 1 g/cm³ = 1000 kg/m³
1 lb/ft³ = 16.018 kg/m³ = 0.016018 kg/l
1 lb/gal (UK) = 0.099776 kg/l, 1 lb/gal (US) = **0.11983** kg/l

°Bé (degrees Baumé) is a measure of the density of liquids which are heavier (+°Bé) or lighter (–°Bé) than water (at 15 °C). Do not use the unit °Bé.
$\varrho = 144.3/(144.3 \pm n)$
ϱ Density in kg/l, n hydrometer degrees in °Bé.
°API (American Petroleum Institute) is used in the USA to indicate the density of fuels and oils.
$\varrho = 141.5/(131.5 + n)$
ϱ Density in kg/l, n hydrometer degrees in °API.

Examples:
–12 °Bé = 144.3/(144.3 + 12) kg/l = 0.923 kg/l
+34 °Bé = 144.3/(144.3 – 34) kg/l = 1.308 kg/l
28 °API = 141.5/(131.5 + 28) kg/l = 0.887 kg/l

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Units of force

Unit		N	kp	lbf
1 N (newton)	=	1	0.101972	0.224809
Do not use 1 kp (kilopond)	=	9.80665	1	2.204615
1 lbf (pound-force)	=	4.44822	0.453594	1

1 pdl (poundal) = 0.138255 N = force which accelerates a mass of 1 lb by 1 ft/s².
1 sn (sthène)* = 10^3 N

Units of pressure and stress

Unit[1])		Pa	µbar	hPa	bar	N/mm²	kp/mm²	at	kp/m²	torr	atm	lbf/in²	lbf/ft²	tonf/in²
1 Pa = 1 N/m²	=	1	10	0.01	10^{-5}	10^{-6}	–	–	0.10197	0.0075	–	–	–	–
1 µbar	=	0.1	1	0.001	10^{-6}	10^{-7}	–	–	0.0102	–	–	–	–	–
1 hPa = 1 mbar	=	100	1000	1	0.001	0.0001	–	–	10.197	0.7501	–	0.0145	2.0886	–
1 bar	=	10^6	10^6	1000	1	0.1	0.0102	1.0197	10197	750.06	0.9869	14.5037	2088.6	–
1 N/mm²	=	10^6	10^7	10000	10	1	0.10197	10.197	101972	7501	9.8692	145.037	20886	0.06475
Do not use														
1 kp/mm²	=	–	–	98066.5	98.0665	9.80665	1	100	10^6	73556	96.784	1422.33	–	0.63497
1 at = 1 kp/cm²	=	98066.5	–	980.665	0.98066	0.0981	0.01	1	10000	735.56	0.96784	14.2233	2048.16	–
1 kp/m²= 1 mmw.g.	=	9.80665	98.0665	0.0981	–	–	10^{-6}	10^{-4}	1	–	–	–	0.2048	–
1 torr = 1 mmHg	=	133.322	1333.22	1.33322	–	–	–	0.00136	13.5951	1	0.00132	0.01934	2.7845	–
1 atm	=	101325	–	1013.25	1.01325	–	–	1.03323	10332.3	760	1	14.695	2116.1	–
British and American units														
1 lbf/in²	=	6894.76	68948	68.948	0.0689	0.00689	–	0.07031	703.07	51.715	0.06805	1	144	–
1 lbf/ft²	=	47.8803	478.8	0.4788	–	–	–	–	4.8824	0.35913	–	–	1	–
1 tonf/in²	=	–	–	–	154.443	15.4443	1.57488	157.488	–	–	152.42	2240	–	1

lbf/in² = pound-force per square inch (psi), lbf/ft² = pound-force per square foot (psf), tonf/in² = ton-force (UK) per square inch
1 pdl/ft² (poundal per square foot) = 1.48816 Pa
1 barye* = 1µbar; 1 pz (pièce)* = 1 sn/m² (sthène/m²)* = 10^3 Pa
Standards: DIN 66 034 Conversion tables, kilopond – newton, newton – kilopond, DIN 66 037 Conversion tables, kilopond/cm² – bar, bar – kilopond/cm², DIN 66 038 Conversion tables, torr – millibar, millibar – torr

[1]) See PP. 15 and 16 for names of units * French units.

Units of energy

(units of work)

Unit[1]	J	kW · h	kp · m	PS · h	kcal	ft · lbf	Btu
1 J =	1	$277.8 \cdot 10^{-9}$	0.10197	$377.67 \cdot 10^{-9}$	$238.85 \cdot 10^{-6}$	0.73756	$947.8 \cdot 10^{-6}$
1 kW · h =	$3.6 \cdot 10^{6}$	1	367098	1.35962	859.85	$2.6552 \cdot 10^{6}$	3412.13
Do not use							
1 kp · m =	9.80665	$2.7243 \cdot 10^{-6}$	1	$3.704 \cdot 10^{-6}$	$2.342 \cdot 10^{-3}$	7.2330	$9.295 \cdot 10^{-3}$
1 PS · h =	$2.6478 \cdot 10^{6}$	0.735499	270000	1	632.369	$1.9529 \cdot 10^{6}$	2509.6
1 kcal[2] =	4186.8	$1.163 \cdot 10^{-3}$	426.935	$1.581 \cdot 10^{-3}$	1	3088	3.9683
British and American units							
1 ft · lbf =	1.35582	$376.6 \cdot 10^{-9}$	0.13826	$512.1 \cdot 10^{-9}$	$323.8 \cdot 10^{-6}$	1	$1.285 \cdot 10^{-3}$
1 Btu[3] =	1055.06	$293.1 \cdot 10^{-6}$	107.59	$398.5 \cdot 10^{-6}$	0.2520	778.17	1

ft lbf = foot pound-force, Btu = British thermal unit,
1 in ozf (inch ounce-force) = 0.007062 J, 1 in lbf (inch pound-force) = 0.112985 J,
1 ft pdl (foot poundal) = 0.04214 J,
1 hph (horsepower-hour) = $2.685 \cdot 10^{6}$ J = 0.7457 kW · h,
1 thermie (France) = 1000 frigories (France) = 1000 kcal = 4.1868 MJ,
1 kg C.E. (coal equivalent kilogram)[4] = 29.3076 MJ = 8.141 kWh,
1 t C.E. (coal equivalent ton)[4] = 1000 kg C.E. = 29.3076 GJ = 8.141 MWh.

Units of power

Unit[1]	W	kW	kp m/s	PS*	kcal/s	hp	Btu/s
1 W =	1	0.001	0.10197	$1.3596 \cdot 10^{-3}$	$238.8 \cdot 10^{-6}$	$1.341 \cdot 10^{-3}$	$947.8 \cdot 10^{-6}$
1 kW =	1000	1	101.97	1.35962	$238.8 \cdot 10^{-3}$	1.34102	$947.8 \cdot 10^{-3}$
Do not use							
1 kp · m/s =	9.80665	$9.807 \cdot 10^{-3}$	1	$13.33 \cdot 10^{-3}$	$2.342 \cdot 10^{-3}$	$13.15 \cdot 10^{-3}$	$9.295 \cdot 10^{-3}$
1 PS =	735.499	0.735499	75	1	0.17567	0.98632	0.69712
1 kcal/s =	4186.8	4.1868	426.935	5.6925	1	5.6146	3.9683
British and American units							
1 hp =	745.70	0.74570	76.0402	1.0139	0.17811	1	0.70678
1 Btu/s =	1055.06	1.05506	107.586	1.4345	0.2520	1.4149	1

hp = horsepower,
1 ft · lbf/s = 1.35582 W,
1 ch (cheval vapeur) (France) = 1 PS = 0.7355 kW,
1 poncelet (France) = 100 kp · m/s = 0.981 kW,
Continuous human power generation ≈ 0.1 kW.

Standards: DIN 66 035 Conversion tables, calorie – joule, joule – calorie,
DIN 66 036 Conversion tables, metric horsepower – kilowatt, kilowatt – metric horsepower,
DIN 66 039 Conversion tables, kilocalorie – watt-hour, watt-hour – kilocalorie.

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[1]) Names of units, see P. 16.
[2]) 1 kcal ≈ quantity of heat required to increase temperature of 1 kg water at 15 °C by 1 °C.
[3]) 1 Btu ≈ quantity of heat required to raise temperature of 1 lb water by 1 °F. 1 therm = 10^{5} Btu.
[4]) The units of energy kg C.E. and t C.E. were based on a specific calorific value H_u of 7000 kcal/kg of coal.
* Metric horsepower

Units of temperature

°C = degree Celsius, K = Kelvin, °F = degree Fahrenheit, °R = degree Rankine.

Temperature points

$$T_K = (273.15\ °C + t_C)\,\frac{K}{°C} = \frac{5}{9}\,T_R$$

$$T_R = (459.67\ °F + t_F)\,\frac{°R}{°F} = 1.8\,T_K$$

$$t_C = \frac{5}{9}\,(t_F - 32°F)\,\frac{°C}{°F} = (T_K - 273.15\ K)\,\frac{°C}{K}$$

$$t_F = (1.8\,t_C + 32°C)\,\frac{°F}{°C} = (T_R - 459.67\ °R)\,\frac{°F}{°R}$$

t_C, t_F, T_K and T_R denote the temperature points in °C, °F, K and °R.

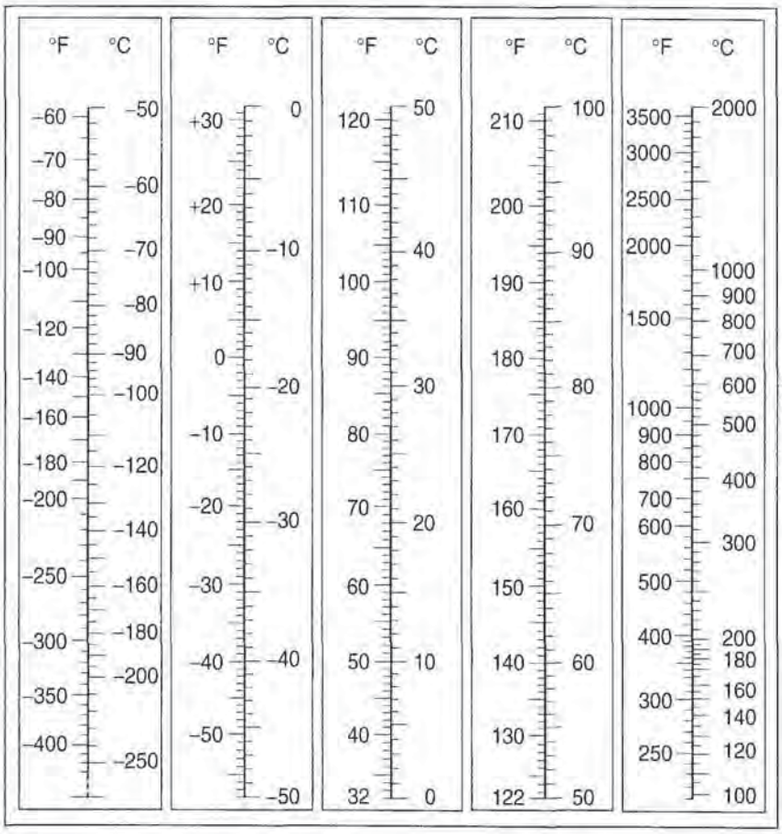
Temperature difference

1 K = 1 °C = 1.8 °F = 1.8 °R

Zero points: 0 °C ≙ 32 °F, 0 °F ≙ −17.78 °C. Absolute zero:
0K ≙ −273.15 °C ≙ 0 °R ≙ −459.67 °F.

International practical temperature scale: Boiling point of oxygen −182.97 °C, triple point of water 0.01 °C[1], boiling point of water 100 °C, boiling point of sulfur (sulfur point) 444.6 °C, setting point of silver (silver point) 960.8 °C, setting point of gold 1063 °C.

[1] That temperature of pure water at which ice, water and water vapor occur together in equilibrium (at 1013.25 hPa). See also Footnote [2] on P. 12.



Units of viscosity

Legal units of kinematic viscosity ν
$1\ m^2/s = 1\ Pa \cdot s/(kg/m^3) = 10^4\ cm^2/s = 10^6\ mm^2/s$.

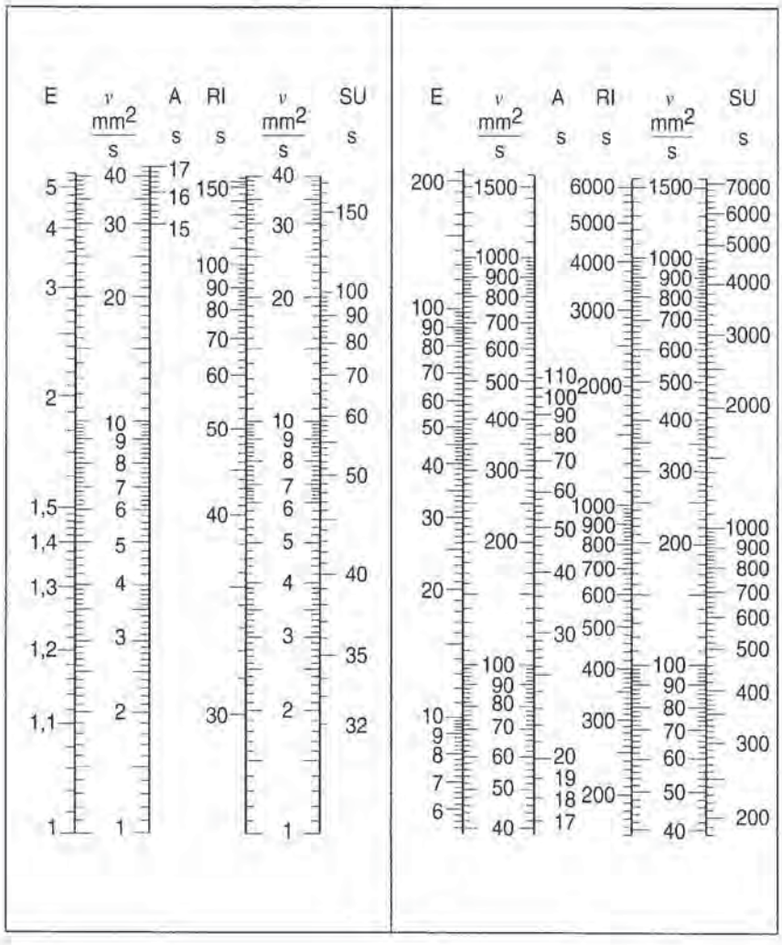
British and American units:
$1\ ft^2/s = 0.092903\ m^2/s$,
RI seconds = efflux time from Redwood-I viscometer (UK),
SU seconds = efflux time from Saybolt-Universal viscometer (US).

Do not use:
St (stokes) = cm^2/s, cSt = mm^2/s.

Conventional units
E (Engler degree) = relative efflux time from Engler apparatus DIN 51 560.
For $\nu > 60\ mm^2/s$, $1\ mm^2/s = 0.132$ E.

At values below 3 E, Engler degrees do not give a true indication of the variation of viscosity; for example, a fluid with 2 E does not have twice the kinematic viscosity of a fluid with 1 E, but rather 12 times that value.

A seconds = efflux time from flow cup DIN 53 211.



Units of time

Unit[1])		s	min	h	d
1 s[2]) (second)	=	1	0.01667	0.2778×10^{-3}	11.574×10^{-6}
1 min (minute)	=	60	1	0.01667	0.6944×10^{-3}
1 h (hour)	=	3600	60	1	0.041667
1 d (day)	=	86 400	1440	24	1

1 civil year = 365 (or 366) days = 8760 (8784) hours (for calculation of interest in banking, 1 year = 360 days),
1 solar year[3]) = 365.2422 mean solar days = 365 d 5 h 48 min 46 s,
1 sidereal year[4]) = 365.2564 mean solar days.

Clock times

The clock times listed for the following time zones are based on 12.00 CET (Central European Time)[5]):

Clock time	Time-zone meridian	Countries (examples)
	West longitude	
1.00	150°	Alaska.
3.00	120°	West coast of Canada and USA.
4.00	105°	Western central zone of Canada and USA.
5.00	90°	Central zone of Canada and USA, Mexico, Central America.
6.00	75°	Canada between 68° and 90°, Eastern USA, Ecuador, Colombia, Panama, Peru.
7.00	60°	Canada east of 68°, Bolivia, Chile, Venezuela.
8.00	45°	Argentina, Brazil, Greenland, Paraguay, Uruguay.
11.00	0°	**Greenwich Mean Time (GMT)**[6]): Canary Islands, Great Britain, Ireland, Portugal, West Africa.
	East longitude	
12.00	15°	**Central European Time (CET):** Austria, Belgium, Denmark, France, Germany, Hungary, Italy, Luxembourg, Netherlands, Norway, Poland, Sweden, Switzerland, Spain; Algeria, Israel, Libya, Nigeria, Tunisia, Zaire.
13.00	30°	**Eastern European Time (EET):** Bulgaria, Finland, Greece, Romania; Egypt, Lebanon, Jordan, Sudan, South Africa, Syria.
14.00	45°	Western Russia, Turkey, Iraq, Saudi Arabia, Eastern Africa.
14.30	52.5°	Iran.
16.30	82.5°	India, Sri Lanka.
18.00	105°	Cambodia, Indonesia, Laos, Thailand, Vietnam.
19.00	120°	Chinese coast, Philippines, Western Australia.
20.00	135°	Japan, Korea.
20.30	142.5°	North and South Australia.
21.00	150°	Eastern Australia.

[1]) See also P. 15.
[2]) Base SI unit, see P. 12 for definition.
[3]) Time between two successive passages of the earth through the vernal equinox.
[4]) True time of revolution of the earth about the sun.
[5]) During the summer months in countries in which daylight saving time is observed, clocks are set ahead by 1 hour (from approximately April to September north of the equator and October to March south of the equator).
[6]) = UT (Universal Time), mean solar time at the 0° meridian of Greenwich, or UTC (Coordinated Universal Time), defined by the invariable second of the International System of Units (P. 12). Because the period of rotation of the earth about the sun is gradually becoming longer, UTC is adjusted to UT from time to time by the addition of a leap second.

Vibration and oscillation

Symbols and units

Quantity		Unit
a	Storage coefficient	
b	Damping coefficient	
c	Storage coefficient	
c	Spring constant	N/m
c_α	Torsional rigidity	N · m/rad
C	Capacity	F
f	Frequency	Hz
f_g	Resonant frequency	Hz
Δf	Half-value width	Hz
F	Force	N
F_Q	Excitation function	
I	Current	A
J	Moment of inertia	kg · m²
L	Self-inductance	H
m	Mass	kg
M	Torque	N · m
n	Rotational speed	1/min
Q	Charge	C
Q	Resonance sharpness	
r	Damping factor	N · s/m
r_α	Rotational damping coefficient	N · s · m
R	Ohmic resistance	Ω
t	Time	s
T	Period	s
U	Voltage	V
v	Particle velocity	m/s
x	Travel/displacement	
y	Instantaneous value	
$\hat{y}$	Amplitude	
$\dot{y}$ ($\ddot{y}$)	Single (double) derivative with respect to time	
y_{rec}	Rectified value	
y_{eff}	Effective value	
α	Angle	rad
δ	Decay coefficient	1/s
Λ	Logarithmic decrement	
ω	Angular velocity	rad/s
ω	Angular frequency	1/s
Ω	Exciter-circuit frequency	1/s
ϑ	Damping ratio	
ϑ_{opt}	Optimum damping ratio	

Subscripts:	
0	Undamped
d	Damped
T	Absorber
U	Base support
G	Machine

Terms

(see also DIN 1311)

Vibrations and oscillations
Vibrations and oscillations are the terms used to denote changes in a physical quantity which repeat at more or less regular time intervals and whose direction changes with similar regularity.

Period
The period is the time taken for one complete cycle of a single oscillation (period).

Amplitude
Amplitude is the maximum instantaneous value (peak value) of a sinusoidally oscillating physical quantity.

Frequency
Frequency is the number of oscillations in one second, the reciprocal value of the period of oscillation T.

Angular frequency
Angular frequency is 2π-times the frequency.

Particle velocity
Particle velocity is the instantaneous value of the alternating velocity of a vibrating particle in its direction of vibration. It must not be confused with the velocity of propagation of a traveling wave (e.g. the velocity of sound).

Fourier series
Every periodic function, which is piecewise monotonic and smooth, can be expressed as the sum of sinusoidal harmonic components.

Beats
Beats occur when two sinusoidal oscillations, whose frequencies do not differ greatly, are superposed. They are periodic. Their basic frequency is the difference between the frequencies of the superposed sinusoidal oscillations.

Natural oscillations
The frequency of natural oscillations (natural frequency) is dependent only on the properties of the oscillating system.

Damping
Damping is a measure of the energy losses in an oscillatory system when one form of energy is converted into another.

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Logarithmic decrement
Natural logarithm of the relationship between two extreme values of a natural oscillation which are separated by one period.

Damping ratio
Measure for the degree of damping.

Forced oscillations
Forced oscillations arise under the influence of an external physical force (excitation), which does not change the properties of the oscillator. The frequency of forced oscillations is determined by the frequency of the excitation.

Transfer function
The transfer function is the quotient of amplitude of the observed variable divided by the amplitude of excitation, plotted against the exciter frequency.

Resonance
Resonance occurs when the transfer function produces very large values as the exciter frequency approaches the natural frequency.

Resonant frequency
Resonant frequency is the exciter frequency at which the oscillator variable attains its maximum value.

Half-value width
The half-value width is the difference between the frequencies at which the level of the variable has dropped to $1/\sqrt{2} \approx 0.707$ of the maximum value.

Resonance sharpness
Resonance sharpness, or the quality factor (Q-factor), is the maximum value of the transfer function.

Coupling
If two oscillatory systems are coupled together – mechanically by mass or elasticity, electrically by inductance or capacitance – a periodic exchange of energy takes place between the systems.

Wave
Spatial and temporal change of state of a continuum, which can be expressed as a unidirectional transfer of location of a certain state over a period of time. There are transversal waves (e.g. waves in rope and water) and longitudinal waves (e.g. sound waves in air).

Interference
The principle of undisturbed superposition of waves. At every point in space the instantaneous value of the resulting wave is equal to the sum of the instantaneous values of the individual waves.

Standing waves
Standing waves occur as a result of interference between two waves of equal frequency, wavelength and amplitude traveling in opposite directions. In contrast to a propagating wave, the amplitude of the standing wave is constant at every point; nodes (zero amplitude) and antinodes (maximum amplitude) occur. Standing waves occur by reflection of a wave back on itself if the characteristic impedance of the medium differs greatly from the impedance of the reflector.

Rectification value
Arithmetic mean value, linear in time, of the values of a periodic signal.

$$y_{rec} = (1/T) \int_0^T | y | \, dt$$

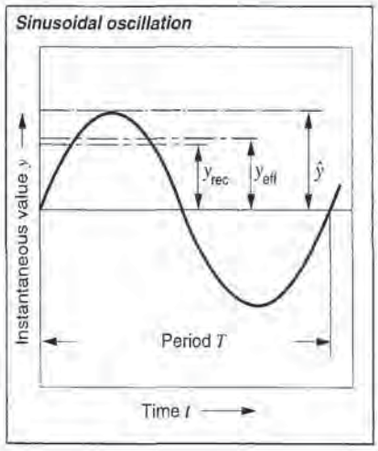
For a sine curve:
$y_{rec} = 2\hat{y}/\pi \approx 0.637\ \hat{y}$.

Effective value
Quadratic mean value in time of a periodic signal.

$$y_{eff} = \sqrt{(1/T) \int_0^T y^2 \, dt}$$

For a sine curve:
$y_{eff} = \hat{y}/\sqrt{2} \approx 0.707\ \hat{y}$.

Sinusoidal oscillation

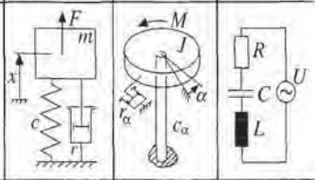


Form factor = y_{eff}/y_{rec}
For a sine curve:
$y_{eff}/y_{rec} \approx 1.111$.

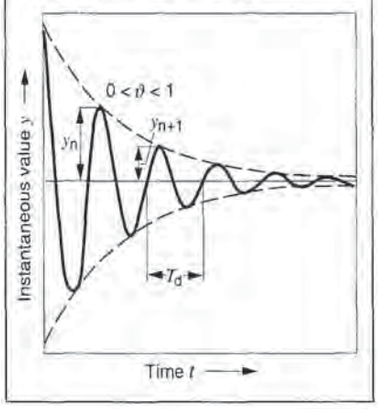
Peak factor = $\hat{y}/y_{eff}$
For a sine curve:
$\hat{y}/y_{eff} = \sqrt{2} \approx 1.414$.

Equations
The equations apply for the following simple oscillators if the general quantity designations in the formulas are replaced by the relevant physical quantities.

Simple oscillatory systems

	Mechanical		Electrical
	Translational	Rotational	
			
Gen. designation	Physical quantity		
y	x	α	Q
$\dot{y}$	$x = v$	$\alpha = \omega$	$Q = I$
$\ddot{y}$	$x = v$	$\alpha = \dot{\omega}$	$Q = I$
F_Q	F	M	U
a	m	J	L
b	r	r_α	R
c	c	c_α	$1/C$

Free oscillation and damping



Differential equations
$a\ddot{y} + b\dot{y} + cy = F_Q(t) = \hat{F}_Q \sin \Omega t$
Period $T = 1/f$
Angular frequency $\omega = 2\pi f$
Sinusoidal oscillation
(e. g. vibration displacement) $y = \hat{y} \sin \omega t$

Free oscillations ($F_Q = 0$)
Logarithmic decrement
$\Lambda = \ln(y_n/y_{n+1}) = \pi b/\sqrt{ca - b^2/4}$
Decay coefficient $\delta = b/(2a)$
Damping ratio $\vartheta = \delta/\omega_0 = b/(2\sqrt{ca})$
$\vartheta = \Lambda/\sqrt{\Lambda^2 + 4\pi^2} \approx \Lambda/(2\pi)$
(low level of damping)
Angular frequency of undamped oscillation ($\vartheta = 0$) $\omega_0 = \sqrt{c/a}$
Angular frequency of damped oscillation ($0 < \vartheta < 1$) $\omega_d = \omega_0\sqrt{1 - \vartheta^2}$
For $\vartheta \geq 1$ no oscillations but creepage.

Forced oscillations
Quantity of transfer function
$\hat{y}/\hat{F}_Q = 1/\sqrt{(c - a\Omega^2)^2 + (b\Omega)^2}$
$= (1/c)/\sqrt{(1 - (\Omega/\omega_0)^2)^2 + (2\vartheta\Omega/\omega_0)^2}$
Resonant frequency $f_g = f_0\sqrt{1 - 2\vartheta^2} < f_0$
Resonance sharpness $Q = 1/(2\vartheta\sqrt{1 - \vartheta^2})$
Oscillator with low level of damping ($\vartheta \leq 0.1$):
Resonant frequency $f_g \approx f_0$
Resonance sharpness $Q \approx 1/(2\vartheta)$
Half-value width $\Delta f = 2\vartheta f_0 = f_0/Q$

Vibration reduction

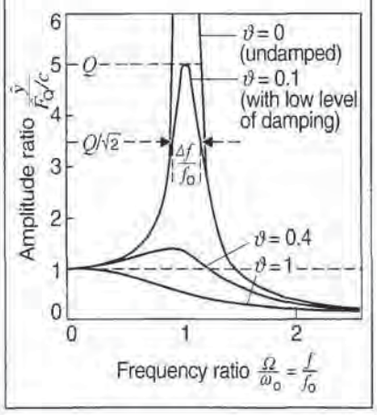
Vibration damping
If damping can only be carried out between the machine and a quiescent point, the damping must be at a high level (cf. "Standardized transmission function" diagram).

Vibration isolation

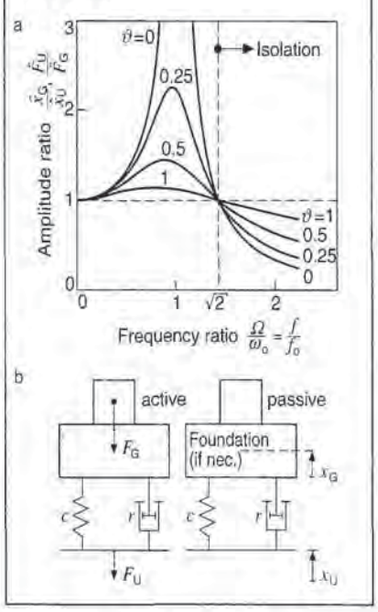
Active vibration isolation
Machines are to be mounted so that the

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Standardized transmission function



Vibration isolation
a Transmission function
b Low tuning



forces transmitted to the base support are small. One measure to be taken: The bearing point should be set below resonance, so that the natural frequency lies below the lowest exciter frequency. Damping impedes isolation. Low values can result in excessively high vibrations during running-up when the resonant range is passed through.

Passive vibration isolation

Machines are to be mounted so that vibration and shaking reaching the base support are only transmitted to the machines to a minor degree. Measures to be taken: as for active isolation.

In many cases flexible suspension or extreme damping is not practicable. So that no resonance can arise, the machine attachment should be so rigid that the natural frequency is far enough in excess of the highest exciter frequency which can occur.

Vibration absorption

Absorber with fixed natural frequency

By tuning the natural frequency ω_T of an absorption mass with a flexible, loss-free coupling to the excitation frequency, the vibrations of the machine are completely absorbed. Only the absorption mass still vibrates. The effectiveness of the absorption decreases as the exciter frequency changes. Damping prevents complete absorption. However, appropriate tuning of the absorber frequency and an optimum damping ratio produce broadband vibration reduction, which remains effective when the exciter frequency changes.

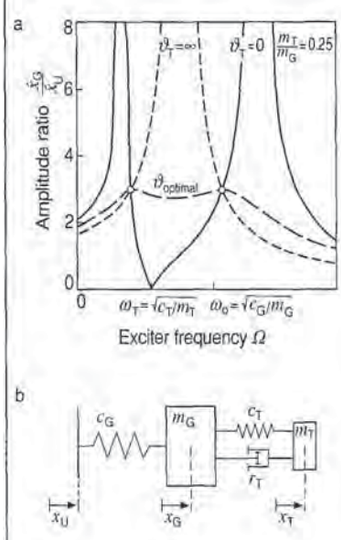
Absorber with changeable natural frequency

Rotational oscillations with exciter frequencies proportional to the rotational speed (e.g. orders of balancing in IC engines, P. 397/398) can be absorbed by absorbers with natural frequencies proportional to the rotational speed (pendulum in the centrifugal force field). The absorption is effective at all rotational speeds.

Absorption is also possible for oscillators with several degrees of freedom and interrelationships, as well as by the use of several absorption bodies.

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Vibration absorption
a Transmission function of machine
b Structure of principle



Modal analysis

The dynamic behavior (oscillatory characteristics) of a mechanical structure can be predicted with the aid of a mathematical model. The model parameters of the modal model are determined by means of modal analysis. A time-invariant and linear-elastic structure is an essential precondition. The oscillations are only observed at a limited number of points in the possible oscillation directions (degrees of freedom) and at defined frequency intervals. The continuous structure is then replaced in a clearly-defined manner by a finite number of single-mass oscillators. Each single-mass oscillator is comprehensively and clearly defined by a characteristic vector and a characteristic value. The characteristic vector (mode form, natural oscillation form) describes the relative amplitudes and phases of all degrees of freedom, the characteristic value describes the behavior in terms of time (damped harmonic oscillation). Every oscillation of the structure can be artificially recreated from the characteristic vectors and values.

The modal model not only describes the actual state but also forms the basis for simulation calculations: In response calculation, the response of the structure to a defined excitation, corresponding, for instance, to test laboratory conditions, is calculated. By means of structure modifications (changes in mass, damping or stiffness) the vibrational behavior can be optimized to the level required by operating conditions. The substructure coupling process collates modal models of various structures, for example, into one overall model. The modal model can be constructed analytically. When the modal models produced by both processes are compared with each other, the modal model resulting from an analytical modal analysis is more accurate than that from an experimental modal analysis as a result of the greater number of degrees of freedom in the analytical process. This applies in particular to simulation calculations based on the model.

Analytical modal analysis

The geometry, material data and marginal conditions must be known. Multibody-system or finite-element models provide characteristic values and vectors. Analytical modal analysis requires no specimen sample, and can therefore be used at an early stage of development. However, it is often the case that precise knowledge concerning the structure's fundamental properties (damping, marginal conditions) are lacking, which means that the modal model can be very inaccurate. As well as this, the error is unidentified. A remedy can be to adjust the model to the results of an experimental modal analysis.

Experimental modal analysis

Knowledge of the structure is not necessary, but a specimen is required. Analysis is based on measurements of the transmission functions in the frequency range in question from one excitation point to a number of response points, and vice versa. The modal model is derived from the matrix of the transmission functions (which defines the response model).

Basic equations used in mechanics

See PP. 14 ... 18 for names of units

Symbol	Quantity	SI unit
A	Area	m^2
a	Acceleration	m/s^2
a_{cf}	Centrifugal acceleration	m/s^2
d	Diameter	m
E	Energy	J
E_k	Kinetic energy	J
E_p	Potential energy	J
F	Force	N
F_{cf}	Centrifugal force	N
G	Weight	N
g	Acceleration of free fall (g = 9.81 m/s^2, see P. 13)	m/s^2
h	Height	m
i	Radius of gyration	m
J	Moment of inertia (second-order moment of mass)	$kg \cdot m^2$
L	Angular momentum	$N \cdot s \cdot m$
l	Length	m
M	Torque	$N \cdot m$

Symbol	Quantity	SI unit
m	Mass (weight)	kg
n	Rotational frequency	s^{-1}
P	Power	W
p	Linear momentum	$N \cdot s$
r	Radius	m
s	Length of path	m
T	Period, time of one revolution	s
t	Time	s
V	Volume	m^3
v	Velocity	m/s
	v_1 Initial velocity	
	v_2 Final velocity	
	v_m Mean velocity	
W	Work, energy	J
α	Angular acceleration	rad/s^2 [1]
ε	Wrap angle	rad[1]
μ	Coefficient of friction	–
ϱ	Density	kg/m^3
φ	Angle of rotation	rad[1]
ω	Angular velocity	rad/s[1]

Relationships between quantities, numbers

If not otherwise specified, the following relationships are relationships between quantities, i.e. the quantities can be inserted using any units (e.g. the SI units given above). The unit of the quantity to be calculated is obtained from the units chosen for the terms of the equation.

In some cases, additional numerical relationships are given for customary units (e.g. time in s, but speed in km/h). These relationships are identified by the term "numerical relationship", and are only valid if the units given for the relationship are used.

Rectilinear motion

Uniform rectilinear motion

Velocity

$v = s/t$

Uniform rectilinear acceleration

Mean velocity

$v_m = (v_1 + v_2)/2$

Acceleration

$a = (v_2 - v_1)/t = (v_2^2 - v_1^2)/(2s)$

Numerical relationship:

$a = (v_2 - v_1)/(3.6\ t)$

a in m/s^2, v_2 and v_1 in km/h, t in s

Distance covered after time t

$s = v_m \cdot t = v_1 \cdot t + (a \cdot t^2)/2$

$= (v_2^2 - v_1^2)/(2a)$

Final velocity

$v_2 = v_1 + a \cdot t = \sqrt{v_1^2 + 2a \cdot s}$

Initial velocity

$v_1 = v_2 - a \cdot t = \sqrt{v_2^2 - 2a \cdot s}$

For uniformly retarded motion (v_2 smaller than v_1) a is negative.

For acceleration from rest, substitute $v_1 = 0$. For retardation to rest, substitute $v_2 = 0$.

[1]) The unit rad (= m/m) can be replaced by the number 1.

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Force
$F = m \cdot a$

Work, energy
$W = F \cdot s = m \cdot a \cdot s = P \cdot t$

Potential energy
$E_p = G \cdot h = m \cdot g \cdot h$

Kinetic energy
$E_k = m \cdot v^2/2$

Power
$P = W/t = F \cdot v$

Lifting power
$P = m \cdot g \cdot v$

Linear momentum
$p = m \cdot v$

Rotary motion

Uniform rotary motion

Peripheral velocity
$v = r \cdot \omega$
Numerical relationship:
$v = \pi \cdot d \cdot n/60$
v in m/s, d in m, n in min^{-1}
$v = 6 \cdot \pi \cdot d \cdot n/100$
v in km/h, d in m, n in min^{-1}

Angular velocity
$\omega = \varphi/t = v/r = 2\pi \cdot n$
Numerical relationship:
$\omega = \pi \cdot n/30$
ω in s^{-1}, n in min^{-1}

Uniform angular acceleration

Angular acceleration
$\alpha = (\omega_2 - \omega_1)/t$
Numerical relationship:
$\alpha = \pi\,(n_2 - n_1)/(30t)$
α in $1/s^2$, n_1 and n_2 in min^{-1},
t in s

Final angular velocity
$\omega_2 = \omega_1 + \alpha \cdot t$

Initial angular velocity
$\omega_1 = \omega_2 - \alpha \cdot t$

For uniformly retarded rotary motion (ω_2 is smaller than ω_1) α is negative.

Centrifugal force
$F_{cf} = m \cdot r \cdot \omega^2 = m \cdot v^2/r$

Centrifugal acceleration
$a_{cf} = r \cdot \omega^2$

Torque
$M = F \cdot r = P/\omega$
Numerical relationship:
$M = 9550 \cdot P/n$
M in N · m, P in kW, n in min^{-1}

Moment of inertia (see P. 38)
$J = m \cdot i^2$

Work
$W = M \cdot \varphi = P \cdot t$

Power
$P = M \cdot \omega = M \cdot 2\pi \cdot n$
Numerical relationship:
$P = M \cdot n/9550$ (see graph, P. 40)
P in kW, M in N · m (= W · s), n in min^{-1}

Energy of rotation
$E_{rot} = J \cdot \omega^2/2 = J \cdot 2\pi^2 \cdot n^2$
Numerical relationship:
$E_{rot} = J \cdot n^2/182.4$
E_{rot} in J (= N · m), J in kg · m^2, n in min^{-1}

Angular momentum
$L = J \cdot \omega = J \cdot 2\pi \cdot n$
Numerical relationship:
$L = J \cdot \pi \cdot n/30 = 0.1047\, J \cdot n$
L in N · s · m, J in kg · m^2, n in min^{-1}

Pendulum motion

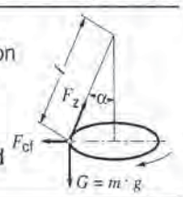
(Mathematical pendulum, i.e. a point-size mass suspended from a thread of zero mass)

Plane pendulum

Period of oscillation (back and forth)
$T = 2\pi \cdot \sqrt{l/g}$
The above equation is only accurate for small excursions α from the rest position (for $\alpha = 10°$, the error is approximately 0.2 %).

Conical pendulum

Time for one revolution
$T = 2\pi \cdot \sqrt{(l \cos \alpha)/g}$
Centrifugal force
$F_{cf} = m \cdot g \cdot \tan \alpha$
Force pulling on thread
$F_z = m \cdot g/\cos \alpha$



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Throwing and falling

(see P. 34 for equation symbols)

Body thrown vertically upward
(neglecting air resistance). Uniform decelerated motion, deceleration
$a = g = 9.81$ m/s²

Upward velocity	$v = v_1 - g \cdot t = v_1 - \sqrt{2g \cdot h}$
Height reached	$h = v_1 \cdot t - 0.5\, g \cdot t^2$
Time of upward travel	$t = \frac{v_1 - v}{g} = \sqrt{\frac{2 \cdot h}{g}}$
At highest point	$v_2 = 0;\ h_2 = \frac{v_1^2}{2g};\ t_2 = \frac{v_1}{g}$

Body thrown obliquely upward
(neglecting air resistance). Angle of throw α; superposition of uniform rectilinear motion and free fall

Range of throw (max. value at $\alpha = 45°$)	$s = \frac{v_1^2 \cdot \sin 2\alpha}{g}$
Duration of throw	$t = \frac{s}{v_1 \cdot \cos \alpha} = \frac{2 v_1 \cdot \sin \alpha}{g}$
Height of throw	$h = \frac{v_1^2 \cdot \sin^2 \alpha}{2g}$
Energy of throw	$E = G \cdot h = m \cdot g \cdot h$

Free fall
(neglecting air resistance). Uniform accelerated motion, acceleration
$a = g = 9.81$ m/s²

Velocity of fall	$v = g \cdot t = \sqrt{2g \cdot h}$
Height of fall	$h = \frac{g \cdot t^2}{2} = \frac{v^2}{2g} = \frac{v \cdot t}{2}$
Time of fall	$t = \frac{2h}{v} = \frac{v}{g} = \sqrt{\frac{2h}{g}}$

Fall with allowance of air resistance
Non-uniform accelerated motion, initial acceleration $a_1 = g = 9.81$ m/s², final acceleration $a_2 = 0$

The velocity of fall approaches a limit velocity v_0 at which the air resistance $F_L = \varrho \cdot c_w \cdot A \cdot v_0^2/2$ is as great as the weight $G = m \cdot g$ of the falling body. Thus:

Limit velocity	$v_0 = \sqrt{2m \cdot g/(\varrho \cdot c_w \cdot A)}$ (ϱ air density, c_w coefficient of drag, A cross-sectional area of body).
Velocity of fall	$v = v_0 \cdot \sqrt{1 - 1/\varkappa^2}$ The following abbreviation is used $\varkappa = e^{g\,h/v_0^2}$; $e = 2.718$
Height of fall	$h = \frac{v_0^2}{2g} \ln \frac{v_0^2}{v_0^2 - v^2}$
Time of fall	$t = \frac{v_0}{g} \ln (\varkappa + \sqrt{\varkappa^2 - 1})$

Example: A heavy body (mass $m = 1000$ kg, cross-sectional area $A = 1$ m², coefficient of drag $c_w = 0.9$) falls from a great height. The air density $\varrho = 1.293$ kg/m³ and the acceleration of free fall $g = 9.81$ m/s² are assumed to be the same over the entire range as at ground level.

Height of fall m	Neglecting air resistance, values at end of fall from indicated height would be: Time of fall s	Velocity of fall m/s	Energy kJ	Allowing for air resistance, values at end of fall from indicated height are: Time of fall s	Velocity of fall m/s	Energy kJ
10	1.43	14.0	98	1.43	13.97	97
50	3.19	31.3	490	3.2	30.8	475
100	4.52	44.3	980	4.6	43	925
500	10.1	99	4900	10.6	86.2	3690
1000	14.3	140	9800	15.7	108	5850
5000	31.9	313	49 000	47.6	130	8410
10 000	45.2	443	98 000	86.1	130	8410

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Drag coefficients c_w

Body shape	c_w	Body shape	c_w
Disc, plate	1.1	Long cylinder	
		$Re < 200\,000$	1.0
		$Re > 450\,000$	0.35
Open dish, parachute	1.4		
Sphere		Long plate $l : d = 30$	
$Re < 200\,000$	0.45	$Re \approx 500\,000$	0.78
$Re > 250\,000$	0.20	$Re \approx 200\,000$	0.66
Slender rotating body $l : d = 6$	0.05	Long airfoil	
		$l : d = 18$	0.2
		$l : d = 8$ $Re = 10^6$	0.1
		$l : d = 5$	0.08
		$l : d = 2$ $Re = 2 \cdot 10^5$	0.2

Reynolds number

$Re = (v + v_0) \cdot l/\nu$

v Velocity of body in m/s,
v_0 Velocity of air in m/s,
l Length of body in m (in direction of flow),
d Thickness of body in m,
ν Kinematic viscosity in m²/s.

For air with $\nu = 14 \cdot 10^{-6}$ m²/s (annual mean 200 m above sea level)

$Re \approx 72\,000\,(v + v_0) \cdot l$ with v and v_0 in m/s
$Re \approx 20\,000\,(v + v_0) \cdot l$ with v and v_0 in km/h

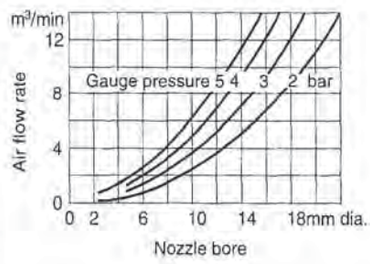
The results of flow measurements on two geometrically similar bodies of different sizes are comparable only if the Reynolds number is of equal magnitude in both cases (this is important in tests on models).

Gravitation

Force of attraction between two masses
$F = f\,(m_1 \cdot m_2)/r^2$
r Distance between centers of mass
f Gravitation constant
$= 6.67 \cdot 10^{-11}$ N · m²/kg²

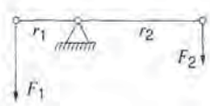
Discharge of air from nozzles

The curves below only give approximate values. In addition to pressure and nozzle cross section, the air discharge rate depends upon the surface and length of the nozzle bore, the supply line and the rounding of the edges of the discharge port.



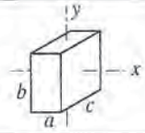
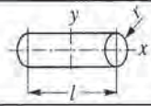
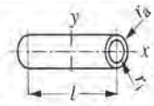
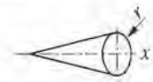
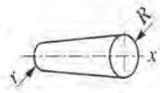
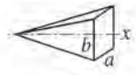
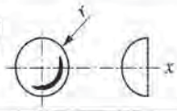
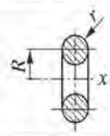
Lever law

$F_1 \cdot r_1 = F_2 \cdot r_2$



Moments of inertia

See P. 34 for symbols; mass $m = V \cdot \varrho$; P. 149 for volumes of solids V; PP. 15, 186 for density ϱ; P. 49 for planar moments of inertia.

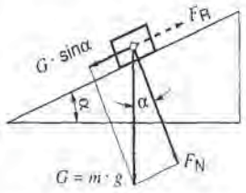
Type of body	Moments of inertia J_x about the x-axis[1]), J_y about the y-axis[1])
Rectangular parallelepiped, cuboid 	$J_x = m \frac{b^2 + c^2}{12}$ $J_y = m \frac{a^2 + c^2}{12}$ Cube with side length a: $J_x = J_y = m \frac{a^2}{6}$
Regular cylinder 	$J_x = m \frac{r^2}{2}$ $J_y = m \frac{3r^2 + l^2}{12}$
Hollow regular cylinder 	$J_x = m \frac{r_a^2 + r_i^2}{2}$ $J_y = m \frac{r_a^2 + r_i^2 + l^2/3}{4}$
Circular cone 	$J_x = m \frac{3r^2}{10}$ Envelope of cone (excluding end base) $J_x = m \frac{r^2}{2}$
Frustrum of circular cone 	$J_x = m \frac{3(R^5 - r^5)}{10(R^3 - r^3)}$ Envelope of cone (excluding end faces) $J_x = m \frac{R^2 + r^2}{2}$
Pyramid 	$J_x = m \frac{a^2 + b^2}{20}$
Sphere and hemisphere 	$J_x = m \frac{2r^2}{5}$ Surface area of sphere $J_x = m \frac{2r^2}{3}$
Hollow sphere r_a outer sphere radius, r_i inner sphere radius	$J_x = m \frac{2(r_a^5 - r_i^5)}{5(r_a^3 - r_i^3)}$
Cylindrical ring 	$J_x = m \left(R^2 + \frac{3}{4}r^2\right)$

[1]) The moment of inertia for an axis parallel to the x-axis or y-axis at a distance a is $J_A = J_x + m \cdot a^2$ or $J_A = J_y + m \cdot a^2$.

Friction

Friction on a horizontal plane
Frictional force (frictional resistance):
$F_R = \mu \cdot m \cdot g$

Friction on an inclined plane
Frictional force (frictional resistance):
$F_R = \mu \cdot F_n = \mu \cdot m \cdot g \cdot \cos \alpha$



Force in direction of inclined plane[1])
$F = G \cdot \sin \alpha - F_R = m \cdot g \, (\sin \alpha - \mu \cdot \cos \alpha)$
Acceleration in direction of inclined plane[1])
$a = g \, (\sin \alpha - \mu \cdot \cos \alpha)$

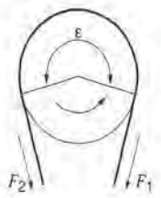
Velocity after distance s
(or height $h = s \cdot \sin \alpha$)
$v = \sqrt{2g \cdot h \, (1 - \mu \cdot \cot \alpha)}$

[1]) The body remains at rest if $(\sin \alpha - \mu \cdot \cos \alpha)$ is negative or zero.

Coefficient of friction
The coefficient of friction μ always denotes a system property and not a material property. Coefficients of friction are among other things dependent on material pairing, temperature, surface condition, sliding speed, surrounding medium (e.g. water or CO_2, which can be adsorbed by the surface) or the intermediate material (e.g. lubricant). The coefficient of static friction is often greater than that of sliding friction. In special cases, the friction coefficient can exceed 1 (e.g. with very smooth surfaces where cohesion forces are predominant or with racing tires featuring an adhesion or suction effect).

Belt-wrap friction
Tension forces:
$F_1 = F_2 \cdot e^{\mu\varepsilon}$

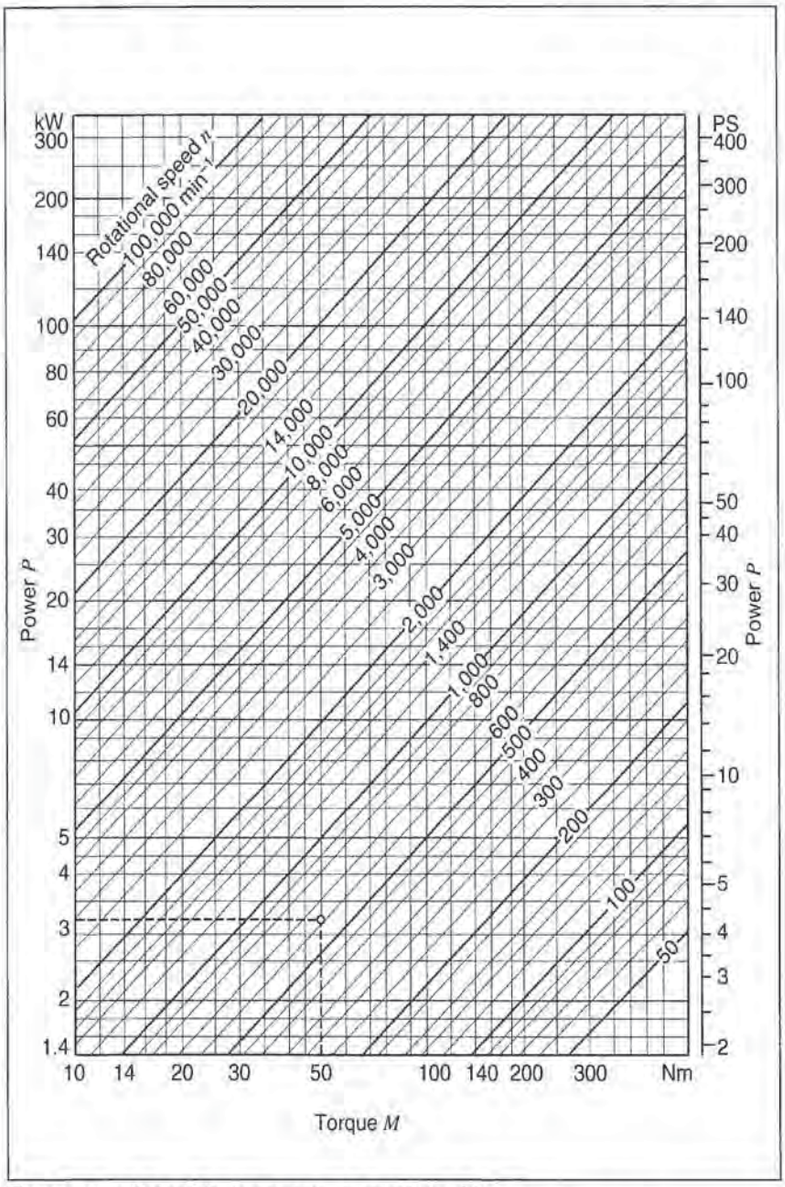
Transmittable peripheral force:
$F_u = F_1 - F_2 = F_1 \, (1 - e^{-\mu\varepsilon}) = F_2 \, (e^{\mu\varepsilon} - 1)$
$e = 2.718$ (base of natural logarithms)



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Power and torque

See P. 35 for equations



The same multiple of P corresponds to a multiple of M or n.

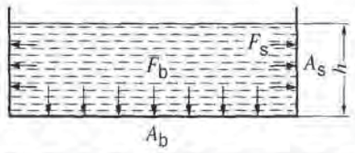
Examples: For M = 50 N · m and n = 600 min^{-1}, P = 3.15 kW (4.3 PS)
For M = 5 N · m and n = 600 min^{-1}, P = 0.315 kW (0.43 PS)
For M = 5000 N · m and n = 60 min^{-1}, P = 31.5 kW (43 PS *)
* PS = Pferdestärke = metric horsepower

Fluid mechanics

Symbol	Quantity	SI unit
A	Cross-sectional area	m^2
A_b	Area of base	m^2
A_s	Area of side	m^2
F	Force	N[1])
F_a	Buoyancy force	N
F_b	Force acting on bottom	N
F_s	Force acting on sides	N
G	Weight	N
g	Acceleration of free fall $g = 9.81\ m/s^2$	m/s^2
h	Depth of fluid	m
m	Mass	kg

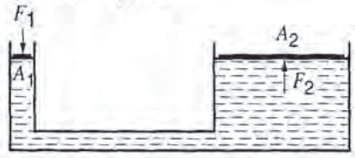
Symbol	Quantity	SI unit
p	Fluid pressure	Pa[2])
	$p_1 - p_2$ differential pressure	Pa
p_e	Gauge pressure compared with atmospheric pressure	Pa
Q	Flow rate	m^3/s
V	Volume	m^3
v	Flow velocity	m/s
ϱ	Density	kg/m^3
	Density of water[3]) $\varrho_w = 1\ kg/dm^3 = 1000\ kg/m^3$	

Fluid at rest in an open container



Force acting on bottom $F_b = A_b \cdot h \cdot \varrho \cdot g$
Force acting on sides $F_s = 0.5\, A_s \cdot h \cdot \varrho \cdot g$
Buoyancy force $F_a = V \cdot \varrho \cdot g$
= weight of displaced volume of fluid.
A body will float if $F_a \geq G$.

Hydrostatic press

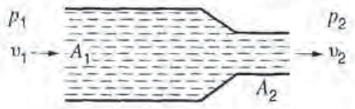


Fluid pressure $p = \frac{F_1}{A_1} = \frac{F_2}{A_2}$

Piston forces $F_1 = p \cdot A_1 = F_2 \cdot \frac{A_1}{A_2}$

$F_2 = p \cdot A_2 = F_1 \cdot \frac{A_2}{A_1}$

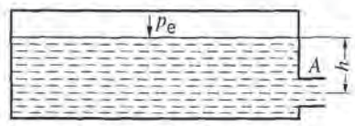
Flow with change in cross section



Flow rate

$$Q = A_1 \cdot v_1 = A_2 \cdot v_2 = \sqrt{\frac{2}{\varrho} \cdot \frac{p_1 - p_2}{1/A_2^2 - 1/A_1^2}}$$

Discharge from vessels



Discharge velocity
$v_a = \psi \cdot \sqrt{2\, g \cdot h + 2p_e/\varrho}$

Discharge rate
$Q_a = \varkappa \cdot A \cdot v_a$
$= \varkappa \cdot \psi \cdot A \cdot \sqrt{2\, g \cdot h + 2p_e/\varrho}$

Coefficient of contraction $\varkappa$ with sharp edge: 0.62 ... 0.64; for slightly broken edge: 0.7 ... 0.8; for slightly rounded edge: 0.9; for heavily rounded, smooth edge: 0.99.
Discharge coefficient $\psi = 0.97 \ldots 0.998$.

[1]) 1 N = 1 kg m/s² (see P. 12).
[2]) 1 Pa = 1 N/m²; 1 bar = 10^5 Pa;
1 at (= 1 kp/cm²) = 0.981 bar ≈ 1 bar (see P. 24 for units of pressure).
[3]) See P. 190 for densities of other fluids.

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Strength of materials

Symbols and units

See PP. 14 ... 18 for names of units

Quantity		Unit
A	Cross-sectional area	mm²
E	Modulus of elasticity	N/mm²
F	Force, load	N
G	Modulus of elasticity in shear	N/mm²
I_a	Axial planar moment of inertia (P. 49)	mm⁴
I_p	Polar planar moment of inertia (P. 49)	mm⁴
l	Length	mm
M_b	Bending moment	N · mm
M_t	Torque; turning moment	N · mm
q	Knife-edge load	N/mm
R	Radius of curvature at neutral axis	mm
R_{dm}	Compression strength	N/mm²
R_e	Yield point	N/mm²
R_m	Tensile strength	N/mm²
$R_{p0.2}$	0.2% yield strength[1])	N/mm²
S	Safety factor	–
s	Maximum deflection	mm
W_b	Section modulus under bending (P. 49)	mm³
W_t	Section modulus under torsion (P. 49)	mm³
α_k	Stress concentration factor (notch factor)	–
β_k	Fatigue-strength reduction factor	–
γ	Elastic shear	rad
δ, A	Elongation at fracture	%
ε	Elastic elongation or compression, strain	%
ν	Poisson's ratio	–
σ	Stress	N/mm²
σ_{zdw}	Reversed-bending fatigue strength	N/mm²
σ_{gr}	Limit stress	N/mm²
σ_D	Endurance limit = fatigue limit	N/mm²
σ_W	Endurance limit at complete stress reversal	N/mm²
σ_a	Stress amplitude	N/mm²
σ_{bB}	Bending strength	N/mm²
σ_{bF}	Elastic limit under bending	N/mm²
σ_{bW}	Fatigue limit under reversed bending stresses	N/mm²
τ	Shear stress	N/mm²
τ_t	Torsional stress	N/mm²
τ_{gr}	Torsional stress limit	N/mm²
τ_{tB}	Torsional strength	N/mm²
τ_{tF}	Elastic limit under torsion	N/mm²
τ_{tW}	Fatigue limit under reversed torsional stress	N/mm²
ψ	Angle of rotation	rad

The equations in this section are general equations of quantities, i.e. they are also applicable if other units are chosen, except equations for buckling.

Mechanical stresses

Tension and compression

(perpendicular to cross-sectional area)

Tensile (compression) stress $\sigma = \frac{F}{A}$

Compression strain $\varepsilon = \frac{\Delta l}{l}$

Δl Increase (or decrease) in length
l Original length

Modulus of elasticity $E = \frac{\sigma}{\varepsilon}$ [2])

Long, thin bars subjected to compressive loads must also be investigated with regard to their buckling strength.

Bending

The effects of a transverse force can be neglected in the case of long beams subjected to bending stress. In calculating bending stresses (resulting from bending moments without transverse force) it can therefore be assumed for reasons of symmetry (the axis of the beam becomes circular) that plane cross sections remain plane. With these assumptions as given, the neutral axis passes through the center of gravity of every conceivable cross section.

The following equation thus applies:

$M_b = \frac{E \cdot I}{R}$

Edge stress $\sigma_b = \frac{M_b}{I} \cdot e = \frac{M_b}{W}$

if $W = \frac{I}{e}$

I Axial moment of inertia: the sum of the products of all cross-sectional elements by the squares of their distances from the neutral axis.

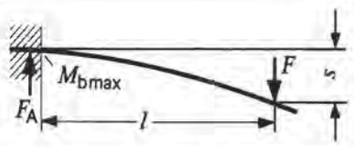
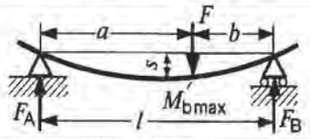
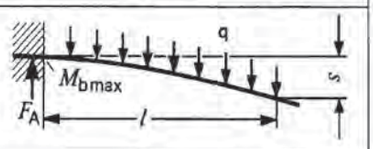
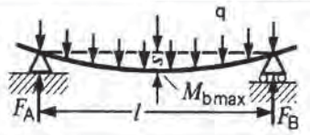
W Section modulus of a cross section: indicates, for the edge stress 1, the inner moment with which the cross section can resist an external bending load.

Q Transverse force: the sum of all forces acting vertically on the beam to the left or right of a given cross section; Q subjects the beam to shearing stress. In the case of short beams, the shearing stress caused by Q must also be taken into account.

e Distance between the neutral-axis zone and the outer-surface zone.

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Table 1. Loading cases under bending

$F_A = F$ $M_{b\,max} = l \cdot F$	$s = \frac{l^3}{3} \cdot \frac{F}{E \cdot I_a}$	
$F_A = \frac{b}{l} F;\ F_B = \frac{a}{l} F$ $M_{b\,max} = \frac{a \cdot b}{l} F$	$s = \frac{a^2 \cdot b^2}{3l} \cdot \frac{F}{E \cdot I_a}$	
$F_A = q \cdot l$ $M_{b\,max} = \frac{q \cdot l^2}{2}$	$s = \frac{l^4}{8} \cdot \frac{q}{E \cdot I_a}$	
$F_A = F_B = \frac{q \cdot l}{2}$ $M_{b\,max} = \frac{q \cdot l^2}{8}$	$s \approx \frac{l^4}{77} \cdot \frac{q}{E \cdot I_a}$	

Buckling

In bars which are subjected to compression, the compressive stress $\sigma = F/A$ must always be less than the permissible buckling stress

$\sigma_{kperm} = \sigma_k/S$

otherwise the bar will buckle.

Depending upon the centricity of the applied force, a factor of safety $S \geq 3 \ldots \geq 6$ must be selected.

Slenderness ratio $\lambda = l_k / \sqrt{I_a / A}$

l_k Free buckling length (see diagram)

Buckling stress $\sigma_k = \pi^2 \frac{E}{\lambda^2} \approx 10 \frac{E \cdot I_a}{l_k^2 \cdot A}$

The above equation for σ_k (Euler's formula) only applies to slender bars with the following slenderness ratios:

$\lambda \geq 100$ for St 37 steel,

$\lambda \geq \pi \sqrt{E / R_e}$ for steels whose R_e values are different from that of St 37,

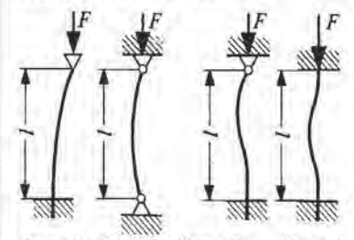
$\lambda \geq 80$ for GG 25 gray cast iron,

$\lambda \geq 100$ for coniferous wood.

According to Tetmajer, the following is valid for lower values of λ:

- for St 37 steel $\sigma_k = (284 - 0.8\,\lambda)$ N/mm²,
- for St 52 steel $\sigma_k = (578 - 3.74\,\lambda)$ N/mm²,
- for GG 25 gray cast iron $\sigma_k = (760 - 12\,\lambda + 0.05\,\lambda^2)$ N/mm² and
- for coniferous wood $\sigma_k = (29 - 0.19\,\lambda)$ N/mm².

Loading cases under buckling



Case 1	Case 2	Case 3	Case 4
$l_k = 2l$	$= l$	$= 0.707l$ [3])	$= 0.5l$ [3])

[1]) 0.2 % yield strength: that stress which causes permanent deformation of 0.2 %.

[2]) Hook's Law applies only to elastic deformation, i.e. in practice approximately up to the elastic limit (yield point, elastic limit under bending, elastic limit under torsion; see also P. 45.

[3]) Applies to ideal clamping point, without eccentricity of the top fixing points. Calculation in accordance with Case 2 is more reliable.

Shear

Shearing stress $\tau = F/A$

τ = shear force per unit area of the cross section of a body. The stress acts in the direction of the plane element. Shear strain γ is the angular deformation of the body element as a result of shear stress. Shear modulus (modulus of rigidity) $G = \tau/\gamma$[1)][2)].

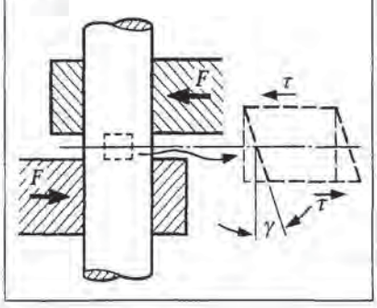
Torsion (twisting)

Torsional stress $\tau_t = M_t/W_t$,
See P. 49 for section moduli W_t.
Torque M_t = torsional force · lever arm.
The torque generates the illustrated shearing-stress distribution in every cross-sectional plane on every diameter.

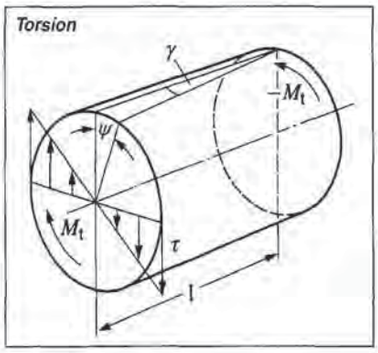
Angle of rotation $\psi = \dfrac{l \cdot M_t}{G \cdot I_p} = \dfrac{l \cdot W_t \cdot \tau}{I_p \cdot G}$

The angle of rotation ψ is the angle of twist in rad of a bar of length l (conversion: 1 rad ≈ 57.3°, see P. 21).
See P. 49 for polar planar moments of inertia I_p.

Shear



Torsion



Notch effect

The equations cited above apply to smooth rods and bars; if notches are present, these equations yield the following nominal stresses (referred to the residual cross section):

$\sigma_{zn} = F/A$ under tension (see diagram) or compression,
$\sigma_{bn} = M_b/W_b$ under bending,
$\tau_{tn} = M_t/W_t$ under torsion.

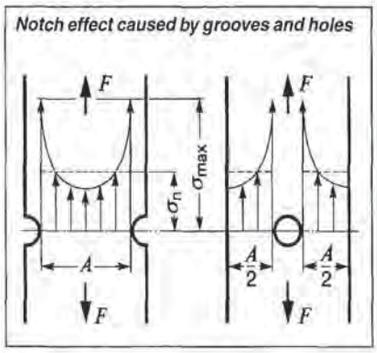
Notches (such as grooves and holes) and changes in cross section (shoulders and offsets) as well as various clamping methods give rise to local stress concentrations σ_{max}, which are usually far in excess of the nominal stresses:

$\sigma_{max} = \alpha_k \cdot \sigma_n$

See P. 48 for the stress concentration factor α_k.

Notches reduce the endurance strength and fatigue limit (see P. 47, Fatigue strength of structure), as well as the impact strength of brittle materials; in the case of tough materials, the first permanent (plastic) deformation occurs earlier. The stress concentration factor α_k increases with the sharpness and depth of the notch (V notches, hairline cracks, poorly machined surfaces). This also holds true the more sharp-edged the changes in cross section are.

Notch effect caused by grooves and holes



[1)] See footnote 2 on P. 43.

[2)] The relationship between the shear modulus G and the modulus of elasticity E is:

$G = \dfrac{E}{2(1+\nu)}$ with ν = Poisson's ratio

For metallic materials with $\nu \approx 0.3$,
$G \approx 0.385\ E$; see P. 193f for values of E.

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Permissible loading

The equations in the sections "Mechanical stresses" and "Notch effect" apply only to the elastic range; in practice they permit calculations approximately up to the elastic limit or up to 0.2% yield strength (see footnote 1, P. 43). The permissible loading in each case is determined by materials testing and the science of the strength of materials and is governed by the material itself, the condition of the material (tough, brittle), the specimen or component shape (notches) and the type of loading (static, alternating).

R_m Tensile strength. For steel up to ≈ 600 HV R_m (in N/mm²) ≈ 3.3 times the HV value; see P. 193 and P. 275.

R_e Stress at the elastic limit (under tension this σ_s is the yield point).

δ (or A) elongation at fracture.

Table 2. Limit stresses σ_{gr}, τ_{gr} under static loading

Generally speaking, the limit stresses σ_{gr} and τ_{gr}, at which failure of the material occurs (permanent deformation or fracture), should not be reached in practice (s. below and P. 46). Depending upon the accuracy of the loading calculation or measurement, the material, the type of stress, and the possible damage in the event of failure, allowance must be made for a safety factor $S = \sigma_{gr}/\sigma_{perm}$ (σ_{perm} is the maximum permissible stress in service). For tough materials, S should be 1.2...2 (...4), and for brittle materials S = (1.2...) 2...4 (...10).

The following must be the case: $\sigma_{max} \leq \sigma_{perm}$ (σ_{max} maximum stress, stress peak in service).

Limit stress	Tough materials	Brittle materials
Under tension	σ_{gr} = yield point R_e (≈ limit of elastic elongation). For steel up to approx. R_m = 600 N/mm² and cold-rolled metals, R_e = 0.6...0.8 R_m. σ_{gr} = 0.2 yield strength $R_{p0.2}$ (see footnote 1, P. 43). For metals without a marked yield point such as steels with $R_m \geq 600$ N/mm², Cu, Al.	σ_{gr} = tensile strength R_m
Under compression	σ_{gr} = compressive yield point σ_{dF} (limit of elastic compression, roughly corresponding to R_e).	σ_{gr} = compression strength R_{dm}.
For compression with danger of buckling	σ_{gr} = buckling strain σ_k.	σ_{gr} = buckling strain σ_k.
Under bending	σ_{gr} = elastic limit under bending σ_{bF} (limit of elastic deflection). σ_{bF} is approximately equal to yield point R_e under tension. Permanent curvature if σ_{bF} is exceeded.	σ_{gr} = bending strength $\sigma_{bB} \approx R_m$. For gray cast iron GG 40, however, σ_{bB} = 1.4...2.0 R_m since $\varepsilon = \sigma/E$ does not apply because the neutral axis is displaced
Under torsion	τ_{gr} = elastic limit under torsion τ_{tF} (limit of elastic twist). Torsional limit $\tau_{tF} \approx 0.5...0.6\ R_e$. If exceeded, twist becomes permanent deformation.	τ_{gr} = torsional strength τ_{tB}. τ_{tB} = 0.5...0.8 σ_B, but for gray cast iron up to GG 25 τ_{tB} = 1...1.3 σ_B.
Under shear	τ_{gr} = elastic limit under shear $\tau_{sF} \approx 0.6\ \sigma_S$.	τ_{gr} = shear strength τ_{sB}.

When minimal plastic deformations can be accepted, it is permissible to extend the loads on tough materials beyond the limits of elastic compression and deflection. The internal areas of the cross section are then stressed up to their yield point while they provide support for the surface-layer zone. The bending force applied to an angular bar can be increased by a maximum factor of 1.5; the maximum increase in torsional force applied to a round torsion bar is 1.33.

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Limit stresses under pulsating loads

If the load alternates between two stress values, different (lower) stress limits σ_g are valid: the largest stress amplitude, alternating about a given mean stress, which can be withstood "infinitely" often without fracture and impermissible distortion, is called the fatigue limit or endurance limit σ_D. It is determined experimentally by applying a pulsating load to test specimens until fracture occurs, whereby with the reduced load the number of cycles to fracture increases and yields the so-called "Wöhler" or stress-number (S/N) curve. The Wöhler curve is nearly horizontal after 2...10 million load cycles for steel, and after roughly 100 million cycles for non-ferrous metals; oscillation stress = fatigue limit in such cases.

If no additional factors are present in operation (wear, corrosion, multiple overloading etc.), fracture does not occur after this "ultimate number of cycles". It should be noted that $S \cdot \sigma_a \leq \sigma_W$ or in the case of increased mean stresses $S \cdot \sigma_a \leq \sigma_D$; safety factor S = 1.25...≥ 3 (stress values have lower-case subscripts, fatigue-strength values have upper-case subscripts). A fatigue fracture generally does not exhibit permanent deformation. With plastics, it is not always possible to give an "ultimate number of cycles" because in this case extensive superimposed creepage becomes effective. With high-tensile steels, the internal stresses resulting from production processes can have a considerable effect upon the fatigue-strength values.

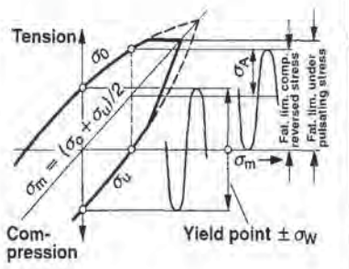
Fatigue-limit diagram

The greatest "infinitely" often endurable stress amplitude can be determined from the fatigue limit diagram (at right) for any minimum stress σ_u or mean stress σ_m. The diagram is produced using several Wöhler curves with various mean stress factors.

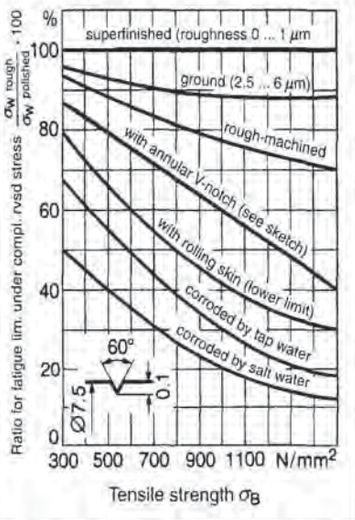
Special cases of fatigue limit

Fatigue limit under completely reversed stress σ_W
The stress alternates between two opposite limit values of the same magnitude; the mean stress is zero.

Fatigue diagram



Effect of surface quality finish on fatigue limit during bending and tension-compression stresses



The fatigue limit σ_W is approximately:

Load	Steel	Non-ferrous metals
Tension/ compression	0.30...0.45 R_m	0.2...0.4 R_m
Bending	0.40...0.55 R_m	0.3...0.5 R_m

Fatigue limit under pulsating stress σ_{sch}
Defines the infinitely endurable number of double amplitudes when the minimum stress is zero (see Fatigue diagram above).

Table 3. Relaxation for various materials

Material	Part	σ_s N/mm²	Initial stress N/mm²	Temperature °C	Time h	Relaxation %
GD-Zn Al4 Cu 1	Thread	280	150[1]	20	500	30
GD-Mg Al8 Zn 1	Compression test specimen	157	60	150	500	63
GD-Al Si12 (Cu)		207	60	150	500	3.3
Cq35	Bolt	800	540	160	500	11
40Cr Mo V 47	Bar under tension	850	372	300	1000	12

Permissible alternating loading of notched machine parts

The fatigue limit of notched parts is usually higher than that calculated using stress concentration factor α_k (see P. 48). Also, the sensitivity of materials to the effect of a notch in case of (alternating) fatigue loading varies, e.g., spring steels, highly quenched and tempered structural steels, and high-strength bronzes are more sensitive than cast iron, stainless steel and precipitation-hardened aluminum alloys. For (alternating) fatigue loading, fatigue-strength reduction factor β_k applies instead of α_k so that e.g. at $\sigma_m = 0$ the effective stress amplitude on the structural member is $\sigma_{wn}\beta_k$ (σ_{wn} the nominal alternating stress referred to the residual cross section). The following must hold true:

$$\sigma_{wn}\beta_k \leq \sigma_{wperm} = \sigma_w/S$$

Attempts have been made to derive β_k from α_k where e.g. Thum introduced notch sensitivity η_k and established that

$$\beta_k = 1 + (\alpha_k - 1)\,\eta_k$$

However η_k is not a material constant, and it also depends upon the condition of the material, the component geometry (notch acuity) and the type of loading (e.g. alternating or dynamic).

Fatigue limit values under reversed stress

σ_w for various materials is given on P. 193/198.

Stress concentration factors

α_k for different notch configurations is given on P. 48.

Fatigue strength of structure

For many component parts, it is difficult or even impossible to determine a stress concentration factor α_k and thus a fatigue-strength reduction factor β_k. In this case the fatigue limit of the entire part (fatigue strength of structural member, e.g., pulsating loads in N or moment of oscillation in N·m) must be determined experimentally and compared with test results given in literature. The local stressing can continue to be measured, using foil strain gauges for instance. As an alternative, or for preliminary design purposes, the finite-element method can be applied to calculate numerically the stress distribution and to compare it with the respective limit stress.

Creep behavior

If materials are subjected for long periods of time to loads at increased temperatures and/or to high stresses, creep or relaxation may occur. If resulting deformations (generally very small) are not acceptable, allowance must be made for the material's "creep behavior".

Creep:
Permanent deformation under constant load, and (at least approximately) constant stress (example: turbine blades).

Relaxation:
Reduction of the tension forces and stresses, whereby the initially applied (usually purely elastic) deformation remains constant (see Table 3 for examples).

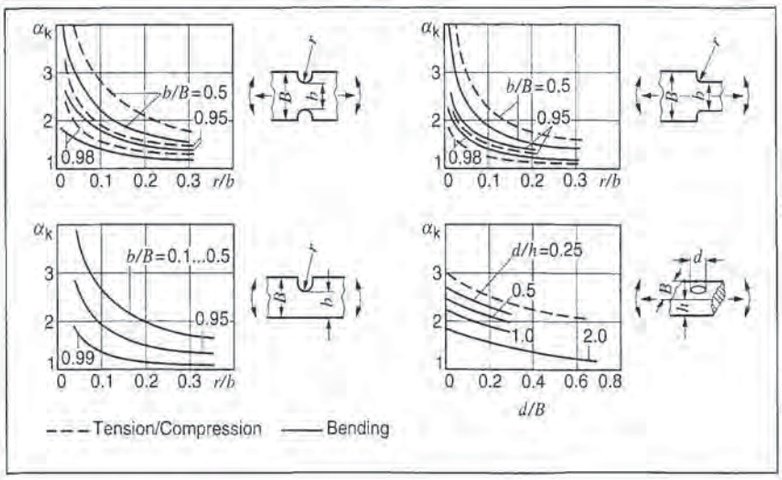
In the case of alternating loads (where $\sigma_a \geq 0.1\ \sigma_B$) and maximum stresses and temperatures such as are encountered in static relaxation tests, the same deformations and losses of force only occur after a period of load which is approximately 10 times (or more) as long as that of the static relaxation tests.

[1] In the stress area of a steel bolt.

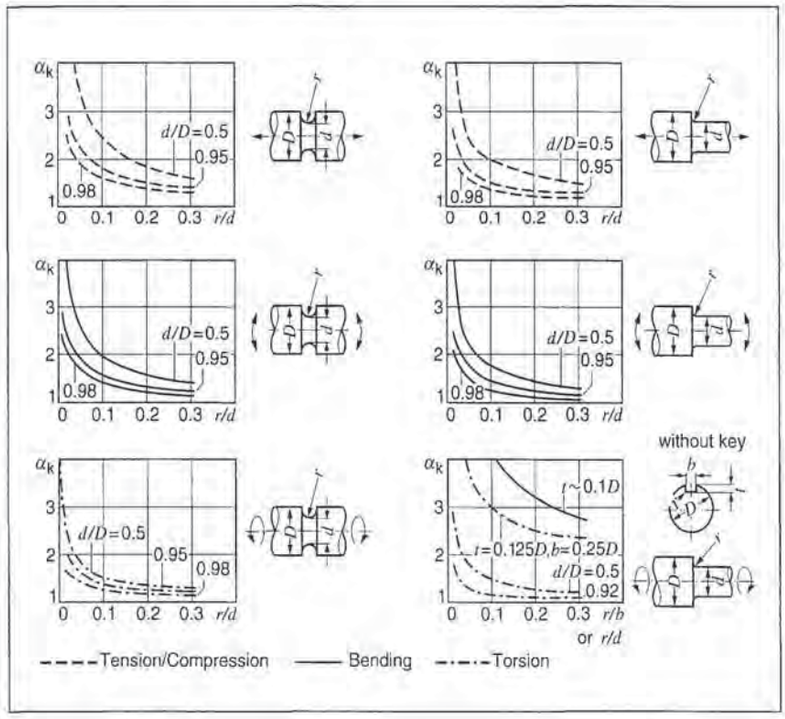
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Stress concentration factor α_k for various notch configurations

Stress concentration factors for flat bars



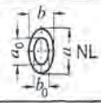
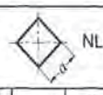
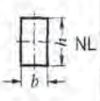
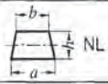
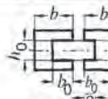
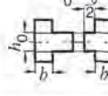
Stress concentration factors for rods



Section moduli and geometrical moments of inertia

NL = "neutral axis"

See P. 38 for mass moments of inertia

	Section modulus W_b under bending W_t under torsion	**Planar moment of inertia** I_a axial, referred to NL I_p polar, referred to center of gravity
	$W_b = 0.098\ d^3$ $W_t = 0.196\ d^3$	$I_a = 0.049\ d^4$ $I_p = 0.098\ d^4$
	$W_b = 0.098\ (d^4 - d_0^4)/d$ $W_t = 0.196\ (d^4 - d_0^4)/d$	$I_a = 0.049\ (d^4 - d_0^4)$ $I_p = 0.098\ (d^4 - d_0^4)$
	$W_b = 0.098\ a^2 \cdot b$ $W_t = 0.196\ a \cdot b^2$	$I_a = 0.049\ a^3 \cdot b$ $I_p = 0.196\ \frac{a^3 \cdot b^3}{a^2 + b^2}$
	$W_b = 0.098\ (a^3 \cdot b - a_0^3 \cdot b_0)/a$ $W_t = 0.196\ (a \cdot b^3 - a_0 \cdot b_0^3)/b$	$I_a = 0.049\ (a^3 \cdot b - a_0^3 \cdot b_0)$ $I_p = 0.196\ \frac{n^3 (b^4 - b_0^4)}{n^2 + 1}$ for $\frac{a}{b} = n \geq 1$ and $\frac{a_0}{b_0} = n$
	$W_b = 0.118\ a^3$ $W_t = 0.208\ a^3$	$I_a = 0.083\ a^4$ $I_p = 0.140\ a^4$
	$W_b = 0.167\ b \cdot h^2$ $W_t = x \cdot b^2 \cdot h$ (In the case of torsion, the initially plane cross sections of a rod do not remain plane.)	$I_a = 0.083\ b \cdot h^3$ $I_p = \eta \cdot b^3 \cdot h$
	$W_b = 0.104\ d^3$ $W_t = 0.188\ d^3$	$I_a = 0.060\ d^4$ $I_p = 0.115\ d^4$
	$W_b = 0.120\ d^3$ $W_t = 0.188\ d^3$	$I_a = 0.060\ d^4$ $I_p = 0.115\ d^4$
	$W_b = \frac{h^2 (a^2 + 4a \cdot b + b^2)}{12\ (2a + b)}$	$I_a = \frac{h^3 (a^2 + 4a \cdot b + b^2)}{36\ (a + b)}$
	$W_b = \frac{b \cdot h^3 - b_0 \cdot h_0^3}{6\ h}$	$I_a = \frac{b \cdot h^3 - b_0 \cdot h_0^3}{12}$
	$W_b = \frac{b \cdot h^3 + b_0 \cdot h_0^3}{6\ h}$	$I_a = \frac{b \cdot h^3 + b_0 \cdot h_0^3}{12}$

$h : b$	x	η
1	0.208	0.140
1.5	0.231	0.196
2	0.246	0.229
3	0.267	0.263
4	0.282	0.281

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Acoustics

Quantities and units
(see also DIN 1332)

Quantity		SI unit
c	Velocity of sound	m/s
f	Frequency	Hz
I	Sound intensity	W/m²
L_I	Sound intensity level	dB
L_{Aeq}	Equivalent continuous sound level, A-weighted	dB (A)
L_{pA}	Sound pressure level, A-weighted	dB (A)
L_r	Rating sound level	dB (A)
L_{WA}	Sound power level, A-weighted	dB (A)
P	Sound power	W
p	Sound pressure	Pa
S	Surface area	m²
T	Reverberation time	s
v	Particle velocity	m/s
Z	Specific acoustic impedance	Pa · s/m
α	Sound absorption coefficient	1
λ	Wavelength	m
ϱ	Density	kg/m³
ω	Angular frequency (= 2 πf)	1/s

General terminology
(see also DIN 1320)

Sound
Mechanical vibrations and waves in an elastic medium, particularly in the audible frequency range (16 to 20,000 Hz).

Ultrasound
Mechanical vibrations above the frequency range of human hearing.

Propagation of sound
In general, sound propagates spherically from its source. In a free sound field, the sound pressure decreases by 6 dB each time the distance from the sound source is doubled. Reflecting objects influence the sound field, and the rate at which the sound level is reduced as a function of the distance from the sound source is lower.

Velocity of sound c
The velocity of sound is the velocity of propagation of a sound wave.

Sound velocities and wave lengths in different materials.

Material/medium	Velocity of sound c m/s	Wavelength λ m at 1000 Hz
Air, 20 °C, 1014 hPa	343	0.343
Water, 10 °C	1440	1.44
Rubber (according to hardness)	60 ... 1500	0.06 ... 1.5
Aluminum (rod)	5100	5.1
Steel (rod)	5000	5.0

Wavelength $\lambda = c/f = 2\,\pi\,c/\omega$

Particle velocity v
Particle velocity is the alternating velocity of a vibrating particle. In a free sound field: $v = p/Z$. At low frequencies, perceived vibration is approximately proportional to the particle velocity.

Sound pressure p
Sound pressure is the alternating pressure generated in a medium by the vibration of sound. In a free sound field, this pressure equals $p = v \cdot Z$. It is usually measured as the RMS value.

Specific acoustic impedance Z
Specific acoustic impedance is a measure of the ability of a medium to transmit sound waves. $Z = p/v = \varrho \cdot c$. For air at 20 °C and 1013 hPa (760 torr) Z = 415 Ns/m³, for water at 10 °C $Z = 1.44 \cdot 10^6$ Ns/m³ = $1.44 \cdot 10^6$ Pa · s/m.

Sound power P
Sound power is the power emitted by a sound source. Sound power of some sound sources:

Normal conversation, average	$7 \cdot 10^{-6}$ W
Violin, fortissimo	$1 \cdot 10^{-3}$ W
Peak power of the human voice	$2 \cdot 10^{-3}$ W
Piano, trumpet	0.2 ... 0.3 W
Organ	1 ... 10 W
Kettle drum	10 W
Orchestra (75 musicians)	up to 65 W

Sound intensity I
(Sound intensity) $I = P/S$, i.e. sound power through a plane vertical to the direction of propagation. In a sound field,
$I = p^2/\varrho \cdot c = v^2 \cdot \varrho \cdot c$.

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Doppler effect
For moving sound sources: If the distance between the source and the observer decreases, the perceived pitch *(f')* is higher than the actual pitch *(f)*; as the distance increases, the perceived pitch falls. The following relationship holds true if the observer and the sound force are moving along the same line: $f'/f = (c - u')/(c - u)$. c = velocity of sound, u' = velocity of observer, u = velocity of sound source.

Interval
The interval is the ratio of the frequencies of two tones. In the "equal-tempered scale" of our musical instruments (introduced by J. S. Bach), the octave (interval 2:1) is divided into 12 equal semitones with a ratio of $\sqrt[12]{2} = 1.0595$, i.e. a series of any number of tempered intervals always leads back to a tempered interval. In the case of "pure pitch", on the other hand, a sequence of pure intervals usually does not lead to a pure interval. (Pure pitch has the intervals 1, 16/15, 9/8, 6/5, 5/4, 4/3, 7/5, 3/2, 8/5, 5/3, 9/5, 15/8, 2.)

Sound spectrum
The sound spectrum, generated by means of frequency analysis, is used to show the relationship between the sound pressure level (airborne or structure-borne sound) and frequency.

Octave band spectrum
The sound levels are determined and represented in terms of octave bandwidth. Octave: frequency ranges with fundamental frequencies in a ratio of 1:2. Mean frequency of octave $f_m = \sqrt{f_1 \cdot f_2}$.
Recommended center frequencies: 31.5; 63; 125; 250; 500; 1000; 2000; 4000; 8000 Hz.

Third-octave band spectrum
Sound levels are determined and represented in terms of third-octave bandwidth. The bandwidth referred to the center frequency is relatively constant, as in the case of the octave band spectrum.

Sound insulation
Sound insulation is the reduction of the effect of a sound source by interposing a reflecting (insulating) wall between the source and the impact location.

Sound absorption
Loss of sound energy when reflected on peripheries, but also for the propagation in a medium.

Sound absorption coefficient α
The sound absorption coefficient is the ratio of the non-reflected sound energy to the incident sound energy. With total reflection, $\alpha = 0$; with total absorption, $\alpha = 1$.

Noise reduction
Attenuation of acoustic emissions: Reduction in the primary mechanical or electrodynamic generation of structure-borne noise and flow noises; damping and modification of sympathetic vibrations; reduction of the effective radiation surfaces; encapsulation.

Low-noise design
Application of simulation techniques (modal analysis, modal variation, finite-element analysis, analysis of coupling effects of airborne noise) for advance calculation and optimization of the acoustic properties of new designs.

Quantities for noise emission measurement

Sound field quantities are normally measured as RMS values, and are expressed in terms of frequency-dependent weighting (A-weighting). This is indicated by the subscript A next to the corresponding symbol.

Sound power level L_w
The sound power of a sound source is described by the sound power level L_w. The sound power level is equal to ten times the logarithm to the base 10 of the ratio of the calculated sound power to the reference sound power $P_0 = 10^{-12}$ W. Sound power cannot be measured directly. It is calculated based on quantities of the sound field which surrounds the source. Measurements are usually also made of the sound pressure level L_p at specific points around the source (see

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DIN 45635). L_W can also be calculated based on sound intensity levels L_I measured at various points on the surface of an imaginary envelope surrounding the sound source. If noise is emitted uniformly through a surface of $S_0 = 1\ m^2$, the sound pressure level L_p and the sound intensity level L_I at this surface have the same value as the sound power level L_W.

Sound pressure level L_p
The sound pressure level is ten times the logarithm to the base 10 of the ratio of the square of the RMS sound pressure to the square of the reference sound pressure $p_0 = 20\ \mu Pa$. $L_p = 10 \log p^2/p_0^2$ or $L_p = 20 \log p/p_0$.
The sound pressure level is given in decibels (dB).

The frequency-dependent, A-weighted sound pressure level L_{pA} as measured at a distance of $d = 1$ m is frequently used to characterize sound sources.

Sound intensity level L_I
The sound intensity level is equal to ten times the logarithm to the base ten of the ratio of sound intensity to reference sound intensity $I_0 = 10^{-12}\ W/m^2$. $L_I = 10 \log I/I_0$.

Interaction of two or more sound sources
If two independent sound fields are superimposed, their sound intensities or the squares of their sound pressures must be added. The overall sound level is then determined from the individual sound levels as follows:

Difference between 2 individual sound levels	Overall sound level = higher individual sound level + supplement of:
0 dB	3 dB
1 dB	2.5 dB
2 dB	2.1 dB
3 dB	1.8 dB
4 dB	1.5 dB
6 dB	1 dB
8 dB	0.6 dB
10 dB	0.4 dB

Motor-vehicle noise measurements and limits

The noise measurements employed to monitor compliance with legal requirements are concerned exclusively with external noise levels. Testing procedures and limit values for stationary and moving vehicles were defined in 1981 with the promulgation of EC Directive 81/334.

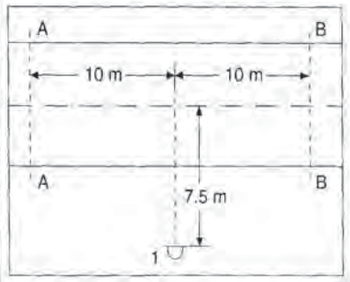
Noise emissions from moving vehicles
The vehicle approaches line AA, which is located 10 m from the microphone plane, at a constant velocity. Upon reaching line AA, the vehicle continues under full acceleration as far as line BB (also placed 10 m from the microphone plane), which serves as the end of the test section. The noise-emissions level is the maximum sound level as recorded by the microphone 7.5 m from the middle of the lane.

Passenger cars with manual transmission and a maximum of 4 forward gears are tested in 2nd gear. Consecutive readings in 2nd and 3rd gear are employed for vehicles with more than 4 forward gears, with the noise emissions level being defined as the arithmetic mean of the two maximum sound levels.

Separate procedures are prescribed for vehicles with automatic transmissions.

Noise emissions from stationary vehicles
Measurements are taken in the vicinity of

Test layout for driving-noise measurement according to DIN 81/334/EEC through 84/424/EEC
1 Microphone



Limits and tolerances in dB(A) for noise emission from motor vehicles

Vehicle category	92/97/EEC since Oct. 1995 dB (A)
Passenger cars	
With spark-ignition or diesel engine	74 + 1
– with direct-injection diesel engine	75 + 1
Trucks and buses	
Permissible total weight below 2 t	76 + 1
– with direct-injection diesel engine	77 + 1
Buses	
Permissible total weight 2 t ... 3.5 t	76 + 1
– with direct-injection diesel engine	77 + 1
Permissible total weight above 3.5 t	
– engine power output up to 150 kW	78 + 1
– engine power output above 150 kW	80 + 1
Trucks	
Permissible total weight 2 t ... 3.5 t	76 + 1
– with direct-injection diesel engine	77 + 1
Permissible total weight above 3.5 t (FMVSS/CUR: above 2.8 t)	
– engine power output up to 75 kW	77 + 1
– engine power output up to 150 kW	78 + 1
– engine power output above 150 kW	80 + 1

Higher limits are valid for off-road and 4WD vehicles.
Supplementary noise limits apply for engine brakes and pneumatic equipment.

the exhaust muffler in order to facilitate subsequent testing of motor-vehicle noise levels. Measurements are carried out with the engine running at $^3/_4$ the speed at which it develops its rated power output. Once the engine speed levels off, the throttle valve is quickly returned to its idle position. During this procedure, the maximum A-weighted sound-pressure level is monitored at a distance of 50 cm from the outlet at a horizontal angle of (45 ±10)° to the direction of exhaust flow. The recorded level is entered in the vehicle documentation in dB(A) with the suffix "P" (making it possible to distinguish between this figure and levels derived using earlier test procedures). No legal maxima have been specified for standing noise levels.

Interior noise level
There are no legal requirements pertaining to interior noise levels. The interior noise is measured, e.g. at constant speed or when gradually accelerating in the range from 60 km/h or 40% of the maximum driving speed, as the A-weighted sound pressure level and then plotted as a function of the driving speed. One series of measurements is always to be made at the driver's seat; other measurement locations are selected in accordance with the passenger seating arrangement inside the vehicle. There are no plans to introduce a single value for indicating inside noise levels.

Quantities for noise immission measurement

Rating sound level L_r
The effect of noise on the human being is evaluated using the rating sound level L_r (see also DIN 45645). This is a measure of the mean noise immission over a period of time (e.g. 8 working hours), and with fluctuating noises is either measured directly with integrated measuring instruments or calculated from individual sound-pressure-level measurements and the associated periods of time of the individual sound effects (see also DIN 45641). Noise immission parameters such as pulsation and tonal quality can be taken into account through level allowances (see table below for reference values).

The following guideline values for the rating sound level (Germany; Technical Instructions on Noise Abatement, 16 July 1968) are measured outside the nearest residential building (0.5 m in front of an open window):

	Day	Night
Purely industrial areas	70 dB (A)	70 dB (A)
Areas with predominantly industrial premises	65 dB (A)	50 dB (A)
Mixed areas	60 dB (A)	45 dB (A)
Areas with predominantly residential premises	55 dB (A)	40 dB (A)
Purely residential areas	50 dB (A)	35 dB (A)
Health resorts, hospitals etc.	45 dB (A)	35 dB (A)

Equivalent continuous sound level L_{Aeq}
In the case of noises which fluctuate in time, the mean A-weighted sound pressure level resulting from the individual sound pressure levels and the individual exposure times, equals the equivalent continuous sound level if it describes the mean sound energy over the entire assessment time period (see DIN 45641). The equivalent continuous sound level in accordance with the German "Aircraft Noise Abatement Law" is arrived at in a different manner (see DIN 45643).

Perceived noise levels

The human ear can distinguish approximately 300 levels of acoustic intensity and 3000 ... 4000 different frequencies (pitch levels) in rapid temporal succession and evaluate them according to complex patterns. Thus there is not necessarily any direct correspondence between perceived noise levels and (energy-oriented) technically-defined sound levels. A rough approximation of subjective sound-level perception is provided by A-weighted sound levels, which take into account variations in the human ear's sensitivity as a function of frequency, the phon unit and the definition of loudness in sone. Sound-level measurements alone do not suffice to define the nuisance and disturbance potential of noise emanating from machinery and equipment. A hardly-perceptible ticking noise can thus be perceived as extremely disturbing, even in an otherwise loud environment.

Loudness level L_S
The loudness level is a comparative measure of the intensity of sound perception measured in phon. The loudness level of a sound (pure tone or noise) is the sound pressure level of a standard pure tone which, under standard listening conditions, is judged by a normal observer to be equally loud. The standard pure tone is a plane sound wave with a frequency of 1000 Hz impinging on the observer's head from the front. A difference of 8 to 10 phon is perceived as twice or half as loud.

Phon
The standard pure tone judged as being equally loud has a specific sound pressure level in dB. This value is given as the loudness level of the tested sound, and has the designation "phon". Because human perception of sound is frequency-dependent, the dB values of the tested sound for notes, for example, do not agree with the dB values of the standard pure tone (exception: reference frequency 1000 Hz), however the phon figures do agree. See the graph below for curves of equal loudness level according to Fletcher-Munson.

Loudness S in sone
The sone is the unit employed to define subjective noise levels. The starting point for defining the sone is: How much higher or lower is the perceived level of a particular sound relative to a specific standard.

Definition: sound level L_S = 40 phon corresponds to loudness S = 1 sone. Doubling or halving the loudness is equivalent to a variation in the loudness level of approx. 10 phon.

There is an ISO standard for calculating stationary sound using tertiary levels (Zwicker method). This procedure takes into account both frequency weighting and the screening effects of hearing.

Pitch, sharpness
The spectrum of perceptible sound can be divided into 24 hearing-oriented frequency groups (bark). The groups define perceived pitch levels. The loudness/pitch distribution (analogous to the tertiary spectrum) can be used to quantify other subjective aural impressions, such as the sharpness of a noise.

Technical acoustics

Measuring equipment for acoustics
- Sound-pressure recording with capacitor microphones, e.g. using sound-level meters in dB(A).
- Artificial-head recordings with ear microphones for faithful sound reproduction (with headphones).

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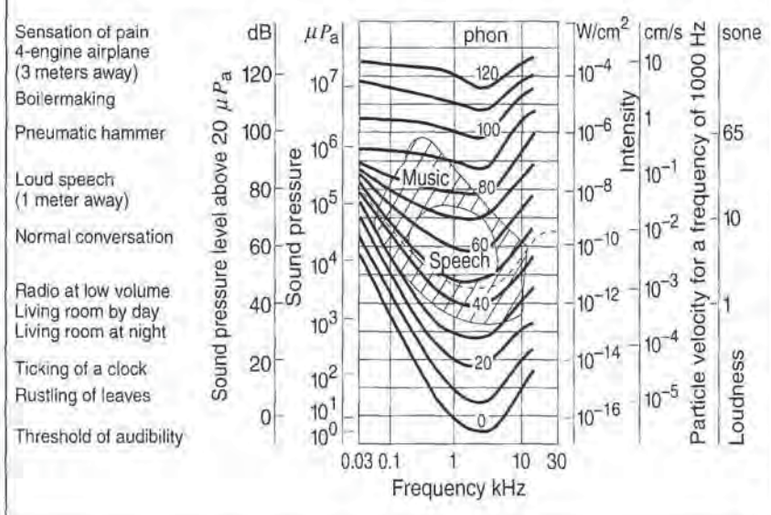
- Measuring rooms for standard sound measurements are generally equipped with highly sound-absorbent walls.
- Vibrations, structure-borne sound: acceleration sensor (mass partly under 1 g), e.g. according to piezoelectric principle; laser vibrometer for rapid non-contact measurement according to Doppler principle.

Calculating methods in acoustics
Vibration/oscillation: FE modeling and natural-oscillation calculation, adjustment with experimental modal analysis. Modeling of forces acting during operation enables calculation of operational vibration shapes. Thus optimization of design with regard to vibrational behavior.
Air-borne noise, fluid-borne noise: Sound-field calculation e.g. of cabinet radiation or in cavities using FEM (finite-element method) or BEM (boundary-element method).

Acoustic quality control
This is the evaluation, predominantly by human testers, of noise and interference levels and the classification of operating defects based on audible sound or structure-borne noise as part of the production process, e.g. in the run-up of electric motors. Automated test devices are used for specialized applications, but they are at present still unable to achieve human levels of flexibility, selectivity and learning ability. Advances have been made through the use of neural networks and combined evaluation of sound properties.

Noise design
Specific configuration of operating noises by means of design measures; subjective aural impressions and psychoacoustics are taken into consideration. The objective is not primarily to reduce noise but rather to achieve a general sound quality, to embody specific features (e.g. sporty exhaust sound by way of rough sounds) or company-specific noises (e.g. a particular door-closing noise in passenger cars, "corporate sound").

Allocation of sounds *to objective and subjective scales, curves of equal loudness level, weighting curve A of sound-level meter.*



Heat

Symbols and units

See PP. 12 ... 18 for names of units, P. 26 for conversion of heat units and P. 180 for thermal expansion, heat of fusion, heat of evaporation.

Quantity		SI unit
A	Area, cross-section	m^2
c	Specific heat capacity c_p Isobaric (constant pressure) c_v Isochoric (constant volume)	J/(kg · K)
H	Enthalpy (heat content)	J
k	Heat transmission coefficient	W/(m² · K)
m	Mass	kg
p	Pressure	Pa = N/m²
Q	Heat	J
$\dot{Q}$	Heat flow = Q/z	W
R_m	Molar gas constant = 8.3145 J/(mol · K) (same for all gases)	J/(mol · K)
R_i	Special gas constant $R_i = R_m/M$ (M = molecular weight)	J/(kg · K)
S	Entropy	J/K
s	Distance	m
T	Thermodynamic temperature $T = t + 273.15$	K
ΔT	Temperature difference $= T_1 - T_2 = t_1 - t_2$ T_1, t_1 higher temperature T_2, t_2 lower temperature	K
t	Celsius temperature	°C
V	Volume	m^3
v	Specific volume	m^3/kg
W	Work	J
z	Time	s
α	Heat transfer coefficient α_a external, α_i internal	W/(m² · K)
ε	Emissivity	–
λ	Thermal conductivity (see P. 17 for values)	W/(m · K)
ϱ	Density	kg/m³

Conversion from outdated units

(see also PP. 16 and 17)

1 kcal (kilocalorie) = 4186.8 J
≈ 4200 J ≈ 4.2 kJ

1 kcal/(m · h · grd) = 1.163 W/(m · K)

Enthalpy (heat content)

$$H = m \cdot c \cdot T$$

Enthalpy difference (ΔH) is the quantity of heat released (Q) as a result of a change in temperature ($\Delta T = T_1 - T_2$)

$$\Delta H = H_1 - H_2 = Q$$
$$= m \cdot c \cdot \Delta T = V \cdot \varrho \cdot c \cdot \Delta T$$

Heat transfer

Heat is transferred in three different ways:
Thermal conduction: Heat is conveyed inside a solid, liquid or gaseous body by contact between the particles.
Convection: Heat is conveyed by the particles of a moving liquid or gaseous body. In natural or free convection, the state of motion is brought about by the effect of buoyancy; in forced convection, however, the motion is maintained artificially.
Radiation: Heat is transferred from one body to another by electromagnetic waves without a material carrier.

Thermal conduction

The heat flow in a body of constant cross section A between two parallel cross-sectional planes separated by a distance s at a temperature difference ΔT is

$$\dot{Q} = \frac{\lambda}{s} A \cdot \Delta T$$

Thermal radiation

Empty space and air are pervious to thermal radiation. Solid bodies and most liquids are impervious to thermal radiation, as are various gases to certain wavelengths.

The thermal radiation emitted by the area A at temperature T is

$$\dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot T^4$$

where $\sigma = 5.67 \cdot 10^{-8}$ W/(m² · K⁴) is the radiation constant of the black-body radiator[1]) and ε is the emissivity of the surface area (see table on opposite page).

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Emissivity ε
up to a temperature of 300 °C (573 K)

Black-body radiator[1])	1.00
Aluminum, unmachined	0.07
Aluminum, polished	0.04
Ice	0.90
Enamel paint, white	0.91
Glass	0.93
Cast iron, rough, oxidized	0.94
Cast iron, turned	0.44
Wood, smooth	0.90
Lime mortar, rough, white	0.93
Copper, oxidized	0.64
Copper, polished	0.05
Brass, matt	0.22
Brass, polished	0.05
Nickel, polished	0.07
Oil	0.82
Paper	0.80
Porce ain, glazed	0.92
Soot	0.93
Silver, polished	0.02
Steel, matt, oxidized	0.96
Steel, polished, oil-free	0.06
Steel, polished, oiled	0.40
Water	0.92
Bricks	0.93
Zinc, matt	0.23
Zinc, polished	0.05
Tin, polished	0.06

Transmission of heat through a wall
The heat flow through a wall of area A and thickness s at a temperature difference ΔT is:

$$\dot{Q} = k \cdot A \cdot \Delta T$$

The heat transmission coefficient k is calculated as follows:

$$1/k = 1/\alpha_i + s/\lambda + 1/\alpha_a$$

Thermal resistance
Thermal resistance is composed of the thermal resistance of the individual layers of the wall:

$$s/\lambda = s_1/\lambda_1 + s_2/\lambda_2 + \ldots$$

See P. 186 for the thermal conductivity λ of various materials.

[1]) A "black-body radiator" completely absorbs all incident light and heat radiation directed against it; and therefore when heated radiates the maximum amount of light which can be emitted by a body. An example of a black-body radiator is the opening in a carbon tube.

Heat transfer coefficients α
(convection + radiation)

Type of material, wall surface etc.	α_i or α_a W/(m² · K)
Natural air movement in a closed room:	
Wall surfaces, interior	
windows	8
Exterior windows	11
Floors, ceilings:	
from bottom upwards	8
from top downwards	6
Forced air movement on a flat wall	
Mean wind velocity w = 2 m/s	15
Mean wind velocity w > 5 m/s	$6.4 \cdot w^{0.75}$
Water on a flat wall	
Still	500 ... 2000
Moving	2000 ... 4000
Boiling	2000 ... 6000

Thermal resistance of air layers s/λ
(conduction + convection + radiation)

Position of air layer	Thickness of air layer mm	Thermal resistance s/λ m² · K/W
Vertical air layer	10	0.14
	20	0.16
	50	0.18
	100	0.17
	150	0.16
Horizontal air layer		
Heat flow	10	0.14
from bottom	20	0.15
upwards	50	0.16
Horizontal air layer		
Heat flow	10	0.15
from top	20	0.18
downwards	50	0.21

Heat required to heat dwellings
50 to 60 W is required to heat each m² of living area.

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Technical temperature measurement

(VDE/VDI Guideline 3511)

Measurement system	Measurement range	Method of operation	Examples of application
Liquid-in-glass thermometers	–200 ... 1000 °C	Thermal expansion of the liquid is visible in a narrow glass tube. Liquid: Pentane (–200 ... 30 °C). Alcohol (–100 ... 210 °C), Toluene (–90 ... 100 °C). Mercury (–38 ... 600 °C), Gallium (...1000 °C).	For liquids and gases, for monitoring steam, heating and drying systems; refrigeration equipment; media flowing through pipes.
Pressure-spring thermometers	–50 ... 500 °C	Due to its expansion pressure (mercury, toluene) or vapor pressure (ether, hexane, toluene, xylene), a liquid in an immersion vessel actuates a pointer or a recording instrument via a Bourdon tube.	For monitoring and recording temperatures (including remote applications up to 35 m) in power plants, factories, heating plants, cold rooms.
Solid expansion thermometers	0 ... 1000 °C	Different thermal expansion of two metals (rod in tube).	Temperature regulators.
Bimetallic thermometers	–50 ... 400 °C	Curvature of a strip consisting of two different metals.	Temperature regulators.
Resistance thermometers	–220 ... 850 °C	Change in resistance caused by change in temperature Platinum wires –220 ... 850 °C, Nickel wires –60 ... 250 °C, Copper wires –50 ... 150 °C, Semiconductors –40 ... 180 °C,	Temperature measurements on machines, windings, refrigeration equipment. Remote transmission possible.
Thermistors	0 ... 500 °C (2200°)	Sharp drop in electrical resistance as the temperature increases.	Measurement of minor temperature differences due to high sensitivity.
Thermocouples	–200 ... 1800 °C	Thermoelectromotive force of two metals whose junctions are at different temperatures.	Temperature measurements on and in machines, engines, etc. Remote transmission possible.
Radiation thermometers (pyrometer, infrared camera, high-speed pyrometer)	–100 ... 3500 °C	The radiation emitted by a body is an indicator of its temperature. It is sensed by using either thermocouples or photocells, or by comparing luminance values. Emissions level must be observed.	Melting and annealing furnaces. Surface temperatures. Moving objects, thermogravimetry, extremely rapid response.
Temperature-sensitive paints, temperature-indicating crayons	40 ... 1350 °C	Color changes when specific temperatures are exceeded. Paints and crayons are available with one or more color changes (up to 4). The new color remains after cooling.	Temperature measurements on rotating parts, in inaccessible places, in machining processes; warning of excessive temperature; material testing (cracks).
Suction thermometers, pyrometers	1800 ... 2800 °C	Gas is extracted from the flame.	Measurement of flame temperature (delayed display).

Other temperature-measurement methods: spectroscopy, interferometry, quartz thermometry, noise thermometry, liquid crystals, acoustic and magnetic thermometers.

Thermodynamics

First law of thermodynamics:
Energy can be neither created nor destroyed. Only the form in which energy exists can be changed, e.g., heat can be transformed into mechanical energy.

Second law of thermodynamics:
Heat cannot be completely converted to another form of energy, e.g., mechanical work. All natural and synthetic energy transformation processes are irreversible and occur in a preferred direction (according to the probable state). On its own, heat passes only from warmer to colder bodies, the reverse is possible only if energy is supplied.

Entropy S is a measure of the thermal energy in a system which is no longer capable of performing work. That proportion of energy available for work is referred to as exergy.

For reversible processes, the sum of the entropy changes is equal to zero.

The greatest efficiency in the conversion of heat to mechanical work is achieved in a reversible process. The following then applies for thermal efficiency:

$\eta_{th} = (Q_1 - Q_2)/Q_1 = (T_1 - T_2)/T_1$
(Carnot cycle)

The maximum work to be gained here is:

$W = Q_1 (T_1 - T_2)/T_1$

Changes of state for gases

(general equation of state: $p \cdot v = R_i \cdot T$)

Change of state	Characteristics	Specific heat capacity[1]	Equations (k, K are constants)[1]	Examples
Isobaric	Constant pressure	c_p	$p = k$ $v = K \cdot T$	"Constant pressure" combustion in diesel engines; heating or cooling in once-through boilers.
Isochoric	Constant volume	c_v	$v = k$ $p = K \cdot T$	"Constant volume" combustion in spark-ignition engines; heating or cooling in closed boilers.
Isothermal	Constant temperature	–	$T = k$ $p \cdot v = K$	Slow change of state (heat flows through partitions).
Adiabatic	Heat neither supplied nor dissipated	–	$P \cdot v^{\varkappa} = k$ $T \cdot v^{\varkappa - 1} = k$	Compression or expansion stroke without cooling losses (the ideal condition which is virtually achieved in high-speed machines).
Isentropic	Adiabatic and friction-free (reversible)	–	$T^{\varkappa} \cdot p^{1-\varkappa} = k$	Theoretically optimum attainable comparison processes.
Polytropic	General change of state	$c = \frac{c_v (n - \varkappa)}{n - 1}$	$P \cdot v^n = K$ $T \cdot v^{n-1} = K$ $T^n \cdot p^{1-n} = K$	Compression and power strokes in internal-combustion engines, steam engines (n = 1.2 ... 1.4).

[1] c_p, c_v and $\varkappa = c_p/c_v$ see P. 192, $n = \frac{\lg p_2 - \lg p_1}{\lg v_1 - \lg v_2}$

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Electrical engineering

Quantities and units

Quantity	SI unit
A Area	m^2
a Distance	m
B Magnetic flux density, induction	$T = Wb/m^2 = V \cdot s/m^2$
C Capacitance	$F = C/V$
D Electrical flux density, displacement	C/m^2
E Electric field strength	V/m
F Force	N
f Frequency	Hz
G Conductance	$S = 1/\Omega$
H Magnetic field strength	A/m
I Current	A
J Magnetic polarization	T
k Electrochemical equivalent[1]	kg/C
L Inductance	$H = Wb/A = V \cdot s/A$
l Length	m
M Electric polarization	C/m^2
P Power	$W = V \cdot A$
P_s Apparent power[2]	$V \cdot A$
P_Q Reactive power[3]	var
Q Quantity of electricity, electric charge	$C = A \cdot s$
q Cross-sectional area	m^2
R Electrical resistance	$\Omega = V/A$
t Time	s
r Radius	m
U Voltage	V
V Magnetic potential	A
W Work, energy	$J = W \cdot s$
w Number of turns in winding	–
X Reactance	Ω
Z Impedance	Ω
ε Dielectric constant	$F/m = C/(V \cdot m)$
ε_0 Electric field constant $= 8.854 \cdot 10^{-12}$ F/m	
ε_r Relative permittivity	–
Θ Current linkage	A
μ Permeability	$H/m = V \cdot s/(A \cdot m)$
μ_0 Magnetic field constant $= 1.257 \cdot 10^{-6}$ H/m	
μ_r Relative permeability	–
ϱ Resistivity[4]	$\Omega \cdot m$
σ Specific conductance $(= 1/\varrho)$	$1/(\Omega \cdot m)$
Φ Magnetic flux	$Wb = V \cdot s$
φ Phase displacement angle	° (degrees)
φ (P) Potential at point P	V
ω Angular frequency $(= 2 \cdot \pi \cdot f)$	Hz

Additional symbols and units are given in the text.

Conversion of obsolete units (see P. 17):
– Magnetic field strength H:
1 Oe (oersted) = 79.577 A/m
– Magnetic flux density B:
1 G (gauss) = 10^{-4} T
– Magnetic flux Φ
1 M (maxwell) = 10^{-8} Wb

Electromagnetic fields

Electrical engineering deals with electromagnetic fields and their effects. These fields are produced by electric charges which are integral multiples of the elementary charge. Static charges produce an electric field, whereas moving charges give rise to a magnetic field as well. The relationship between these two fields is described by Maxwell's equations. The presence of these fields is evidenced by the effects of their forces on other electric charges. The force between two point charges Q_1 and Q_2 is defined by Coulomb's Law:

$$F = Q_1 \cdot Q_2/(4\pi \cdot \varepsilon_0 \cdot a^2)$$

The force acting on a moving charge in a magnetic field is expressed by the Lorentz force equation:

$$F = Q \cdot \upsilon \cdot B \cdot \sin\alpha$$

ε_0 = Electric constant, Q_1 and Q_2 = Charges, a = Distance between Q_1 and Q_2, υ = Velocity of charge Q, B = Magnetic induction, α = Angle between direction of motion and magnetic field.

[1]) The unit in common use is g/C.
[2]) Apparent power is usually given in $V \cdot A$ rather than in W.
[3]) Reactive power is usually given in var (volt-ampere reactive) rather than in W.
[4]) The unit in common use is $\Omega mm^2/m$, with the wire cross-section in mm^2 and wire length in m; conversion: $1\ \Omega mm^2/m = 10^{-6}\ \Omega m = 1\ \mu\Omega m$.

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Electric field

An electric field can be defined by the following quantities:

Electric potential φ (P) and voltage U
The electric potential φ (P) at point P is a measure of the work required per charge to move the charge Q from a reference point to point P:

$$\varphi(P) = W(P)/Q$$

The voltage U is the potential difference (using the same reference point) between two points P_1 and P_2:

$$U = \varphi(P_2) - \varphi(P_1)$$

Electric field strength E
The electric field strength at point P depends on the location P and its surrounding charges. It defines the maximum slope of the potential gradient at point P. The following equation applies to the field strength at a distance a from a point charge Q:

$$E = Q/(4\pi \cdot \varepsilon_0 \cdot a^2)$$

The following force acts on a charge Q at point P:

$$F = Q \cdot E$$

Electric field and matter
Electric polarization M and dielectric displacement density D

In a material which can be polarized (dielectric), an electric field generates electric dipoles (positive and negative charges at a distance a; $Q \cdot a$ is called the dipole moment). The dipole moment per unit volume is called the polarization M.

The dielectric displacement density D indicates the density of the electric displacement flux, and is defined as follows:

$$D = \varepsilon \cdot E = \varepsilon_r \cdot \varepsilon_0 \cdot E = \varepsilon_0 \cdot E + M$$

where

ε: Dielectric constant of the material, $\varepsilon = \varepsilon_r \cdot \varepsilon_0$

ε_0: Electric field constant (dielectric constant of vacuum)

ε_r: Relative permittivity (relative dielectric constant) $\varepsilon_r = 1$ for air, see PP. 217, 218 for other materials.

Capacitor
Two electrodes separated by a dielectric form a capacitor. When a voltage is applied to the capacitor, the two electrodes receive equal but opposite charges. The following equation holds for the received charge Q:

$$Q = C \cdot U$$

C is the capacitance of the capacitor. It is dependent on the geometric shape of the electrodes, the distance by which they are separated and the dielectric constant of the dielectric.

Energy content of charged capacitor:

$$W = Q \cdot U/2 = Q^2/(2C) = C \cdot U^2/2$$

The force of attraction between two parallel plates (surface area A) at a distance a is:

$$F = E \cdot D \cdot A/2 = \varepsilon_r \cdot \varepsilon_0 \cdot U^2 \cdot A/(2a^2)$$

Capacitance C of some conductor arrangements in F

Plate capacitor with n parallel plates	$C = (n-1)\frac{\varepsilon_r \cdot \varepsilon_0 \cdot A}{a}$	ε_r, ε_0 n A a	See above Number of plates Surface area of one plate in m² Distance between plates in m
Parallel conductors (twin conductors)	$C = \frac{\pi \cdot \varepsilon_r \cdot \varepsilon_0 \cdot l}{\ln\left(\frac{a-r}{r}\right)}$	l a r	Length of twin conductors in m Distance between conductors in m Conductor radius in m
Concentric conductor (cylindrical capacitor)	$C = \frac{2\pi \cdot \varepsilon_r \cdot \varepsilon_0 \cdot l}{\ln(r_2/r_1)}$	l r_2, r_1	Length of conductor in m Conductor radius in m where $r_2 > r_1$
Conductor to ground	$C = \frac{2\pi \cdot \varepsilon_r \cdot \varepsilon_0 \cdot l}{\ln(2a/r)}$	l a r	Length of conductor in m Distance from conductor to ground in m Conductor radius in m
Sphere with respect to distant surface	$C = 4\pi \cdot \varepsilon_r \cdot \varepsilon_0 \cdot r$	r	Sphere radius in m

Direct current (DC)

Moving charges give rise to a current I, which is characterized by its intensity and measured in amperes. The direction of flow and magnitude of direct current are independent of time.

Direction of current flow and measurement

Current flowing from positive pole to negative pole outside the current source is designated as positive (in reality, the electrons travel from the negative to the positive pole).

An ammeter (A) in the current path measures current flow; voltage is measured by a voltmeter (V) connected in shunt.

Ohm's Law

Ohm's law defines the relationship between voltage and current in solid and liquid conductors.

$$U = R \cdot I$$

The constant of proportionality R is called ohmic resistance and is measured in ohms (Ω). The reciprocal of resistance is called conductance G

$$G = 1/R$$

Ohmic resistance[1])

Ohmic resistance depends upon the material and its dimensions.

Round wire $R = \varrho \cdot l/q = l/(q \cdot \sigma)$

Hollow conductor $R = \ln (r_2/r_1)/(2\pi \cdot l \cdot \sigma)$

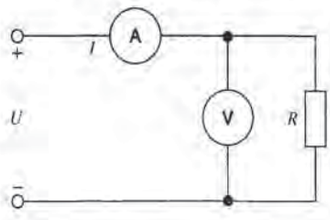
ϱ Resistivity in $\Omega mm^2/m$

$\sigma = 1/\varrho$ Conductivity

l Wire length in m

q Wire cross section in mm^2

Current and voltage measurement
R Load, A Ammeter in circuit, V Shunt-connected voltmeter.



r_2 and r_1 Wire radii where $r_2 > r_1$

In the case of metals, resistance increases with temperature:

$$R_\vartheta = R_{20} [1 + \alpha (\vartheta - 20\,°C)]$$

R_ϑ Resistance at ϑ °C

R_{20} Resistance at 20 °C

α Temperature coefficient[2]) in 1/K (= 1/°C)

ϑ Temperature in °C

Near absolute zero (–273 °C) the resistance of many metals approaches zero (superconductivity).

Work and power

In a resistor through which current passes, the following holds for the work produced or for the quantity of heat developed:

$$W = U \cdot I \cdot t = R \cdot I^2 \cdot t$$

and thus for the power:

$$P = U \cdot I = R \cdot I^2$$

Kirchhoff's Laws

First Law

The current flowing to each junction in a circuit is equal to the current flowing away from that point.

Second Law

The algebraic sum of the voltage drops in any closed path in a circuit is equal to the algebraic sum of the electromotive forces in that path.

[1]) See P. 215 for table of ϱ values.
[2]) See P. 215 for table of α values.

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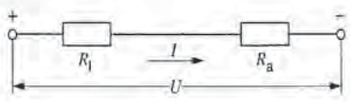
Direct-current circuits

Circuit with load

$U = (R_a + R_i) \cdot I$

R_a = Load

R_i = Line resistance

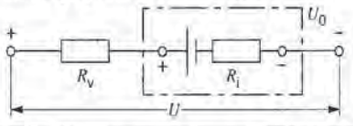


Battery-charging circuit

$U - U_0 = (R_v + R_i) \cdot I$

U Line voltage, U_0 Open-circuit voltage[1]) of battery, R_v Series resistance, R_i Internal resistance of battery.

Condition for charging: charging voltage > battery open-circuit voltage.



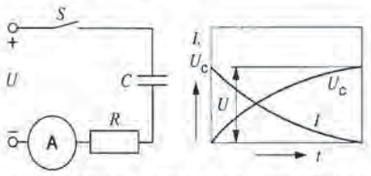
Charging and discharging a capacitor

The time constant $\tau = R \cdot C$ is the decisive factor in the charging and discharging of a capacitor.

Charging

$I = U/R \cdot \exp(-t/\tau)$

$U_C = U\,[1 - \exp(-t/\tau)]$



Circuit diagram, voltage and current curves

Discharging

$I = I_0 \cdot \exp(-t/\tau)$

$U_C = U_0 \cdot \exp(-t/\tau)$

U Charging voltage, I Charging current, U_C Capacitor voltage, I_0 Initial current, U_0 Voltage at start of discharge.

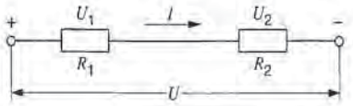
[1]) Formerly called emf (electromotive force).

Series connection of resistors

$R_{total} = R_1 + R_2 + \ldots$

$U = U_1 + U_2 + \ldots$

The current is the same in all resistors.



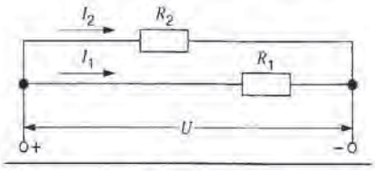
Parallel connection of resistors

$1/R_{total} = 1/R_1 + 1/R_2$ or

$G = G_1 + G_2$

$I = I_1 + I_2$; $I_1/I_2 = R_2/R_1$

The voltage is the same across all resistors (Kirchhoff's second law).



Measurement of a resistance

A resistance can be measured by measuring current and voltage, by using a direct-reading ohmmeter or a bridge circuit, e.g., Wheatstone bridge. If sliding contact D is set so that Wheatstone bridge galvanometer A reads zero, the following equations apply:

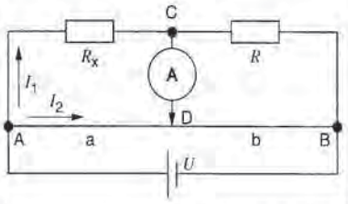
$I_1 \cdot R_x = I_2 \cdot \varrho \cdot a/q$

$I_1 \cdot R = I_2 \cdot \varrho \cdot b/q$

thus: $R_x = R \cdot a/b$

Wheatstone bridge circuit

R_x Unknown resistance, R Known resistance, AB Homogeneous measuring wire (resistivity ϱ) with same cross-section q at every point, A Galvanometer, D Sliding contact.



Electrolytic conduction

Substances whose solutions or melts (salts, acids, bases) conduct current are called electrolytes. In contrast to conduction in metals, electrolytic conduction involves chemical decomposition at the electrodes. This decomposition is called electrolysis and the electrodes are termed anode (positive pole) and cathode (negative pole).

When dissolved, the electrolyte dissociates into various ions which move freely. When voltage is applied, the positive ions (cations) migrate toward the cathode and the negative ions (anions) migrate toward the anode. Cations are e.g. all metal ions but also include ammonia ions (NH_4^+) and hydrogen ions (H^+). Anions comprise the ions of the non-metals, oxygen, halogens, acid radical ions and OH ions (see P. 869 for use in batteries).

The ions are neutralized at the electrodes and precipitate out of solution. Faraday's laws describe the relationship between the amount of precipitated material and the transported charge:

1. The amount of precipitate is proportional to the current and time

$$m = k \cdot I \cdot t$$

m Mass in g, I Current in A, t Time in s, k Electrochemical equivalent in g/C. The electrochemical equivalent k indicates how many g of ions are precipitated by 1 coulomb:

$$k = A/(F \cdot w) = 1.036 \cdot 10^{-5}\, A/w$$

A Atomic weight, see P. 176, w Valence (see table), F Faraday constant with the value F = 96485 C/g equivalent. The g equivalent is the mass in g which corresponds to the equivalent weight A/w.

2. When the same quantity of electricity is passed through different electrolytes, the masses of the precipitates are proportional to their equivalent weights.

Electrolytic polarization

Ohm's law is also essentially applicable with electrolysis. In electrolysis, however, the so-called inconstant elements precipitate out at the electrodes and create a voltage U_z which is opposite in polarity to the applied voltage. The following holds for the current in the cell with resistance R:

$$I = (U - U_z)/R$$

Electrochemical equivalent k

Substance	Valence w	Electrochemical equivalent k 10^{-3} g/C
Cations		
Aluminum Al	3	0.0932
Lead Pb	2	1.0735
Chromium Cr	3	0.1796
Cadmium Cd	2	0.5824
Copper Cu	1	0.6588
	2	0.3294
Sodium Na	1	0.2384
Nickel Ni	2	0.3041
	3	0.2027
Silver Ag	1	1.1180
Hydrogen H	1	0.01044
Zinc Zn	2	0.3387
Anions		
Chlorine Cl	1	0.3675
Oxygen O	2	0.0829
Hydroxyl OH	1	0.1763
Chlorate ClO_3	1	0.8649
Chromate CrO_4	2	0.6011
Carbonate CO_3	2	0.3109
Manganate MnO_4	2	0.6163
Permanganate MnO_4	1	1.2325
Nitrate NO_3	1	0.6426
Phosphate PO_4	3	0.3280
Sulfate SO_4	2	0.4978

The change in the electrodes is called galvanic or electrolytic polarization. It can be largely avoided through the use of oxidizing chemicals (called depolarizers), e.g. manganese dioxide to prevent the formation of H_2.

Galvanic cells

Galvanic cells convert chemical energy to electrical energy. They consist of two different metals in one or two electrolytic solutions. The open-circuit voltage of the cell depends upon the electrode materials and the substance used as the electrolyte.

Examples:

Weston normal cell
Electrodes: Cd + Hg(−) and
Hg_2SO_4 + Hg(+)
Electrolyte: $CdSO_4$
Voltage: 1.0187 V at 20 °C

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Leclanché cell (dry cells)
Electrodes: Zn(−) and C(+)
Depolarizer: MnO_2
Electrolyte: NH_4Cl
Voltage: 1.5 V

Storage battery or battery (see P. 869).

Alternating current (AC)

Alternating current is a current whose magnitude and direction vary periodically (often sinusoidally). Its value lies in the fact that it is well suited to remote energy transmission because it can be stepped up to high voltages by means of transformers.
Standard frequencies for alternating-current power lines:
Africa: 50 Hz; most of Asia: 50 Hz; Australia: 50 Hz; Europe: 50 Hz; North America: 60 Hz; South America: 50/60 Hz.
Railroad power lines: Austria, Germany, Norway, Sweden, Switzerland: $16^2/_3$ Hz; USA: 20 Hz.

Electrolytic (galvanic) mean of sinusoidal alternating current.
This value is the arithmetic mean, i.e.

$I_{galv} = 2\,\hat{i}/\pi = 0.64\,\hat{i}$
$U_{galv} = 2\,\hat{u}/\pi = 0.64\,\hat{u}$

and has the same electrolytic effect as a direct current of this magnitude.

Root-mean-square values of sinusoidal alternating current:

$I\,(= I_{rms}) = \hat{i}/\sqrt{2} = 0.71\,\hat{i}$
$U\,(= U_{rms}) = \hat{u}/\sqrt{2} = 0.71\,\hat{u}$

These equations indicate the magnitude of direct current which will generate the same amount of heat.

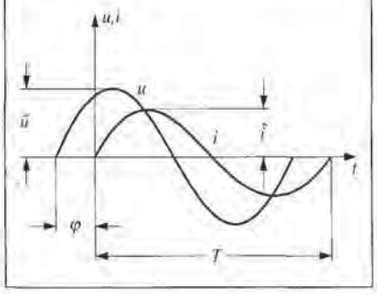
There are three kinds of power specified in an alternating-current circuit:

Active power $P = U \cdot I \cdot \cos\varphi$
Reactive power $P_q = U \cdot I \cdot \sin\varphi$
Apparent power $P_s = U \cdot I$

The power factor $\cos\varphi$ indicates what percentage of the apparent power is useful as actual power. The remainder, called reactive power, is useless, and oscillates between the source and the load, and loads the lines.

In order to reduce the necessary size of the lines, the phase displacement angle φ is kept as small as possible, usually by using phase shifters (e.g. capacitors).

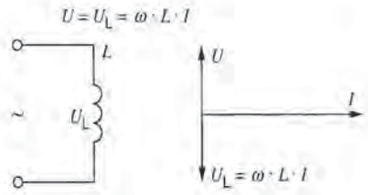
Alternating-current diagram
T Duration of one complete oscillation (period) in s, f Frequency in Hz (f = 1/T), $\hat{i}$ Peak value (amplitude) of current, $\hat{u}$ Peak value (amplitude) of voltage, ω Angular frequency in 1/s (ω = 2π · f), φ Phase displacement angle between current and voltage (phase-displaced means: current and voltage reach their peak values or cross the zero axis at different times).



Alternating-current circuits

Alternating-current circuit with coils

A coil of inductance L (see P. 73) acts as a resistance of magnitude $R_L = \omega \cdot L$ (inductive resistance). Because it consumes no energy, it is also called reactance. The induced countervoltage U_L (see P. 72 for law of induction) lags the current by 90°, which in turn lags the applied voltage by 90°.

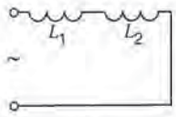


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Inductance of coils connected in series and parallel:

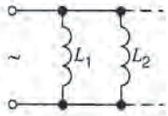
Coils connected in series

$L_{total} = L_1 + L_2$



Coils connected in parallel

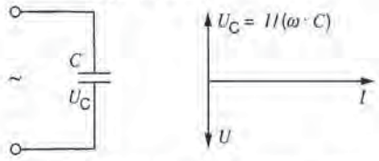
$$\frac{1}{L_{total}} = \frac{1}{L_1} + \frac{1}{L_2} + \ldots$$



Alternating-current circuit with capacitor

A capacitor of capacitance C acts as a resistance of magnitude $R_C = 1/(\omega \cdot C)$ (capacitive reactance); it also consumes no power (reactance). The countervoltage U_C across the capacitor leads the current by 90°, which in turn leads the applied voltage U by 90°.

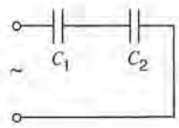
$U = U_C = I/(\omega \cdot C)$



Capacitance of capacitors connected in series and parallel:

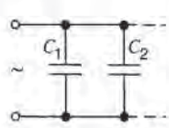
Capacitor connected in series

$1/C_{total} = 1/C_1 + 1/C_2$



Capacitor connected in parallel

$C_{total} = C_1 + C_2 + \ldots$

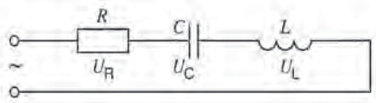


Ohm's Law for alternating current (AC)

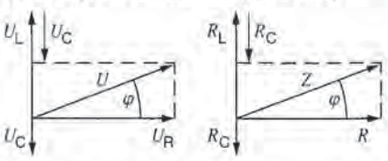
In an alternating-current circuit with ohmic resistance (R), coil (inductance L) and capacitor (capacitance C), the same laws apply to the electrical parameters of resistance, voltage and current as in a direct-current circuit.

In calculating the total resistance, the voltage and the current in the circuit, however, phase angle must also be considered, i.e. the vectors of the values must be added together. Vector diagrams are often used for this purpose.

Series connection



Vector diagrams for determining U, Z and φ



Ohm's law states that $U = Z \cdot I$

Z is termed impedance and is the vector sum of the individual resistances.

$$Z = \sqrt{R^2 + X^2}$$

R Ohmic resistance, X Reactance

$X = \omega \cdot L - 1/(\omega \cdot C)$

$\omega \cdot L$ is the inductive and $1/(\omega \cdot C)$ the capacitive component of reactance.

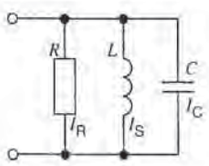
The following equation defines the phase displacement φ between current and voltage:

$\tan\varphi = [\omega \cdot L - 1/(\omega \cdot C)]/R$

The maximum possible current ($I = U/R$) flows when the circuit resonates; the circuit will resonate if:

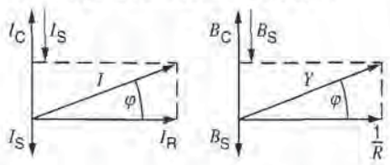
$\omega^2 \cdot L \cdot C = 1$ (i.e. $X = 0$)

Parallel connection



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Vector diagrams for determining I, Y and φ



Current is determined by the following equation (Ohm's Law):

$I = U \cdot Y$

Y is the complex admittance,

$Y = \sqrt{G^2 + B^2}$

G (= $1/R$) is the conductance
B [= $\omega \cdot C - 1/(\omega \cdot L)$] is the susceptance

The following equation describes the phase displacement between current and voltage:

$\tan\varphi = R \cdot [\omega \cdot C - 1/(\omega \cdot L)]$

As in the case of series connection, the circuit will resonate (minimum current flows in the main winding) if:

$\omega^2 \cdot L \cdot C = 1$ (i. e. $B = 0$)

Three-phase current

Three-phase alternating current in which the phases differ by 120° is called three-phase current. Three-phase current is generated by three-phase generators which have three mutually independent windings which are displaced relative to one another by two-thirds of a pole pitch (120°).

The number of conductors carrying voltage is reduced from six to either three or four by linking the component voltages; customary conductor configurations are the star (Y) and delta connections.

Star (Y) connection

$I = I_p$
$U = \sqrt{3} \cdot U_p$

Delta connection

$I = \sqrt{3} \cdot I_p$
$U = U_p$

I Line current, I_p Phase current, U Line voltage, U_p Phase voltage.

The transmitted power is independent of the type of connection, and is determined by the following equations:

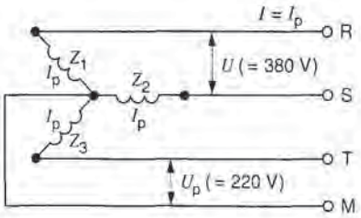
Apparent power:

$P_s = \sqrt{3} \cdot U \cdot I = 3\, U_p \cdot I_p$

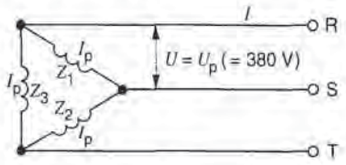
True power:

$P = P_s \cdot \cos\varphi = \sqrt{3} \cdot U \cdot I \cdot \cos\varphi$

Star (Y) connection



Delta connection



Magnetic field

Magnetic fields are produced by moving electric charges, current-carrying conductors, magnetized bodies or by an alternating electric field.

They can be detected by their effect on moving electric charges (Lorentz force) or magnetic dipoles (like poles repel, and unlike poles attract).

Magnetic fields are characterized by the vector of the magnetic flux density B (induction). This vector can be determined by measuring either force or voltage, because a voltage is induced in a loop of wire by a changing magnetic field (see P. 72 for law of induction):

$U = \Delta\,(B \cdot q)/t$

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Δ ($B \cdot q$) Change in the product of magnetic induction (in T) and area of the conductor loop (in m²), t Time (in s). The following equations show the relationships between induction B and the other field parameters:

Magnetic flux Φ

$\Phi = B \cdot q$

q = Cross-sectional area in m²

Magnetic field strength H

In a vacuum:

$B = \mu_0 \cdot H$

$\mu_0 = 1.257 \cdot 10^{-6}$ H/m, magnetic field constant.

Magnetic field and matter

In matter, induction B theoretically consists of two components. One component comes from the applied field ($\mu_0 \cdot H$), and the other from the material (J) (see also the relationship between electric displacement density and electric field strength).

$B = \mu_0 \cdot H + J$

J is the magnetic polarization and describes that component of flux density contributed by the material. In physical terms, J is the magnetic dipole moment per unit volume, and is generally a function of field strength H. $J \ll \mu_0 \cdot H$ for many materials, and is proportional to H, so that:

$B = \mu_r \cdot \mu_0 \cdot H$

μ_r Relative permeability. In a vacuum, $\mu_r = 1$.

Materials are divided into 3 groups according to their relative permeability values:

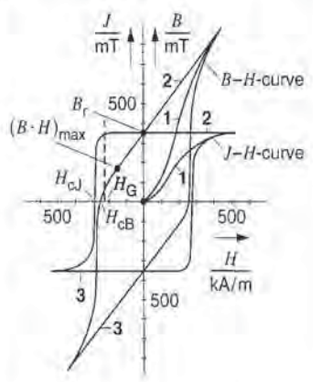
Diamagnetic materials ($\mu_r < 1$)
(e.g. Ag, Au, Cd, Cu, Hg, Pb, Zn, water, organic materials, gases)
μ_r is independent of magnetic field strength and smaller than 1; the values are in the range

$(1 - 10^{-11}) > \mu_r > (1 - 10^{-5})$

Paramagnetic materials ($\mu_r > 1$)
(e.g. O_2, Al, Pt, Ti)
μ_r is independent of magnetic field strength and greater than 1; the values are in the range

$(1 + 4 \cdot 10^{-4}) > \mu_r > (1 + 10^{-8})$

Hysteresis loop *(e.g. hard ferrite)*



The most important parameters of the hysteresis loop are:

- Saturation polarization J_s,
- Remanence B_r (residual induction for $H = 0$),
- Coercive field strength H_{cB} (demagnetizing field strength where B becomes equal to 0) or
- Coercive field strength H_{cJ} (demagnetizing field strength where J becomes equal to 0; of significance only for permanent magnets),
- Limiting field strength H_G (a permanent magnet remains stable up to this field strength),
- μ_{max} (maximum slope of the rise path; significant only for soft magnetic materials),
- Hysteresis loss (energy loss in the material during one remagnetizing cycle, corresponds to the area of the B–H hysteresis loop; significant only for soft magnetic materials).

Ferromagnetic materials ($\mu_r \gg 1$)
(e.g. Fe, Co, Ni, ferrites)
The magnetic polarization in these materials is very high, and its change as a function of the field strength H is non-linear; it is also dependent upon hysteresis. Nevertheless, if, as is usual in electrical engineering, the relationship $B = \mu_r \cdot \mu_0 \cdot H$ is chosen, then μ_r is a function of H and exhibits hysteresis; the values for μ_r are in the range $5 \cdot 10^5 > \mu_r > 10^2$

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The hysteresis loop, which illustrates the relationship between B and H as well as J and H, is explained as follows:

If the material is in the unmagnetized state ($B = J = H = 0$) when a magnetic field H is applied, the magnetization of the material follows the rise path (1). From a specific, material-dependent field strength, all magnetic dipoles are aligned and J reaches the value of saturation polarization (material-dependent) which can no longer be increased. If H is now reduced, J decreases along section (2) of the curve and at $H = 0$ intersects the B or J axis at the remanence point B_r or J_r (in which case $B_r = J_r$). The flux density and polarization drop to zero only upon application of an opposing field whose field strength is H_{cB} or H_{cJ}; this field strength is called the coercive field strength. As the field strength is further increased, saturation polarization in the opposite direction is reached. If the field strength is again reduced and the field reversed, curve (3), which is symmetrical to curve section 2, is traversed.

Ferromagnetic materials

Ferromagnetic materials are divided into soft and permanent magnetic materials. The chart on P. 211 shows a comparison of the range of magnetic characteristic values covered by the technically conventional, crystalline materials and the direction in which the materials are developed. What must be emphasized is the immense range of 8 powers of ten covered by the coercive field strength.

Permanent-magnet materials

Permanent-magnet materials have high coercive field strengths; the values lie in the range

$$H_{cJ} > 1 \frac{kA}{m}$$

Thus high demagnetizing fields H can occur without the material losing its magnetic polarization. The magnetic state and operating range of a permanent magnet lie in the 2nd quadrant of the hysteresis loop, on the so-called demagnetization curve. In practice, the operating point of a permanent magnet never coincides with the remanence point because a demagnetizing field is always present due to the intrinsic self-demagnetization of the magnet which shifts the operating point to the left.

The point on the demagnetization curve at which the product $B \cdot H$ reaches its maximum value, $(B \cdot H)_{max}$, is a measure for the maximum attainable air-gap energy. In addition to remanence and coercive field strength, this value is important for characterizing permanent magnets.

AlNiCo, ferrite, FeNdB (REFe), and SeCo magnets are currently the most important types of permanent magnets in terms of technical applications; their demagnetization curves exhibit characteristics typical of the individual magnet types (see P. 209 for characteristics of permanent-magnet materials).

Soft magnetic materials

Soft magnetic materials have a low coercive field strength ($H_C < 1000$ A/m), i.e. a narrow hysteresis loop. The flux density assumes high values (large μ_r values) already for low field strengths such that in customary applications $J \gg \mu_0 \cdot H$, i.e. in practice, no distinction need be made between $B(H)$ and $J(H)$ curves (see P. 203 for characteristics).

Due to their high induction at low field strengths, soft magnetic materials are used as conductors of magnetic flux. Because they exhibit minimal magnetic loss (hysteresis), materials with low coercive field strengths are particularly well-suited for application in alternating magnetic fields.

The characteristics of soft magnetic materials depend essentially upon their pretreatment. Machining increases the coercive field strength, i.e. the hysteresis loop becomes broader. The coercive field strength can be subsequently reduced to its initial value through material-specific annealing at high temperatures (magnetic final annealing). The magnetization curves, i.e. the B–H relationships, are set out below for several important soft magnetic materials.

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Remagnetization losses

In the table below, P1 and P1.5 represent the remagnetization losses for inductions of 1 and 1.5 tesla respectively, in a 50 Hz field at 20 °C. These losses are composed of hysteresis losses and eddy-current losses. The eddy-current losses are caused by voltages which are induced (law of induction) in the magnetically soft circuit components as a result of changes in flux during alternating-field magnetization. Eddy-current losses can be kept low by applying the following measures to reduce electric conductivity:

- lamination of the core,
- use of alloyed materials (e.g. silicon iron),
- use of insulated powder particles (powdered cores) in the higher frequency range,
- use of ceramic materials (ferrites).

The magnetic circuit

In addition to material equations, the following equations also determine the design of magnetic circuits:

1. Ampère's law (equation of magnetic voltage).

The following equation holds true for a closed magnetic circuit:

$$\sum_i H_i \cdot l_i = V_1 + V_2 + \ldots + V_i = I \cdot w \text{ or } 0,$$

depending upon whether or not the circuit includes a power source.

$I \cdot w = \Theta$ ampere-turns,

$H_i \cdot l_i = V_i$ magnetic voltage

($H_i \cdot l_i$ is to be calculated for circuit components in which H_i is constant).

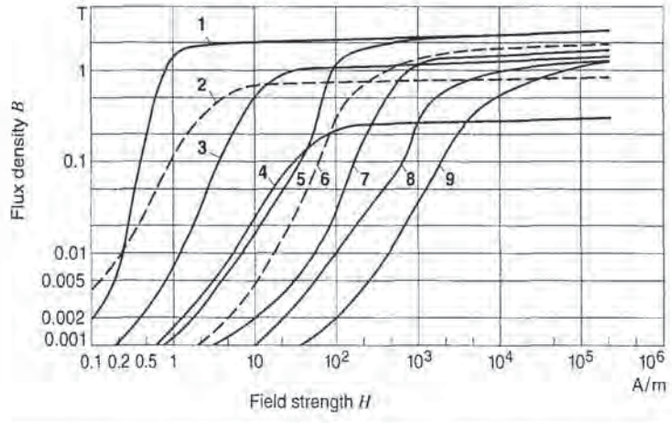
2. Law of continuity (equation of magnetic flux).

The same magnetic flux flows in the indi-

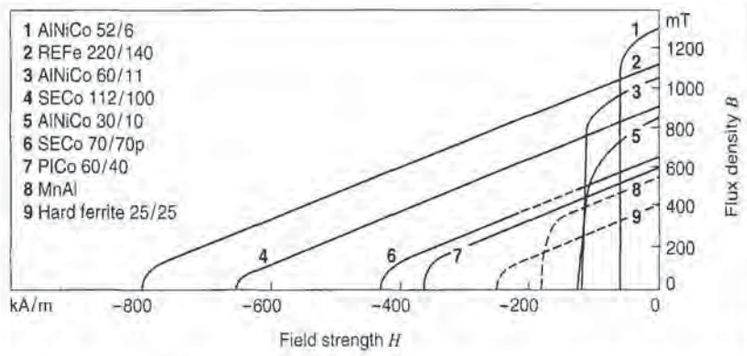
Type of steel sheet	Nominal thickness mm	Specific total loss W/kg P1	P1.5	B (for H = 10 kA/m) T
M 270 – 35 A	0.35	1.1	2.7	1.70
M 330 – 35 A	0.35	1.3	3.3	1.70
M 400 – 50 A	0.5	1.7	4.0	1.71
M 530 – 50 A	0.5	2.3	5.3	1.74
M 800 – 50 A	0.5	3.6	8.1	1.77

Magnetization curves for soft magnetic materials

1 Pure iron
2 78 NiFe (Permalloy)
3 36 NiFe
4 Ni-Zn ferrite
5 50 CoFe
6 V360-50A (magnetic sheet steel)
7 Structural steel
8 Cast iron
9 Powder Fe core



Demagnetization curves for various permanent-magnet materials



vidual components of the circuit

Φ (= $B \cdot A$):

Φ = const or $\Phi_1 = \Phi_2 = ... = \Phi_i$

The quality of a circuit is determined by the amount of flux available in the air gap. This flux is called useful flux; the ratio of useful flux to total flux (flux of the permanent magnet or electromagnet) is called the leakage coefficient σ (practical values for σ are between 0.2 and 0.9). The leakage flux – the difference between the total flux and the useful flux – does not pass through the air gap and does not add to the power of the magnetic circuit.

Magnetic field and electric current

Moving charges generate a magnetic field, i.e. conductors through which current flows are surrounded by a magnetic field. The direction in which the current flows (⊗ current flow into the page, ⊙ current flow out of the page) and the direction of the magnetic field strength form a right-handed screw. See the table on Page 73 for the magnetic field H of various conductor configurations.

Two parallel conductors through which current flows in the same direction attract each other; if the current flows in opposite directions, they repel each other. The force acting between two conductors of length l separated by distance a and carrying currents I_1 and I_2 is governed by the equation:

$$F = \frac{\mu_0 \cdot \mu_r \cdot I_1 \cdot I_2 \cdot l}{2\pi \cdot a}$$ [1])

In air, the approximate force is given by the equation:

$$F = 0.2 \cdot 10^{-6} \cdot I_1 \cdot I_2 \cdot l/a$$ [1])

In a magnetic field B, a force is exerted on a current-carrying conductor (current I) of length l; if the conductor and the magnetic field form an angle of α, the following applies:

$$F = B \cdot I \cdot l \cdot \sin\alpha$$ [1])

The direction of this force can be determined using the right-hand rule (when the thumb is pointed in the direction of current flow, and the index finger in the direction of the magnetic field, the middle finger indicates the direction of force).

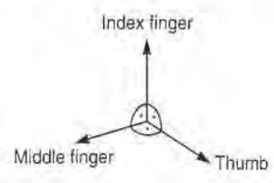
[1]) F Force in N; I_1, I_2 and I Current in A; l and a Length in m; B Inductance in T.

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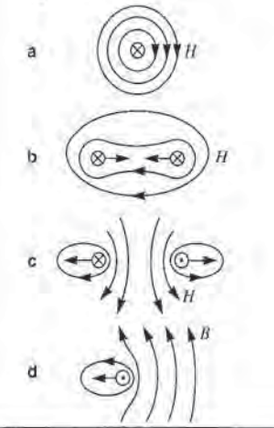
Law of induction

Any change in the magnetic flux Φ around which there is a conducting loop, caused for example by movement of the loop or changes in field strength, induces a voltage U_i in the loop.

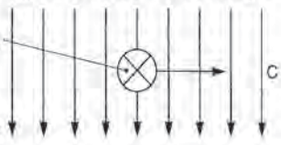
Three-finger rule



Current-carrying conductors and associated lines of force *(H)*
a) A single current-carrying conductor with magnetic field. b) Parallel conductors attract each other if current flows in the same direction. c) Parallel conductors repel each other if current flows in opposite directions. d) A magnetic field (B) exerts a force on a current-carrying conductor. The direction in which force is exerted is determined using the three-finger rule.



Induction. *B Magnetic field, C Direction of moving conductor, U_i Induced voltage.*



A voltage U_i going into the page is induced in a conductor moving in direction C through a magnetic field:

$$U_i = B \cdot l \cdot v$$

U_i in V, B in T, l Conductor length in m, v Velocity in m/s.

In a direct-current machine

$$U_i = p \cdot n \cdot z \cdot \Phi/(60a)$$

U_i in V, Φ Magnetic flux generated by the excitation (field) winding in Wb, p Number of pole pairs, n Rotational speed in min^{-1}, z Number of wires on armature surface, a Half the number of parallel armature-winding paths.

In an alternating-current machine

$$U_i = 2.22 f \cdot z \cdot \Phi$$

U_i in V, Φ Magnetic flux generated by the excitation winding in Wb, f Frequency of alternating current in Hz = $p \cdot n/60$, p Number of pole pairs, n Rotational speed in min^{-1}, z Number of wires on armature surface.

In a transformer

$$U_1 = 4.44 f \cdot w \cdot \Phi$$

U_1 in V, Φ Magnetic flux in Wb, f Frequency in Hz, w Number of windings on the coil which surround the flux Φ.

The terminal voltage U is smaller (generator) or larger (motor) than U_i by the ohmic voltage drop in the winding (approx. 5 %). In the case of alternating voltage, U_i is the rms value.

Self-induction

The magnetic field of a current-carrying conductor or a coil changes with the conductor current. A voltage proportional to the change in current is induced in the conductor itself and counteracts the current change producing it:

$$U_s = -L \frac{dI}{dt}$$

The inductance L depends upon the relative permeability μ_r which is constant and practically equal to 1 for most materials with the exception of ferromagnetic materials (see P. 69). In the case of iron-core coils therefore, L is highly dependent upon the operating conditions.

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Field strength H of several conductor configurations

Circular conductor	$H = I/(2\,a)$ at center of circle	H Field strength in A/m I Current in A a Radius of circular conductor in m
Long, straight conductor	$H = I/(2\pi \cdot a)$ outside conductor $H = I \cdot a/(2\pi \cdot r^2)$ inside conductor	a Distance from conductor axis in m r Conductor radius in m
Cylindrical coil (solenoid)	$H = I \cdot w/l$	w Number of turns on coil l Length of coil in m

Inductance L of several conductor configurations

Cylindrical coil	$L = \frac{1.257\,\mu_r}{10^6} \cdot \frac{w^2 \cdot q}{l}$	L Inductance in H μ_r Relative permeability w Number of turns q Coil cross-section in m² l Coil length in m
Twin conductor (in air, $\mu_r = 1$)	$L = \frac{4\,l}{10^7} \cdot \ln(a/r)$	l Length of conductors in m a Distance between conductors in m r Conductor radius in m
Conductor to ground (in air, $\mu_r = 1$)	$L = \frac{2\,l}{10^7} \cdot \ln(2a/r)$	l Length of conductor in m a Distance from conductor to ground in m r Conductor radius in m

Energy of the magnetic field

$$W = L \cdot I^2/2$$

Electric effects in metallic conductors

Contact potential between conductors

Contact potential occurs in conductors, and is analogous to the triboelectricity or contact emf in insulators (e.g. glass, hard rubber). If two dissimilar metals (at the same temperature) are joined to make metal-to-metal contact with one another and are then separated, a contact potential is present between them. This is caused by the different work functions of the two metals. The magnitude of contact potential depends upon the element positions in the electrode-potential series. If more than two conductors are so joined, the resulting contact potential is the sum of the individual contact potential values.

Contact potential values

Material pair	Contact potential
Zn/Pb	0.39 V
Pb/Sn	0.06 V
Sn/Fe	0.30 V
Fe/Cu	0.14 V
Cu/Ag	0.08 V
Ag/Pt	0.12 V
Pt/C	0.13 V
Zn/Pb/Sn/Fe	0.75 V
Zn/Fe	0.75 V
Zn/Pb/Sn/Fe/Cu/Ag	0.97 V
Zn/Ag	0.97 V
Sn/Cu	0.44 V
Fe/Ag	0.30 V
Ag/Au	−0.07 V
Au/Cu	−0.09 V

Thermoelectricity

A potential difference, the galvanic voltage, forms at the junction of two conductors due to their dissimilar work functions. The sum of all galvanic voltages is zero in a closed conductor loop (in which the temperature is the same at all points). Measurement of these potentials is only possible by indirect means as a function of temperature (thermoelectric effect, Seebeck effect). The thermoelectric po-

tential values are highly dependent upon impurities and material pretreatment. The following equation gives an approximate value for thermoelectric potential in the case of small temperature differences:

$U_{th} = \Delta T \cdot a + \Delta T^2 \cdot b/2 + \Delta T^3 \cdot c/3$

where U_{th} Thermoelectric voltage

$\Delta T = T_1 - T_2$ Temperature difference

a, b, c Material constants

The thermoelectric series gives the differential thermoelectromotive forces referred to a reference metal (usually platinum, copper or lead). At the hot junction, current flows from the conductor with the lower differential thermoelectromotive force to that with the higher force. The thermoelectromotive force η of any pair (thermocouple) equals the difference of the differential thermoelectromotive forces.

The reciprocal of the Seebeck effect is the Peltier effect, in which a temperature difference is created by electrical energy (heat pump).

If current flows through an A-B-A sequence of conductors, one thermojunction absorbs heat while the other produces more heat than can be accounted for by the Joule effect. The amount of heat produced is governed by the equation:

$\Delta Q = \pi \cdot I \cdot \Delta t$

π Peltier coefficient,
I Current, Δt Time interval

Thermoelectric series
(referred to platinum)

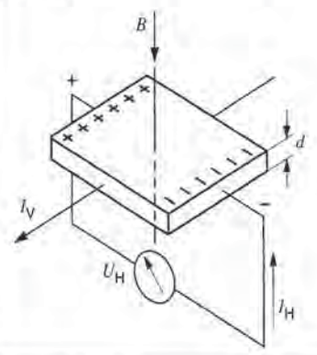
Material	Thermoelectric voltage 10^{-6} V/°C
Selenium	1003
Tellurium	500
Silicon	448
Germanium	303
Antimony	47 ... 48.6
Nickel chromium	22
Iron	18.7 ... 18.9
Molybdenum	11.6 ... 13.1
Cerium	10.3
Cadmium	8.5 ... 9.2
Steel (V2A)	7.7
Copper	7.2 ... 7.7
Silver	6.7 ... 7.9
Tungsten	6.5 ... 9.0
Iridium	6.5 ... 6.8
Rhodium	6.5
Zinc	6.0 ... 7.9
Manganin	5.7 ... 8.2
Gold	5.6 ... 8.0
Tin	4.1 ... 4.6
Lead	4.0 ... 4.4
Magnesium	4.0 ... 4.3
Aluminum	3.7 ... 4.1
Platinum	±0
Mercury	−0.1
Sodium	−2.1
Potassium	−9.4
Nickel	−19.4 ... −12.0
Cobalt	−19.9 ... −15.2
Constantan	−34.7 ... −30.4
Bismuth ⊥ axis	−52
Bismuth ∥ axis	−77

Thermocouples in common use[1])

Material pair	Temperature
Copper/constantan	up to 600 °C
Iron/constantan	up to 900 °C
Nickel-chromium/constantan	up to 900 °C
Nickel-chromium/nickel	up to 1200 °C
Platinum-rhodium/platinum	up to 1600 °C
Platinum-rhodium/platinum-rhodium	up to 1800 °C
Iridium/iridium-rhodium	up to 2300 °C
Tungsten/tungsten-molybdenum[2])	up to 2600 °C
Tungsten/tantalum[2])	up to 3000 °C

[1]) In addition to their use for measuring temperature, thermocouples are used as thermal generators. Efficiencies hitherto achieved: approx. 10 % (application in satellites).
[2]) In reducing atmosphere.

Hall effect
B Magnetic field, I_H Hall current, I_V Supply current, U_H Hall voltage, d Thickness of conductor.



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The relationship between Peltier coefficient and thermoelectromotive force η is as follows:

$$\pi = \eta \cdot T$$

where T is temperature

Current flowing through a homogeneous conductor will also generate heat if a temperature gradient $\Delta T/l$ is maintained in the conductor (Thomson effect). Whereas the power developed by the Joule effect is proportional to I^2, the power developed by the Thomson effect is as follows:

$$P = -\sigma \cdot I \cdot \Delta T$$

σ Thomson coefficient, I Current, ΔT Temperature difference

The reciprocal of the Thomson effect is the Benedicks effect, in which an electric potential is produced as a result of asymmetrical temperature distribution (particularly at points where there is a significant change in cross-sectional area).

Galvanomagnetic and thermomagnetic effects

Such effects are understood to be changes caused by a magnetic field in the flow of electricity or heat within a conductor. There are 12 different recognized effects which fall into this category, the most well-known of which are the Hall, Ettingshausen, Righi-Leduc and Nernst effects.

The Hall effect is of particular significance in technical applications (see P. 99 for a discussion of the Hall-effect sensor). If a voltage is applied to a conductor located in a magnetic field perpendicular to the direction of applied voltage, a voltage is produced which is perpendicular to both the flow of current and the magnetic field. This voltage is called the Hall voltage U_H:

$$U_H = R \cdot I_V \cdot B/d$$

R Hall constant, I_V Supply current, B Magnetic field, d Thickness of conductor

The Hall constant can be used to determine particle density and movement of electrons and holes. In ferromagnetic materials the Hall voltage is a function of magnetization (hysteresis).

Gas and plasma discharge

Gas discharge describes the process that occurs when electric current travels through a space containing a gas or vapor atmosphere.

The free charge carriers present in the gas accelerate within the field between the two charged electrodes, producing charge-carrier cascades due to impact ionization. This, in turn, results in the actual current discharge, which ignites with voltages of up to 100 million volts (atmospheric lightning), depending upon the type of gas, the pressure and the gap between electrodes. Self-discharge occurs when the excitation energy from the discharge frees electrons at the cathodes; the current flow is then maintained at sharply reduced arc voltages. Glow discharge generally takes place at low gas pressures.

The characteristic radiation of light is determined by the transport and reaction zones produced by field forces and ionic diffusion at low current densities. At higher currents, thermal ionization in the plasma concentrates the current flow, i.e. the discharge contracts.

Thermal electron emission from the cathode results in the transition to arc discharge. The current increases (limited by the external circuit). At temperatures of up to 10^4 K, intense light is then emitted around the electrodes and from the bow-shaped (due to convection) plasma column located between them. The arc voltage drops to just a few volts. The discharge is terminated when voltage drops below the characteristic extinction potential for the specific momentary condition.

Technical applications: Spark-discharge gap as switching element, arc welding, spark ignition for combustion of gases, discharge lamps, high-pressure arc lamps.

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Electronics

Fundamentals of semiconductor technology

Electrical conductivity in solid bodies

An individual material's capacity for conducting electricity is determined by the number and mobility of the free charge carriers which it contains. The disparities in the electrical conductivities displayed by various solid bodies at room temperature extend through a range defined by 10 to the 24th power. Accordingly, materials are divided into three electrical classes (examples):

Conductors, metals	Semi-conductors	Non-conductors, insulators
Silver Copper Aluminum	Germanium Silicon Gallium-arsenide	Teflon Quarz glass Aluminum-oxide

Metals, insulators, semiconductors

All solid bodies contain approximately 10^{22} atoms per cm^3; these are held together by electrical forces.

In metals the number of free charge carriers is extremely high (one to two free electrons per atom). The free carriers are characterized by moderate mobility and high conductivity. Conductivity of good conductors: 10^6 siemens/cm.

In insulators the number of free charge carriers is practically nil, resulting in negligible electrical conductivity. Conductivity of good insulators: 10^{-18} siemens/cm.

The electrical conductivity of semiconductors lies between that of metals and insulators. The conductivity response of the semiconductor varies from that of metals and insulators in being extremely sensitive to factors such as variations in pressure (affects the mobility of the charge carriers), temperature fluctuations (number and mobility of the charge carriers), variations in illumination intensity (number of charge carriers), and the presence of additives (number and type of charge carriers).

Because they respond to changes in pressure, temperature and light intensity, semiconductors are suitable for application in sensors.

Doping (controlled addition of electrically active foreign substances to the base material) makes it possible to define and localize the semiconductor's electrical conductivity. This procedure forms the basis of present-day semiconductor components. Doping can be used for technically assured production of silicon-based semiconductors with conducting capacities ranging from 10^4 to 10^{-2} siemens/cm.

Electrical conductivity of semiconductors

The following discussion focuses on the silicon-based semiconductor. In its solid state, silicon assumes the form of a crystal lattice with four equidistant contiguous atoms. Each silicon atom has 4 outer electrons, with two shared electrons forming the bond with the contiguous atoms. In this ideal state silicon has no free charge carriers; thus it is not conductive. The situation changes dramatically with the addition of appropriate additives and the application of energy.

N-doping:
Because only 4 electrons are required for bonding in a silicon lattice, the introduction of foreign atoms with 5 outer electrons (e.g. phosphorus) results in the presence of free electrons. Thus each additional phosphorus atom will provide a free, negatively charged electron. The silicon is transformed into an N conductor: N-type silicon.

P-doping:
The introduction of foreign atoms with 3 outer electrons (e.g. boron) produces electron gaps ("holes") which result from the fact that the boron atom has one electron too few for complete bonding in the silicon lattice. This gap in the bonding pattern is also called a hole.

As the latter designation indicates, these holes remain in motion within the silicon; in an electric field, they migrate in a direction opposite to that of the electrons. The holes exhibit the properties of a free positive charge carrier. Thus every additional boron atom provides a free, positively-charged electron gap (positive

hole). The silicon is transformed into a P conductor: P-type silicon.

Intrinsic conduction
Heat and light also generate free mobile charge carriers in untreated silicon; the resulting electron-hole pairs produce intrinsic conductivity in the semiconductor material. This conductivity is generally modest in comparison with that achieved through doping. Increases in temperature induce an exponential rise in the number of electron-hole pairs, ultimately obviating the electrical differences between the p and n regions produced by the doping procedure. This phenomenon defines the maximum operating temperatures to which semiconductor components may be subjected:

Germanium	90...100 °C
Silicon	150...200 °C
Gallium arsenide	300...350 °C

A small number of opposite-polarity charge carriers is always present in both n-type and p-type semiconductors. These minority carriers exert a considerable influence on the operating characteristics of virtually all semiconductor devices.

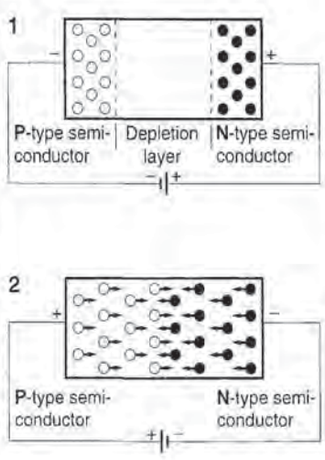
The pn-junction in the semiconductor
The area of transition between a p-type and an n-type zone within the same semiconductor crystal is referred to as the pn-junction. The properties of this area exercise a major influence on the operating properties of most semiconductor components.

pn-junction without external voltage
The p-type zone has numerous holes (○), and the n-type zone has only very few. On the other hand, there are only an extremely limited number of electrons in the p-type zone, while in the n-type zone there are a very large number (●). Each type of mobile charge carrier tends to move across the concentration gradient, diffusing into the opposed zone (diffusion currents).

The loss of holes in the p-type zone results in a negative charge in this area, while electron depletion in the n-type zone produces a positive charge in this region. The result is an electrical potential (diffusion potential) between the p and n-type zones. This potential opposes the respective migration tendencies of the charge carriers, ultimately bringing the exchange of holes and electrons to a halt.

Result: An area deficient in mobile charge carriers is produced at the pn-junction. This area, the space-charge region or depletion layer, is characterized by both severely attenuated electrical conductivity and the presence of a strong electrical field.

The pn-junction with external voltage
1 Reverse-biased, 2 Forward-biased.



pn-junction with external voltage
Reverse state: The negative pole at the p-type zone and the positive pole at the n-type zone extends the space charge region. Consequently, the flow of current is blocked except for a minimal residual current (reverse current) which stems from the minority charge carriers.

Forward state:
With the positive pole at the p-type zone and the negative pole at the n-type zone, the depletion layer is reduced and charge carriers permeate the pn-junction, resulting in a large current flow in the normal direction of conductance.

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Breakdown voltage:
This is the level of reverse-direction voltage beyond which a minimal increase in voltage will suffice to produce a sharp rise in reverse blocking current.

Cause: Separation of bonded electrons from the crystal lattice, either by high field strength (Zener breakdown), or due to accelerated electrons colliding with the bonded electrons and separating them from their valence bonds due to impact. This ultimately produces a dramatic rise in the number of charge carriers (avalanche breakdown).

Discrete semiconductor devices

The properties of the pn-junction and the combination of several pn-junctions in a single semiconductor-crystal wafer (chip) provide the basis for a steadily increasing array of inexpensive, reliable, rugged, compact semiconductor devices.

A single pn-junction forms a diode, two pn-junctions are used for transistors, and three or more pn-junctions make up a thyristor. The planar technique makes it possible to combine numerous operating elements on a single chip to form the extremely important component group known as integrated semiconductor circuits. These combine the device and the circuitry in a single unit.

Semiconductor chips measure no more than several square millimeters and are usually installed in standardized housings (metal, ceramic, plastic).

Diodes

The diode is a semiconductor device incorporating a single pn-junction. An individual diode's specific properties are determined by the distribution pattern of the dopant in the crystal. Diodes which conduct currents in excess of 1 A in the forward direction are referred to as power diodes.

Rectifier diode
The rectifier diode acts as a form of current valve; it is therefore ideally suited for rectifying alternating current. The current in the reverse direction (reverse current) can be approximately 10^7 times lower than the forward current. It rises rapidly in response to increases in temperature.

Rectifiers for high reverse voltages
At least one zone with low conductivity is required for high reverse voltages (high resistance in forward direction results in generation of excessive heat). The insertion of a weakly doped zone (I) between the highly doped p- and n-type zones produces a PIN rectifier. This type of unit is characterized by a combination of high reverse voltage and low forward-flow resistance (conductivity modulation).

Switching diode
These devices are generally employed for rapid switching between high and low impedances. More rapid switching response can be achieved by diffusing gold into the material (promotes the recombination of electrons and holes).

Zener diode
This is a semiconductor diode which, once a specific initial level of reverse voltage is reached, responds to further increases of reverse voltage with a sharp rise in current flow. This phenomenon is a result of a Zener and/or avalanche breakdown. Zener diodes are designed for continuous operation in this breakdown range.

Variable-capacitance diode (varactor)
The space charge region at the pn-junction functions as a capacitor; the dielectric element is represented by the semiconductor material in which no charge carriers are present. Increasing the applied voltage extends the depletion layer and reduces the capacitance, while reducing the voltage increases the capacitance.

Schottky barrier diode (Schottky diode)
A semiconductor diode featuring a metal-to-semiconductor junction. Because the electrons move more freely from the n-type silicon into the metal layer than in the opposite direction, an electron-depleted region is created in the semiconductor material; this is the Schottky barrier layer. Charges are carried exclusively by the electrons, a factor which results in extremely rapid switching, as the minority carriers do not perform any charge storage function.

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Photodiode
This is a semiconductor diode designed to exploit the photovoltaic effect. Reverse voltage is present at the pn-junction. Incident light releases electrons from their lattice bonds to produce additional free electrons and holes. These increase the reverse current (photovoltaic current) in direct proportion to the intensity of the light.

Photovoltaic cell
(See Solar cell)

LED (light-emitting diode)
See "Technical optics", P. 143.

Transistors
Two contiguous pn-junctions produce the transistor effect, a feature employed in the design of components used to amplify electrical signals and to assume switching duties.

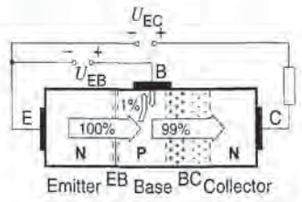
Bipolar transistors
Bipolar transistors consist of three zones of varying conductivity, the configuration being either pnp or npn. The zones (and their terminals) are called: emitter E, base B and collector C.

There are different transistor classifications, depending on the fields of application: small-signal transistors (power dissipation up to 1 watt), power transistors, switching transistors, low-frequency transistors, high-frequency transistors, microwave transistors, phototransistors etc. They are termed bipolar because charge carriers of both polarities (holes and electrons) are active. In the npn transistor, the base current's positive charge carriers (holes) control the flow of 100 times their number in negative charge carriers (electrons) from the emitter to the collector.

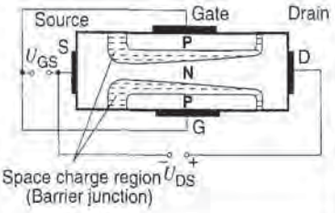
Operation of a bipolar transistor
(explanation based on the npn transistor)
The emitter-base junction (EB) is forward biased. This causes electrons to be injected into the base region.

The base-collector junction (BC) is reverse biased. This induces the formation of a space-charge region with a strong electrical field. Significant coupling (transistor effect) occurs if the two pn-junctions lie in close proximity to each other (in silicon ≈ 10 µm). The electrons injected at the EB then diffuse through the base to the collector. Upon entering the BC's electrical field, they are accelerated into the collector region, whence they continue to flow in the form of collector current. Thus the concentration gradient in the base is retained, and additional electrons continue to migrate from the emitter to the collector. In standard transistors 99 % or more of all the electrons emanating from the emitter reach the space-charge region and become collector current. The few missing electrons are caught in the electron gaps while traversing the p-doped base. Left to their own devices, these electrons would produce a negative charge in the base; almost immediately (50 ns), repulsive forces would bring the flow of additional electrons to a halt. A small base current comprised of positive charge carriers (holes) provides partial or complete compensation for this negative charge in the transistor. Small variations in the base current produce substantial changes in the emitter-collector current. The npn transistor is a bipolar, current-controlled semiconductor amplifier.

***Bipolar npn transistor** (diagram)*



***Junction field-effect transistor** (diagram)*



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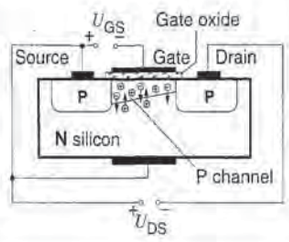
Field-effect transistors (FET)
In these devices, control of the current flow in a conductive path is exercised essentially by an electric field. The field, in turn, is generated with voltage applied at the control electrode, or gate. Field-effect transistors differ from their bipolar counterparts in utilizing only a single type of charge carrier (electrons or holes), giving rise to the alternate designation "unipolar transistor". They are subdivided into the following classifications:
- Junction-gate field-effect transitors (junction FET, JFET).
- Insulated-gate field-effect transistors, particularly MOS field-effect transistors (MOSFET), in short: MOS transistors.

MOS transistors are well suited for application in highly-integrated circuitry. Power FETs represent a genuine alternative to bipolar power transistors in many applications. Terminals:
gate (G), source (S), drain (D).

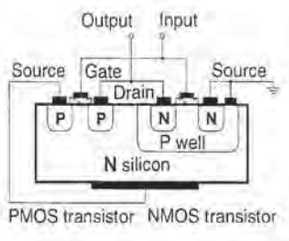
Operation of a junction FET
(applies to the n-channel FET)
DC voltage is present at the ends of an n-type crystal. Electrons flow from the source to the drain. The width of the channel is defined by two laterally diffused p-type zones and by the negative voltage present within them. Raising the negative gate voltage causes the space-charge regions to extend further into the channel, thereby constricting the current path. Thus the current between source S and drain D is governed by the voltage at the control electrode G. Only charge carriers of one polarity are required for FET operation. The power necessary for controlling the current is virtually nil. Thus the junction FET is a unipolar, voltage-controlled component.

Operation of an MOS transistor
(applies to the p-channel enhancement device)
MOS represents the standard layer configuration: Metal Oxide Semiconductor. If no voltage is applied at the gate electrode, then no current will flow between the source and the drain: the pn-junctions remain in the blocking mode. The application of negative voltage at the gate causes

***PMOS transistor** (diagram)*



***CMOS transistor pair** (diagram)*



the electrons in the adjacent n-type region to be displaced toward the interior of the crystal, while holes – which are always present in n-type silicon in the form of minority charge carriers – are pulled to the surface. A narrow p-type layer forms beneath the surface: this is called the P channel. Current can now flow between the two p-type regions (source and drain). This current consists exclusively of holes. Because the gate voltage is exercised through an insulating oxide layer, no current flows in the control circuit: no power is required for the control function. In summary, the MOS transistor is a unipolar, voltage-controlled component.

PMOS, NMOS, CMOS transistors
If a p-channel MOS transistor (PMOS transistor) is doped with a donor impurity rather than an acceptor impurity, it becomes an NMOS transistor. Because the electrons in the NMOS transistor are more mobile, it operates more rapidly than the PMOS device, although the latter was the first to become available due to the fact that it is physically easier to manufacture.

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It is also possible to employ complementary MOS technology to pair PMOS and NMOS transistors in a single silicon chip; the resulting devices are called Complementary MOS, or CMOS transistors. The specific advantages of the CMOS transistor: extremely low power dissipation, a high degree of immunity to interference, relative insensitivity to varying supply voltages, suitability for analog signal processing and highly-integrated applications.

BCD hybrid technology
Integrated power structures are becoming increasingly important. Such structures are realized by combining bipolar and MOS components on a single silicon chip, thereby utilizing the advantages of both technologies. The BCD hybrid process (Bipolar/CMOS/DMOS) is a significant manufacturing process in automotive electronics and also facilitates the manufacture of MOS power components (DMOS).

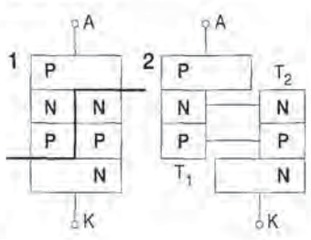
Thyristors
Three consecutive pn-junctions provide the thyristor effect, which is applied for components which act as snap switches when triggered by an electrical signal. The term "thyristor" is the generic designation for all devices which can be switched from the forward (conducting) state to the reverse (blocking) state (or vice versa). Applications in power electronics: Control of frequency and min^{-1}; rectification and frequency conversion; switching. In specialized usage, "thyristor" is understood to mean a reverse-blocking triode thyristor.

Four-layer diode
DIN definition: A reverse-blocking diode thyristor. A semiconductor device with two terminals (anode A, cathode K) and switch characteristics. It has four layers of alternating doping. This device's electrical response is best understood by visualizing the four-layer structure as representing two transistor paths T_1 and T_2. Increasing the current between A and K induces a rise in the reverse currents of both transistors. At a specific voltage value of U_{AK} (switching voltage), the reverse current of the one transistor increases to such a degree that it begins to exert a slight bias effect on the other transistor, resulting in conduction. Meanwhile, the second transistor operates in the same fashion. The mutual bias effect exerted by the two transistor units reaches such an intensity that the four-layer diode begins to act as a conductor: this is the thyristor effect.

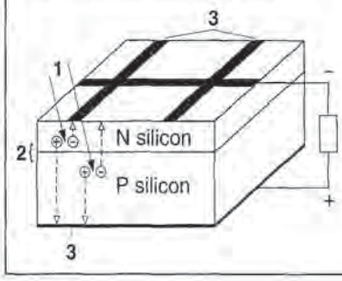
Thyristor with control terminal
DIN definition: Triode thyristor (also SCR, silicon-controlled rectifier), a controllable device with switching characteristics. It consists of four zones of alternating conductivity type. Like the four-layer diode, it has two stable states (high resistance and low resistance). The switching operations between the respective states are governed via the control terminal (gate) G.

GTO thyristor
DIN definition: Gate turn-off (acronym: GTO) switch activated by positive trigger pulse, with deactivation via a negative trigger pulse at the same gate.

Four-layer diode and thyristor effect
1 Four-layer structure, 2 Separated into two transistor paths.



Solar cell
1 Light, 2 Electric field, 3 Metal contact.



Triac
DIN definition: Bidirectional triode thyristor (triac = triode alternating current switch), a controllable thyristor with three terminals. It maintains essentially identical control properties in both of its two switching directions.

Photovoltaic solar cells

The photovoltaic effect is applied to convert light energy directly into electrical energy.

Solar cells, consisting largely of semiconductor materials, are the basic elements of photovoltaic technology. Exposure to light results in the creation of free charge carriers (electron-hole pairs) in the semiconductor material due to the "internal photo-electric effect". If the semiconductor incorporates a pn-junction, then the charge carriers separate in its electric field before proceeding to the metal contacts on the semiconductor's surface. Depending on the semiconductor material being used, a DC voltage (photovoltage) ranging between 0.5 and 1.2 V is created between the contacts. Connection of a load resistor results in a current flow (photocurrent) of e.g. 2.8 A for a 100 cm^2 Si solar cell at 0.58 V.

The efficiency level with which radiated light energy is converted into electrical energy (indicated in percent) depends both upon how well the semiconductor material is suited to the light's spectral distribution, and the efficiency with which the generated free charge carriers can be isolated and conducted to the appropriate surface contacts.

The paths within the semiconductor should be short (thin layers from several µm to 300 µm) to prevent the free charge carriers from recombining. The structure of the crystal lattices in the material must be as perfect as possible, while the material itself must be free of impurities. The manufacturing processes include procedures of the type employed for microelectronics components. Silicon is the most commonly used material for solar cells. It is used in single-crystal, polycrystalline and amorphous modification. Typical efficiency levels achieved under laboratory conditions include:

Silicon	– single crystal	24 %
	– polycrystalline	19 %
	– amorphous	13 %
CdTe		16 %
$CuInSe_2$		18 %
GaAs[1])		28 %
Si/GaAs tandem[1])		37 %.

[1]) Concentrated sunlight.

Average efficiency levels obtained from mass-produced solar cells are approximately one third lower. The "tandem cells" achieve their high efficiency by incorporating two solar cells – made of different materials – in consecutive layers; the unit is thus capable of converting light from various spectral ranges into charge carriers.

The individual solar cells are interconnected within a circuit to form solar modules. The output is always DC voltage; an inverter can be used for the conversion to AC (e.g., for discharge into mains electrical supply). The characteristic data of a module are its output voltage and power output in W_P referred to full solar exposure (≈ 1000 W/m^2).

The ultimate objective is to develop inexpensive processes allowing the manufacture of large-area solar cells. Proven procedures include extracting crystals from molten mass, or cutting cast crystals into individual wafers and blocks. Research is now extending into new areas such as strip pulling, foil casting and separation of thin semiconductor layers. Although the energy generated by photovoltaic processes is still more expensive than that provided by convential power stations, improvements in cell manufacturing techniques, increases in efficiency, and large-scale production will combine to allow further reductions in cost. For applications involving isolated systems (consumers without external electrical connections) and minimal power requirements (watches, pocket calculators), photovoltaics already represents the best solution. With a worldwide installed power output of 1 GW_P, the photovoltaics market is currently growing by 16 % every year.

Monolithic integrated circuits

Monolithic integration

Planar technology is based on the oxidation of silicon wafers being a relatively simple matter, and the speed with which the dopants penetrate into silicon being expo-

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nentially greater than that with which they enter the oxide – doping only occurs at those locations where openings are present in the oxide layer. The specific design requirements of the individual integrated circuit determine the precise geometric configuration, which is applied to the wafer in a photolithographic process. All processing procedures (oxidizing, etching, doping and separation) progress consecutively from the surface plane (planar).

Planar technology makes it possible to manufacture all circuit componentry (resistors, capacitors, diodes, transistors, thyristors) and the associated conductor strips on a single silicon chip in a unified manufacturing process. The semiconductor devices are combined to produce monolithic integrated circuits: IC = Integrated Circuit.

This integration generally comprises a subsystem within the electronic circuit and increasingly comprises the entire system: System on a Chip.

Integration level

Either the number of individual functional elements, the number of transistors, or the number of gates on a single chip. The following classifications relate to the level of integration (and chip surface):

- SSI (Small-Scale Integration). Up to roughly 100 function elements per chip, mean chip surface area 3 mm², but can also be very much larger in circuits with high power outputs (e.g. smart power transistors).
- MSI (Medium-Scale Integration). Roughly 100 to 1000 function elements per chip, mean chip surface area 8 mm².
- LSI (Large-Scale Integration). Up to 100 000 function elements per chip, mean chip surface area 20 mm².
- VLSI (Very-Large-Scale Integration). Up to 1 million function elements per chip, mean chip surface area 30 mm².
- ULSI (Ultra-Large-Scale Integration). Over 1 million function elements per chip, surface area up to 300 mm², smallest structure sizes 0.25 µm.

Computer-aided simulation and design methods (CAE/CAD) are essential elements in the manufacture of integrated circuits. Entire function blocks are used in VLSI and ULSI as otherwise the time expenditure and failure risk would make development impossible.

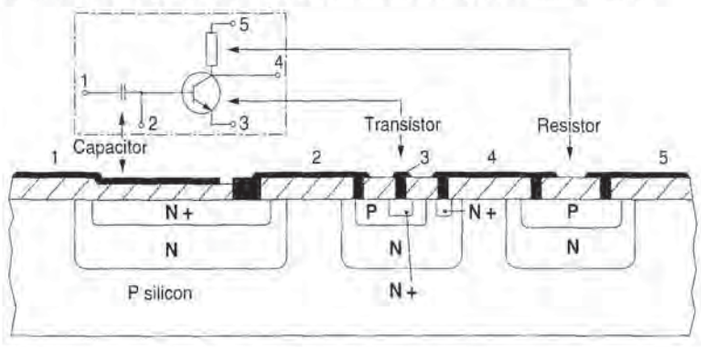
Classifications for integrated circuitry

- According to transistor engineering: Bipolar, MOS, mixed (bipolar/MOS, BiCMOS, BCD).
- According to circuit engineering: Analog, digital, mixed (analog/digital, mixed signal).
- According to component families: Analog, microcomponents, memories, logic circuits.
- According to application: Standard IC, application-specific IC (ASIC)

Integrated analog circuits

- Basic structures: Stabilized-voltage supply, stabilized-current supply, differential amplifier

Basic monolithic integrated circuit (bipolar). *Circuit and configuration. 1...5 terminals.*



components, switching elements, potential shift, output stages.
- Application-oriented classes:
  Operational amplifiers (OP), voltage regulators, comparators, timers, converters, interface circuits.
- Special analog ICs:
  Voltage references, wideband amplifiers, analog multipliers, function generators, phase-lock circuits, analog filters, analog switches.

Integrated digital circuits

The scale ranges from LSI (logic chips) through to ULSI (memories, microcomponents).

Several conditions must be met before logic chips can be combined within a single system: The voltage supply, logic level, the circuit speed and the signal transit time must all be identical. This requirement is met within the respective circuit families. The most important are:
- Various bipolar types: TTL (Transistor-Transistor-Logic), Schottky TTL, Low-Power Schottky TTL, ECL (Emitter-Coupled Logic) and I^2L (Integrated Injection Logic),
- MOS logic, especially CMOS logic.
  MOS and CMOS chips make up 97 % (and the trend is rising) of the production of integrated digital circuits.

Semiconductor memories

Data storage includes the following operations: Recording (writing, entering), storage (data storage in the narrow sense), retrieval and readout. The memory operates by exploiting physical properties that facilitate unambiguous production and recognition of two opposed states (binary information). In semiconductor memories, the states produced are "conductive/non-conductive" or "charged/discharged"; the latter state relies on special properties in the silicon/silicon oxide or silicon nitride/metal junction.

Semiconductor memories are divided into the two main categories of "volatile" and "non-volatile". Virtually all of them are manufactured according to CMOS technology.
- Volatile memories (short-term memories) can be read out and written over an unlimited number of times, and are thus referred to as RAMs (Random Access Memory). The data which they contain is lost as soon as the power supply is switched off.
- Non-volatile memory chips (long-term memories) retain their data even when the power supply is switched off; they are also referred to as ROMs (Read-Only Memory).

The chart shows the relationships and classification of the most common types of memory.

Microprocessors and microcomputers

The microprocessor represents the integration of a computer's central processing unit on a single chip. Microprocessor design seeks to avoid individualization in the face of large-scale integration, and the units can be programmed to meet the varied requirements associated with specific operating conditions. There are two different main groups of processor:
- For use in PCs (personal computers), CISC processors are used (CISC: Complete Instruction Set Computing). These processors are very versatile and user-programmable.
- In WS (work stations), RISC processors are usually used (RISC: Reduced Instruction Set Computing). These processors are very much faster for the specific tasks frequently associated with WS use, but are significantly slower for all other tasks.

A microprocessor cannot operate by itself: it always acts as part of a microcomputer.

The microcomputer consists of:
- Microprocessor serving as CPU (central processing unit). The microprocessor contains the controller, and the arithmetic and logic unit. The arithmetic and logic unit performs the operations indicated by its name, while the controller ensures implementation of the commands stored in the program memory.
- Input and output units (I/O), which control data communication with the peripherals.
- Program memory which provides permanent storage for the operating program (user program), thus ROM, PROM or EPROM.

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Overview of semiconductor memory devices

- Data memory for the data being run at any given time. These data change continually; thus the storage medium for this application is the RAM.
- Clock generator and power-supply system.

The bus system links the individual elements of the microcomputer.

A clock generator ensures that all the operations in the microcomputer take place within a specified timeframe.

Chips for special applications, e.g. for interrupting a program, inserting an intermediate program etc., are called logic circuits.

Input and output devices and external memories are classed as peripherals.

The main components of a microcomputer are normally combined as separate components on printed-circuit boards. For simpler tasks, such as e.g. in wireless communications in the case of Internet access, single-chip computers are increasingly being used which integrate the above-mentioned functions on a single silicon chip (system on a chip). The performance of these highly integrated systems is limited by the relatively small amount of RAM which can be accommodated at viable expense on the chip.

The microcontroller combines the CPU function, read-only memory (as ROM, EPROM or EEPROM), input/output capability (I/O) and read/write memory (RAM) on a single chip. In contrast to the microcomputer, the controller reacts with a prespecified program which provides particular output values depending on the input information. It is used to control self-regulating systems such as e.g. engine management.

The transputer is a special type of microprocessor which is especially useful for building parallel computer networks. In addition to the standard microprocessor components, the chip is also equipped with communications and processing hardware.

It has at least four bidirectional serial transmission channels (links) allowing extremely rapid communication (500 Mbit/s per link) with many other transputers. Because communications are completely asynchronous, distributed networks do not require a common clock circuit. Each link has its own DMA controller; once initialized by the CPU, it can carry out data transmission on its own. Thus processing and communications are essentially parallel operations. Of particular significance are the extremely short process switchover and interrupt response times of $\ll 1$ µs. The transputer does not need a real-time operating system for this; instead it has the necessary processing commands directly in its command set.

The transputer operates as a communications node within the parallel network, meaning that it serves as both computer and communications interface. The transputer can therefore be employed to avoid one of the gravest liabilities of many parallel systems, which is the inherent need to share a common bus. Maximum-performance computers are therefore built using transputers.

Application-specific ICs

Application-specific ICs (ASICs: Application-Specific Integrated Circuits) differ from standard ICs in that they are conceived to fulfill a single purpose. They are the result of fruitful cooperation between users, with their specialized system experience, and manufacturers, who enjoy access to the requisite technology. The essential advantages of ASICs: fewer components, lower system costs, increased reliability, more difficult to copy.

The ASIC family is generally classified according to the development method which has been selected: chip-mounted circuitry, constructed from individual function elements (full-custom IC), provides the best results with regard to operation and packaging density. It is, however, only suited for large-series applications (time and expense).

Standardized basic circuit functions (developed and tested in advance) represent one step towards rationalizing the development process. The circuits are incorporated in elements of varying sizes (ROM, RAM, computer core, or individualized, application-specific circuit groups). Depending upon the number of available user-specific elements, this method can be employed to reduce development times without sacrificing efficient exploita-

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tion of the chip surface.

The next stage is the use of standardized, relatively complex basic functions which are developed in advance in standard cells of the same height and variable width. They are available in the form of cell libraries. These standard cells are automatically placed in series and then automatically connected with polysilicon and aluminum conductors. A dual or triple-layer metallic coating can be applied to achieve even better utilization of the surface area.

Gate arrays are predeveloped as far as the transistor/gate connection, and are manufactured in advance, leaving only the final masking operations for later completion. The connection with the application-specific circuitry is then automatic. Rationalization is achieved by providing standard circuits for frequent basic computer functions (similar to a cell library). Special gate arrays designed for specific applications have particular advantages (e.g. pure computer-oriented digital circuits under the general conditions usual for computers).

Programmable logic devices (PLDs) – completely preassembled transistor arrays – are programmed by the user in the same way as a special-application PROM. PLDs thus provide system developers with the option of producing silicon breadboard circuits within a short period of time. The production of complex systems in silicon is becoming increasingly important, as it allows the production of practical working models in the development phase.

Smart-power ICs

Automotive and industrial systems rely upon electronics to govern numerous final-control elements and other loads. The power switches must be capable of assuming auxiliary functions extending beyond the control of circuit power: driver circuits for activating switching transistors, protective circuits for excess current, voltage and temperature, fault acknowledgments in case of incorrect operation. Such bipolar or MOS-technology power ICs are generically termed smart-power ICs.

Film and hybrid circuits, MCM

Film circuits

The integrated film circuit features passive circuit elements – these include capacitors and inductors, as well as conductor tracks, insulators and resistors. An integrated film circuit is produced by applying the layers which contain these elements to a substrate carrier. The terms "thin-film" and "thick-film" circuit derive from the fact that the film thickness was originally the determining factor for tailoring to specific performance characteristics; present technology employs a variety of manufacturing techniques to achieve the same end.

Thin-film circuits

Integrated film circuits on which the individual layers are applied to glass or ceramic substrata, usually in a vacuum coating process. Advantages: fine structures (to approx. 10 µm) provide high circuit-element density, extremely good HF characteristics and low-noise resistor elements. On the minus side are the relatively high manufacturing costs.

Thick-film circuits

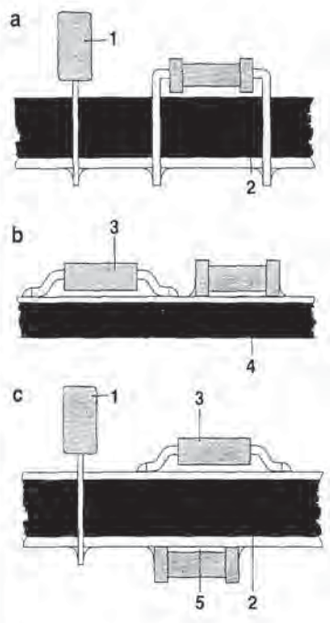
Integrated film circuits in which the layers are usually applied to ceramic carriers in a silk-screening process before being fused on. Advantages: Multi-layer construction provides high circuit-element density and good HF characteristics. A high degree of manufacturing automation is possible for large-scale production.

Multilayer ceramic substrates

The base material for the multilayer ceramic substrate is the unfired ceramic foil to which conductor tracks are applied in a silk-screening process. In the next step, a number of these foils are laminated together to form a multilayer substrate. This device is then sintered at high temperature (850 ... 1600 °C) to form a hard ceramic device featuring integrated conductive paths. A metal paste is applied to the orifices between the individual foils to form the interlayer electrical connections. Special materials are employed to

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Circuit-board technology, design options
a) Insertion mounting (conventional), b) SMD mounting on ceramic substrate (hybrid technology), c) Mixed mounting. 1 Wired components, 2 Circuit board, 3 Chips, 4 Ceramic substrate, 5 Bonding material.



integrate resistors and capacitors in the device. This process provides for substantially higher levels of circuit density than thick-film devices.

Hybrid circuits
Integrated film circuits with additional discrete components such as capacitors and integrated semiconductor circuits (ICs) which are attached by soldering or adhesive bonding. A high component density is achieved by using unpacked semiconductor chips which are contacted by means of "bonding", or SMD components (SMD Surface Mounted Device). A multilayer ceramic substrate can be used to achieve extremely small hybrid control devices (microhybrids). Advantages: The good thermal dissipation allows high installation temperatures, while compact construction provides good vibration resistance along with good HF response characteristics. Hybrid circuits are especially well-suited for automotive applications and for telecommunications.

MCM
MCM (Multi-Chip Module) is used to identify an electronic component consisting of numerous "unpacked" integrated semiconductors (ICs). The basic element is the carrier substrate with its internal circuits. The ICs are unpacked and contacted by means of bonding or TAB or flip-chip soldering. An MCM can also contain resistors and capacitors as required.

Classification is according to the selected substrate material:
- MCM-C multilayer ceramic substrate,
- MCM-D thin-layer design, generally on silicon,
- MCM-L organic multilayer laminate.

The MCM is generally selected to achieve compliance with specific operating requirements. It combines rapid switching response in processor cores with favorable EMC characteristics and extremely compact packages. The MCM is frequently employed to obtain electrical performance characteristics that would be either prohibitively expensive or downright impossible to obtain from current IC technology.

Circuit-board technology, SMT

The circuitry of an electronic system can basically be implemented in accordance with semiconductor, hybrid and circuit-board technologies. Selection is contingent upon such factors as economy (cost, production-run sizes), time (development time, service life) and environmental conditions (electrical, thermal, physical).

Circuit boards represent the classical form for producing an electrical circuit. On the most basic type of circuit board, the electronic components are mounted on a

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Variable	Unit	Silicon	Steel (max.)	Stainless steel
Tensile load	10^5 N/cm^2	7.0	4.2	2.1
Knoop hardness	kg/mm^2	850	1500	660
Elastic modulus	10^7 N/cm^2	1.9	2.1	2.0
Density	g/cm^3	2.3	7.9	7.9
Thermal conductivity	W/cm · K	1.57	0.97	0.33
Thermal expansion	10^{-6}/K	2.3	12.0	17.3

fiberboard or fiberglass-reinforced synthetic-resin carrier. A printing process is employed to apply the conductor tracks (copper foil) to the board (thus: printed circuit). An alternative is to etch the circuit from a copper-plated board. The components' contact pins are inserted through holes in the board and soldered into position.

The increasing IC integration level resulted in a commensurate rapid increase in the number of terminals (pins). This development initiated the transition from conventional insertion-mounting to SMT (Surface Mounting Technology). In the meantime, there is a very wide range of surface-mountable components (SMD Surface Mount Devices) which are soldered flat to the circuit board. These SMD components and their housing configurations (SOT, PQFP, PLCC, Flat Pack etc.) are particularly suitable for processing in automatic insertion machines.

The most important application advantages provided by surface-mounting technology include:

- Efficient production of subassemblies (high insertion capacity and reliability),
- Low space requirements with the same function capacity even in the case of insertion on both sides,
- Use of normal circuit boards (e.g. laminated epoxy-resin plastic FR4),
- Omission or reduction of holes in each circuit board,
- Can be combined with wired components,
- Increased reliability due to reduction of connection points,
- Improved circuit design, coupling and reproducibility,
- Better HF characteristics.

Surface-mounting technology is much more sensitive to the combination of processing techniques than is conventional insertion mounting. The advantages of SMT are directly proportional to the care with which componentry, circuit-board layout, automatic mounting, joining techniques, testing, repair, etc., are mutually adapted for optimal performance.

Micromechanics

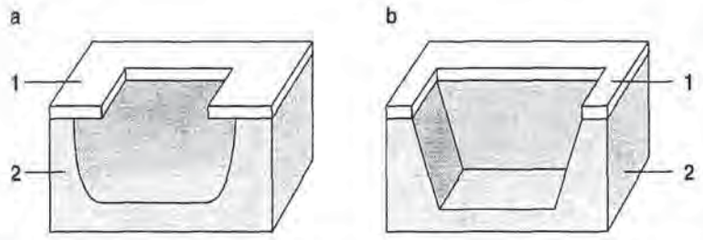
The term "micromechanics" is employed to designate the production of mechanical components using semiconductors (generally silicon) and semiconductor technology. This type of application exploits both the semiconductive and the mechanical properties of silicon. The first micromechanical silicon pressure sensors were installed in motor vehicles at the beginning of the 1980's. Typical mechanical dimensions can extend into the micrometer range.

The mechanical characteristics of silicon (e.g., strength, hardness and Young's modulus, see Table) can be compared to those of steel. However, silicon is lighter and has greater thermal conductivity. Single-crystal Si wafers with almost perfect physical response characteristics are used: Hysteresis and surface diffusion are negligible. Due to the brittleness of the single-crystal material, the stress-strain curve does not display a plastic range; the material ruptures when the elastic range is exceeded.

Two methods of manufacturing micromechanical structures in silicon have established themselves: bulk micromechanics and surface micromechanics.

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Electrochemical etching
a) Isotropic (in acid etching media), b) Anisotropic (in alkaline etching media).
1 Etching mask (e.g. oxide or nitride), 2 (100)-silicon.



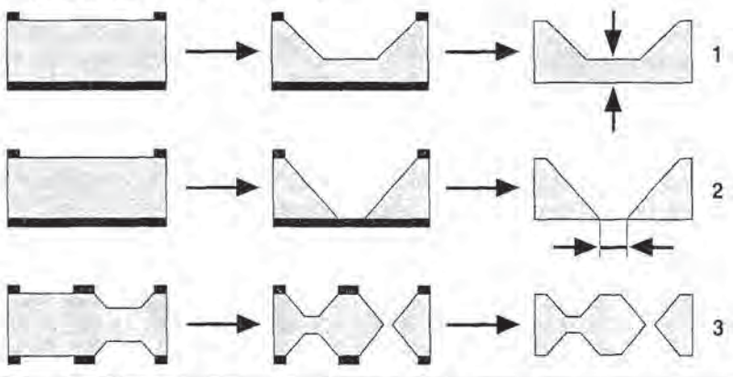
Both methods use the standard procedures of microelectronics (e.g. epitaxial growth, oxidation, diffusion and photolithography) together with some additional special procedures: For the removal of material, bulk micromechanics requires anisotropic etching with or without electrochemical etch stop, while surface micromechanics requires vapor-phase etching and deep trenching. Anodic bonding and seal-glass bonding are used to hermetically join two wafers (capping, inclusion of reference vacuum).

Bulk micromechanics (BMM)

This method involves etching the entire wafer from the reverse side in order to produce the desired structure. The etching process takes place in alkaline media (caustic potash solution), in which the etching behavior of silicon demonstrates pronounced anisotropy, i.e. the etching rate is greatly dependent on the crystal direction. It is thus possible to represent the structure very accurately in terms of depth. When silicon wafers with (100)-orientation are used, the (111)-surfaces for example remain virtually unaffected. In the case of anisotropic etching, (111)-surfaces therefore develop which form with the (100)-surface a characteristic angle of 54.74°.

In the simplest case, the etching process is stopped after a certain period of time while wafer thickness and etching rate are taken into consideration (time etching). However, for the most part, an electrochemical etch stop is engaged whereby the etching comes to a halt at the boundary of a pn-junction. BMM can be used to produce diaphragms with typical thicknesses of between 5 and 50 µm for

Structures produced with bulk micromechanics
1 Diaphragms, 2 Openings, 3 Beams, bridges.



applications such as pressure sensors and air-mass meters.

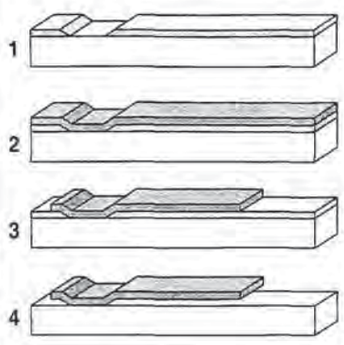
Surface micromechanics (SMM)
In contrast to bulk micromechanics, SMM merely uses the silicon wafer as the base material. Moving structures are formed from polycrystalline silicon layers which, similar to a manufacturing process for integrated circuits, are deposited on the surface of the silicon by epitaxial growth.

When an SMM component is made, a "sacrificial layer" of silica is first applied and structured with standard semiconductor processes. An approx. 10 µm thick polysilicon layer (epipoly layer) is then applied at high temperatures in an epitaxial reactor. The epipoly obtains the desired structure with the aid of a lacquer mask and anisotropic, i.e. vertical etching (deep trenching). The vertical side walls are obtained by an alternation of etching and passivation cycles. After an etching cycle, the etched side-wall section is provided during passivation with a polymer as protection so that it is not attacked during the subsequent etching. Vertical side walls with a high representation accuracy are created in this way. In the last process stage, the sacrificial oxide layer beneath the polysilicon layer is removed with gaseous hydrogen fluoride in order to expose the structures.

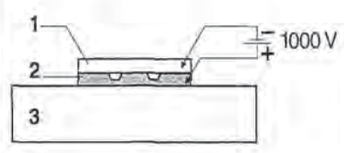
Among other things, SMM is used in the manufacture of capacitive acceleration sensors with movable and fixed electrodes for capacitive evaluation, and rotation-rate sensors with quasirotatory oscillators.

Wafer bonding
In addition to structuring the silicon, joining two wafers represents another essential task for micromechanical production engineering. Joining technology is required in order for example to hermetically seal cavities (e.g. inclusion of reference vacuum in pressure sensors), to protect sensitive structures by applying caps (e.g. for acceleration and rotation-rate sensors), or to join the silicon wafer with intermediate layers which minimize the thermal and mechanical stresses (e.g. glass base on pressure sensors).

Process stages in surface micromechanics
1 Separation and structuring of sacrificial layer, 2 Separation of polysilicon, 3 Structuring of polysilicon, 4 Removal of sacrificial layer and thus creation of freely moving structures on surface.



Anodic wafer bonding
1 Pyrex glass, 2 Silicon, 3 Heating plate (T = 400 °C).



With anodic bonding, a Pyrex-glass wafer is joined to a silicon wafer at a voltage of some 100 V and a temperature of approx. 400 °C. At these temperatures, the alkaline ions in the Pyrex glass move. This creates a depletion layer at the boundary to the silicon, through which the applied voltage drops. A strong electrostatic attraction and an electrochemical reaction (anodic oxidation) result in a permanent hermetic bond between the glass and the silicon.

With seal-glass bonding, two silicon wafers are contacted by way of a glass-solder layer applied in the screen-printing process at approx. 400 °C and under the exertion of pressure. The glass solder melts at this temperature and produces a hermetically sealed bond with the silicon.

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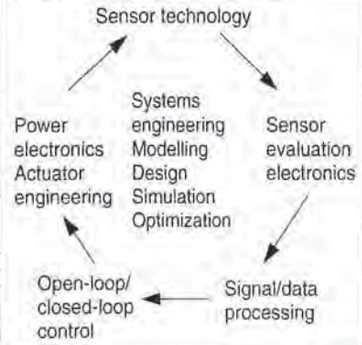
Mechatronics

Mechatronics is a branch of engineering which seeks to enhance the functionality of technical systems by close integration of mechanical, electronic and data-processing components. Mechatronic systems play an important role in the form of complex control structures (especially in automotive and production engineering). Examples are engine-management systems for spark-ignition and diesel engines, ABS, TCS, stability and steering systems, electrical drives, CNC machine tools and handling systems. The mechanical components in these systems are frequently characterized by both non-linear response and extensive operating ranges.

The development of mechatronic systems requires a synergistic, interdisciplinary approach which combines modelling on different abstraction levels and inter-domain, model-supported design procedures and software engineering. Here, the classical analysis and design procedures of control engineering are being supplemented and partially replaced by real-time simulations, identification and parameter optimization with the inclusion of real components (hardware-in-the-loop).

The objective of microsystems technology is to miniaturize mechatronic systems by integrating microelectronics and micromechanics.

Interrelationships in mechatronics



Analog/digital conversion

Analog signals are electrical quantities whose amplitude, frequency and phase convey information on physical variables or technical processes. Data registration is continuous in both time and quantity; within certain limits, analog signals can reflect any number of quantitative variations at any given point in time. Analog technology provides means for processing these signals. Initial processing, consisting of filtering and amplification, can be supplemented by mathematical operations such as addition and multiplication, as well as integration over time, etc. The operational amplifier (OP) is an integrated circuit of extreme importance in analog technology. Under ideal conditions, a relatively simple external circuit is sufficient for determining its operating characteristics (infinite amplification, no input current).

Analog units also have several disadvantages: the characteristic response curves of the various components alter with age, temperature fluctuations influence precision, and the manufacturing process must generally be supplemented by subsequent calibration.

Conversion to digital signals entails a transition to discrete monitoring of both time and intensity, i.e., the analog signal is sampled with specific periodicity (scan spots). The sampled values are assigned a numeric expression in which the number of possible values and thus the resolution are limited (quantification).

Instead of using the decimal system, digital technology uses the binary system which is easier for the computer to handle.

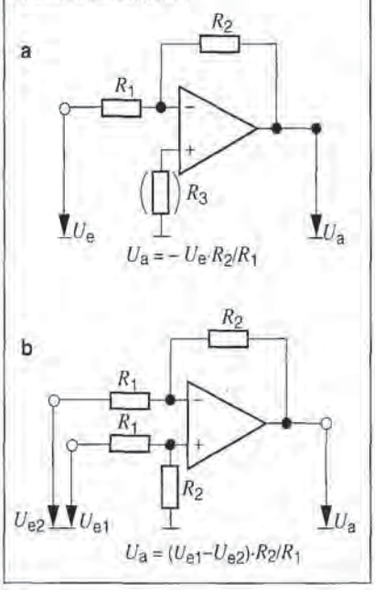
Example: 101 (dual) =
$1 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0 = 5$ (decimal).

The bit (position) with the greatest value is termed the MSB (Most Significant Bit), the lowest the LSB (Least Significant Bit). When represented as a two's complement, the MSB provides the prefix for the decimal number (1 ≙ negative, 0 ≙ positive). Values ranging from −4 to + 3 can be represented with a 3-bit word.

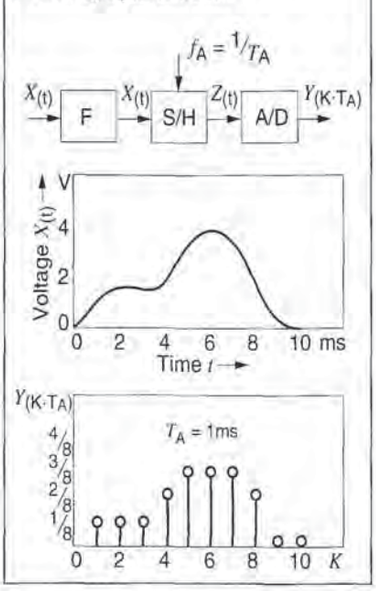
Example: 101 =
$-1 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0 = -3$.

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Operational amplifier (OP)
a) Inversion amplifier,
b) Differential amplifier.



Digital conversion of an analog signal
F Filter, S/H Sample-and-hold element, A/D Analog/digital converter.



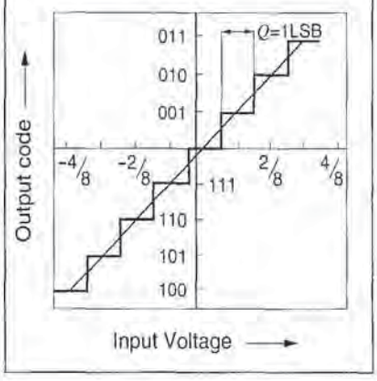
A word of n bits in length is able to represent 2^n different values. This is 256 for 8 bits, for 16 bits it is 65 536. An analog input voltage of ± 5 V (FSR – Full Scale Range) results in a resolution (LSB value) of 39 mV for 8 bits and 0.15 mV for 16 bits.

It is necessary to limit the bandwidth of the time signal being scanned (anti-aliasing filter). The highest signal frequency f_g must be less than half the scanning frequency f_A ($f_A > 2 \cdot f_g$). If a sample-and-hold scanning element is not employed, the maximum allowable variation in input voltage during the A/D converter's conversion period (aperture time) is one LSB.

The transfer function illustrates how a single digital value is assigned to various input voltages. The maximum amplitude of the quantification error is $Q/2$ (rounding-off error) at Q = FSR/(2^n) ≙ LSB.

The quantification process results in an overlay of quantification noise which contaminates the actual data signal. If a sinus-curve signal is employed for full modulation in the A/D converter, the result is a signal-to-noise ratio which increases by about 6 dB for each additional bit of resolution. Actual A/D converters display deviations from the ideal transfer curve. These are caused by offset, amplification and linearity errors (static errors) as well as aperture inconsistency and finite settling times (dynamic error).

Transfer function of an ideal 3-bit A/D converter



Sensors

Basics

Assignment

Sensors convert a physical or chemical (usually non-electrical) quantity into an electrical quantity (non-electrical intermediate stages may be employed).

Classifications

1. Purpose and application
- Function (open-loop and closed-loop control circuits),
- Safety and back-up,
- Monitoring and information.

2. Types of characteristic curve
- Continuous linear: Control applications across a broad measurement range,
- Continuous non-linear: Closed-loop control of a measured variable within a narrow measurement range,
- Discontinuous multi-stage: Monitoring in applications where a punctual signal is required when a limit value is reached,
- Discontinuous dual-stage (with hysteresis in some cases): Monitoring of correction thresholds for immediate or subsequent adjustments.

3. Type of output signal

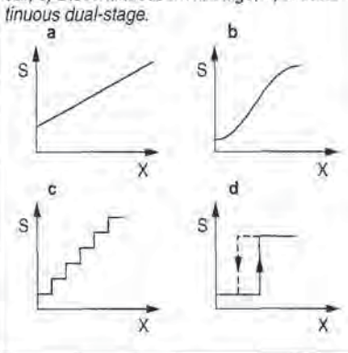
Output signal proportional to:
- current/voltage, amplitude,
- frequency/periodicity,
- pulse duration/pulse duty factor.

Discrete output signal:
- dual stage (binary),
- multi-stage (irregular graduation),
- multi-stage (equidistant) or digital.

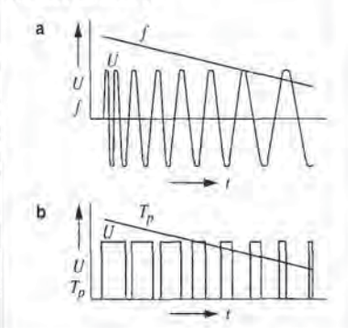
Automotive applications

In their function as peripheral elements, sensors and actuators form the interface between the vehicle with its complex drive, braking, chassis, suspension and body functions (including guidance and navigation functions) and the usually digital-electronic control unit (ECU) as the processing unit. An adapter circuit is generally used to convert the sensor's signals into the standardized form (measuring chain, measured-data registration system) required by the ECU.

Types of characteristic curve
S Output signal, X Measured variable. a) Continuous linear, b) Continuous nonlinear, c) Discontinuous multi-stage, d) Discontinuous dual-stage.



***Signal shapes** (examples)*
Output signal U: a) Frequency f, b) Pulse duration T_P.



In addition, system operation can be influenced by sensor information from other processing elements and/or by driver-operated switches.

Display elements provide the driver with information on the static and dynamic status of vehicle operation as a single synergistic process.

Main technical requirement, trends

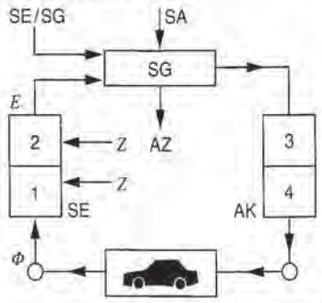
The degree of stress to which the sensor is subjected is determined by the operating conditions (mechanical, climatic, chemical, electromagnetic influences) present at the installation location (for standard Degrees of Protection, see DIN 40 050, Sheet 9).

According to application and technical

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requirements, automotive sensors are assigned to one of three reliability classes:
Class 1: Steering, brakes, passenger protection,
Class 2: Engine, drivetrain, suspension, tires,
Class 3: Comfort and convenience, information/diagnosis, theft deterrence.
Miniaturization concepts are employed to achieve compact unit dimensions:
- Substrate and hybrid technology (pressure and temperature sensors),
- Semiconductor technology (monitoring rotational speed, e.g., with Hall sensors),
- Micromechanics (pressure and acceleration sensors),
- Microsystem technology (combination of micromechanics, micro-electronics, can also include micro-optics).

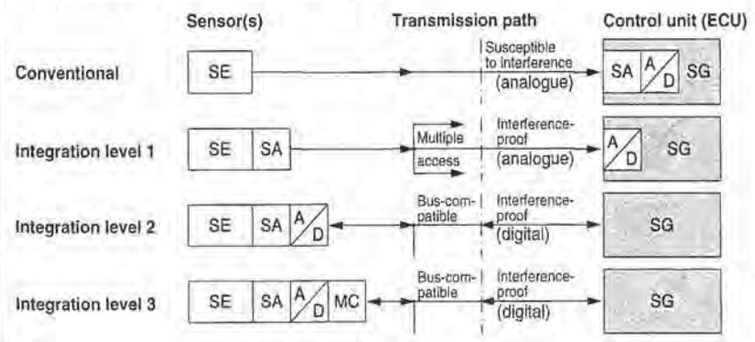
Automotive sensors
Φ Physical quantity, E Electrical quantity, Z Influencing quantities, AK *Actuator,* AZ *Display,* SA *Switch,* SE *Sensor(s),* SG *Control unit (ECU).*
1 Measuring sensor, 2 Adapter circuit, 3 Driver, 4 Actuators.



Integrated "intelligent" sensors
Systems range from hybrid and monolithic integrated sensors and electronic signal-processing circuits at the measuring point, all the way to complex digital circuitry, such as A/D converters and microcomputers (mechatronics), for complete utilization of the sensor's inherent precision. These systems offer the following benefits and options:
- Reduction of load on the ECU,
- Uniform, flexible, bus-compatible communications links,
- Multiple application of sensors,
- Multi-sensor designs,
- By means of local amplification and demodulation, very small quantities and HF signals can be processed,
- Correction of sensor deviations at the measuring point, and common calibration and compensation of sensor and circuit, are simplified and improved by storage of the individual correction information in PROM.

Fiber-optic sensors
Various physical factors can be employed to modify the intensity, phase (coherent laser light) and polarization of the light conducted in the optical fibers. Fiber-optic sensors are impervious to electromagnetic interference; they are, however, sensitive to physical pressure (intensity-modulation sensors), and, to some degree, to

Sensor integration levels
SE *Sensor(s),* SA *Signal processing (analog),* A/D *Analog-digital converter,* SG *Digital control unit (ECU),* MC *Microcomputer.*



contamination and aging. Inexpensive plastic fibers are now available for application within some of the temperature ranges associated with automotive applications. These sensors require special couplers and plug connections.

Extrinsic sensors: The optical conductor generally conducts the light to an end point; it must emerge from the conductor to exert an effect.
Intrinsic sensors: The measurement effect occurs internally within the fibers.

Sensor types

Position sensors (displacement/angle)
Position sensors employ both contact wipers and non-contacting (proximity) designs to register displacement and angle.

Directly monitored variable quantities:
- Throttle-valve position,
- Accelerator-pedal position,
- Seat and mirror position,
- Control-rack travel and position,
- Fuel level,
- Travel of clutch servo unit, vehicle obstruction,
- Steering (wheel) angle,
- Tilt angle,
- Vehicle-course angle,
- Brake-pedal position.

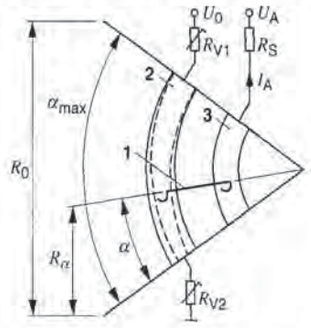
Indirectly monitored variable quantities:
- Sensor-flap deflection angle (flow rate/FLR),
- Deflection angle of a spring-mass system (acceleration),
- Diaphragm deflection angle (pressure),
- Suspension compression travel (headlamp vertical-aim adjustment),
- Torsion angle (torque).

Wiper or film potentiometers
The wiper potentiometer measures travel by exploiting the proportional relationship between the length of a wire or film resistor (conductor track) and its electrical resistance. This design currently provides the most economical travel and angle sensors.

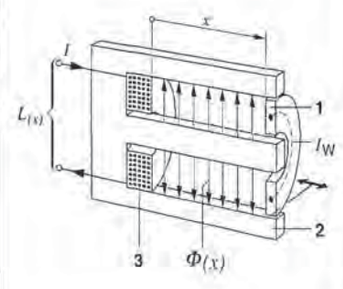
The voltage on the measurement track is usually routed through smaller series resistors R_V for overload protection (as well as for zero and progression-rate adjustments). The shape of the contour across the width of the measurement track (including that of individual sections) influences the shape of the characteristic curve.

The standard wiper connection is furnished by a second contact track consisting of the same material mounted on a low-resistance substrate. Wear and measurement distortions can be avoided by minimizing the current at the pickup (I_A < 1 mA) and sealing the unit against dust.

Wiper potentiometer
1 Wiper, 2 Resistor track, 3 Contact track. U_0 Supply voltage, U_A Measurement voltage, R Resistor, α Measurement angle.



Short-circuiting ring sensor
1 Short-circuiting ring (movable), 2 Soft magnetic core, 3 Coil.
I Current, I_W Eddy current, $L(x)$ Inductance and $\Phi(x)$ magnetic flux at travel x.



Short-circuiting ring sensors

Short-circuiting ring sensors consist of a laminated soft-magnetic core (straight/curved U- or E-shape), a coil and a moving, highly-conductive short-circuiting ring made of copper or aluminum.

When an AC voltage is applied at the coil, a current I is created which is dependent on the inductance of the coil. The eddy currents thereby created in the short-circuiting ring limit expansion of the magnetic flux to the area between the coil and the ring itself. The position of the short-circuiting ring influences the inductance and thus the coil current. The current I is thus a measure of the position of the short-circuiting ring. Virtually the entire length of the sensor can be utilized for measurement purposes. The mass to be moved is very low. Contouring the distance between the sides influences the shape of the characteristic curve: Reducing the distance between the sides toward the end of the measuring range further enhances the good natural linearity. Operation is generally in the 5...50 kHz range, depending on material and shape.

Half-differential sensors employ a moving measuring ring and a stationary reference short-circuiting ring to meet exacting demands for precision (on diesel fuel-injection pumps, the rack-travel sensor for in-line units, and angular-position sensors in the injected-fuel-quantity actuator of distributor-type injection pumps); they measure by acting as

- inductive voltage dividers (evaluation L_1/L_2 or $(L_1-L_2)/(L_1+L_2)$), or as
- frequency-definition elements in an oscillating circuit, producing a signal proportional to frequency (excellent interference resistance, easy digital conversion).

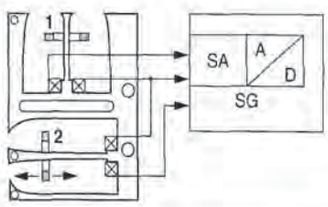
The measuring effect is fairly substantial, typically $L_{max}/L_{min} = 4$.

Other sensor types

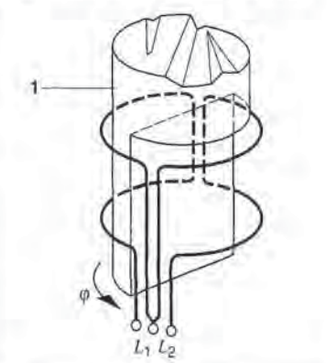
Solenoid plunger, differential-throttle and differential-transformer sensors operate based on the variation in the inductance of an individual coil and the proportional relationship of voltage dividers (supplied either directly or via inductive coupling) with moving cores. The overall length is often considerably greater than the measurement travel. This disadvantage is avoided by using a multistage winding in chambers of different dimensions. With this sensor, for angular measurement, the angle of rotation must be mechanically converted to a linear movement.

HF eddy-current sensors (electronics at the measuring point) are suitable e.g. for non-contact measurement of the throttle angle and the accelerator-pedal position. Here, the inductance of mostly nonferrous coils is modified by the approach of conductive shaped parts (spoilers) or by variable overlapping with them. Because of the frequently high operating frequency (MHz range), the signal electronics is mostly accommodated directly on the

Half-differential sensor
1 Reference (fixed), 2 Short-circuiting ring (movable), A/D Analog-digital converter, SA Signal processing, SG Control unit (ECU).



Eddy-current pedal-travel sensor
1 Spoiler. φ Angle of rotation, L_1, L_2 Inductance of semicylindrical coils.



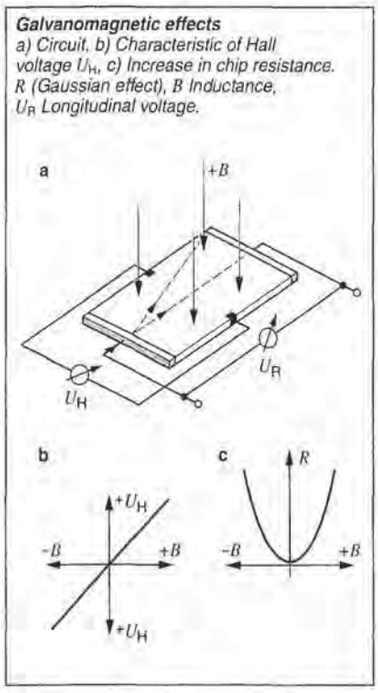
sensor. This is the case for example when two coils are wound onto a common cylinder (differential sensor) for measuring the throttle angle. The same principle is used on sensors incorporating single lateral coils to measure clutch positions (70 mm measurement range) at substantially lower frequencies (approx. 7.5 kHz). The first of the above sensor types features a cylindrical aluminum spoiler with special recesses and is designed to pivot over the coil winding. The second concept monitors the penetration depth of an aluminum short-circuit tube within the sensor coil.

Integrated Hall ICs

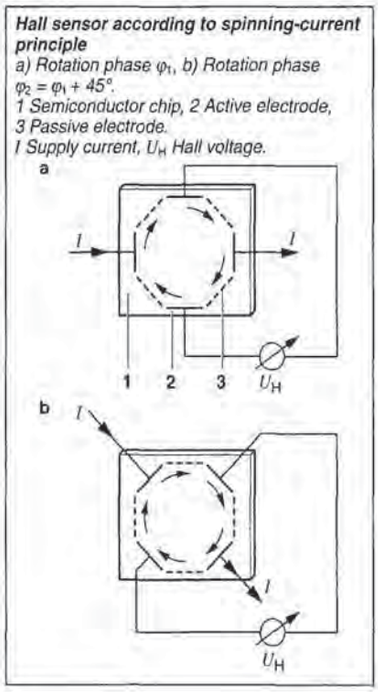
The Hall effect is a galvanomagnetic effect and is evaluated mainly by means of thin semiconductor chips. When such a current-carrying chip is permeated vertically by a magnetic induction B, a voltage U_H proportional to the field can be picked off transversely to the current direction (Hall effect) while the chip resistance simultaneously increases in accordance with a roughly parabolic characteristic (Gaussian effect, magnetoresistor). When Si is used as the base material, a signal-conditioning circuit can at the same time be integrated on the chip, which makes such sensors very economical.

A disadvantage in the past proved to be their sensitivity to the mechanical stress which was inevitable due to packaging and resulted in an unfavorable offset temperature coefficient. This disadvantage has been overcome by the application of the "spinning-current" principle. This now made Hall ICs well suited for analog sensor applications. Mechanical interference (piezoresistive effects) is suppressed by rapid, electronically controlled rotation of the electrodes or cyclical switching of the electrodes and averaging of the output signal.

Such integrated Hall ICs are mainly suitable for measuring limited travel ranges in that they register the fluctuating field strengths of a permanent magnet as a function of the magnet's distance from the IC. Larger angles up to 360° (e.g. for recording the camshaft position) can be



Galvanomagnetic effects
a) Circuit, b) Characteristic of Hall voltage U_H, c) Increase in chip resistance. R (Gaussian effect), B Inductance, U_R Longitudinal voltage.



Hall sensor according to spinning-current principle
a) Rotation phase φ_1, b) Rotation phase $\varphi_2 = \varphi_1 + 45°$.
1 Semiconductor chip, 2 Active electrode, 3 Passive electrode.
I Supply current, U_H Hall voltage.

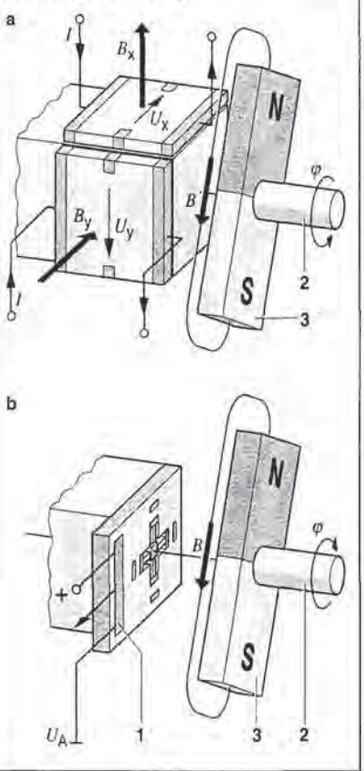
measured e.g. with the configuration shown in the illustration: The two Hall-effect sensors arranged at right angles supply sinusoidal/cosinusoidal signals which can be converted by means of the arctan function into the angle of rotation φ. In principle, the configuration can also be integrated in planar form with VHDs (Vertical Hall Devices).

It is also possible with a rotating magnet ring and some fixed soft-magnetic conductors to obtain a linear output signal directly for larger angle ranges without conversion. In this case, the bipolar field of the magnet ring is passed through a Hall-effect sensor arranged between semicircular flux concentrating pieces. The effective magnetic flux through the Hall-effect sensor is dependent on the angle of rotation φ.

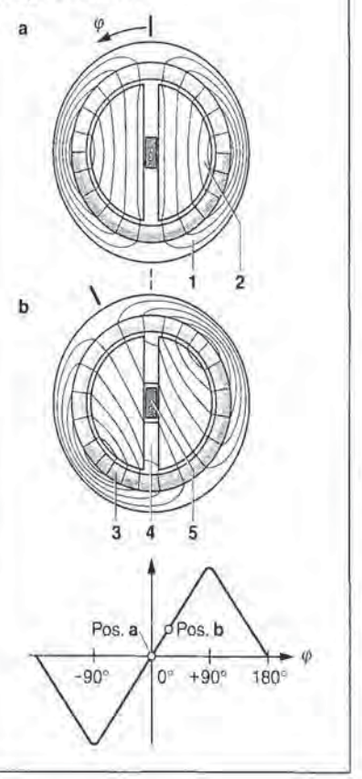
The disadvantage here is the persisting dependency on geometrical tolerances of the magnetic circuit and intensity fluctuations of the permanent magnet.

The simplest Hall ICs ("Hall-effect switches") also permit – in conjunction with a small working-point magnet – the construction of digital angle sensors up to 360°. For this purpose, for an n-bit resolution, n Hall-effect switches are arranged equidistantly in a circle. A soft-magnetic code disk blocks the field of the individual

Analog Hall sensor for 360°
a) Built from discrete Hall ICs,
b) Built from planar-integrated Hall ICs.
1 Signal electronics, 2 Camshaft,
3 Control magnet.
B Inductance, I Current, U Voltage,
U_A Measurement voltage.



Analog Hall angle sensor with linear characteristic for angles up to approx. 180°
a) Position a, b) Position b, c) Output signal.
1 Magnetic yoke, 2 Stator (1, 2 Soft iron),
3 Rotor (permanent magnet), 4 Air gap,
5 Hall sensor.
φ Angle of rotation.



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overlying permanent magnets, or enables it, so that when the disk is rotated further the Hall-effect switches in succession generate n different code words. The Gray code is used to avoid large indication errors in intermediate states. To implement a steering-wheel angle sensor, for example, the code disk is connected to the steering spindle while the rest of the sensor is connected to the chassis. Multiple rotations can be recorded with an additional, simple 3-bit configuration whose code disk is moved by means of a reduction gear. The resolution of such configurations is mostly no better than 2.5°.

Sensors of the future

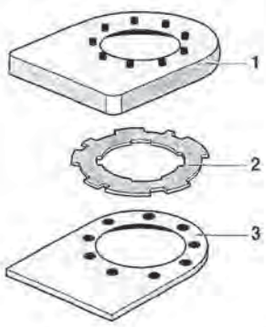
Magnetoresistive NiFe thin-film sensors (AMR – anisotropic magnetoresistive thin-film NiFe, permalloy) provide extremely compact designs for contactless, proximity-based angular-position sensors.

The substrate consists of oxidized silicon layers in which electronic signal-processing circuits can be incorporated as desired. The magnetic control field B is usually generated by a pivoting magnet located above the sensor.

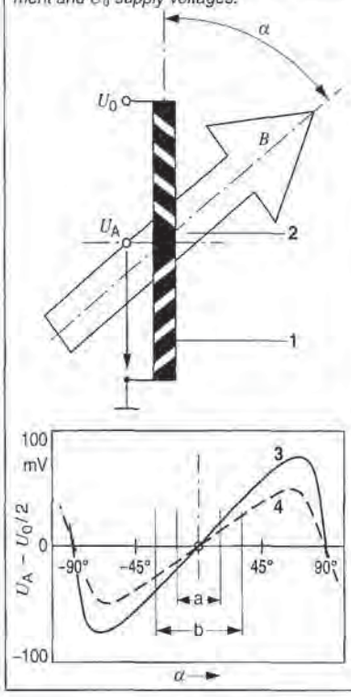
Magnetoresistive angle sensors in "barber's pole" configuration display serious limitations in both precision and measurement ranges (max. ±15°). Operation is based on the detuning of a magnetoresistant voltage divider consisting of longitudinal permalloy resistors with high-conductance lateral strips in gold.

Magnetoresistive angle sensors in "pseudo-Hall" configuration utilize the inherent precision in the sinusoidal pattern of signals monitored at the output terminals of a quadripolar planar sensor structure. A second element installed at 45° generates a supplementary cosinusoidal signal. From the mutual relationship of the two signal voltages, it is possible (e.g. using the arctan function) to determine the angle α (e.g. with a microcontroller or

Digital 360° Hall angle sensor with a circular, equidistant arrangement of simple Hall switches
1 Housing cover with permanent magnets, 2 Code disk (soft-magnetic material), 3 Board with Hall switches.



Magnetoresistive angle sensor (barber's pole configuration)
1 AMR, anisotropic magnetoresistive element (barber's pole), 2 Rotating permanent magnet with control inductance B, 3 Response curves for low, and, 4 for high operating temperature. a Linear, b Effective measurement range. α Measurement angle, U_A Measurement and U_0 supply voltages.



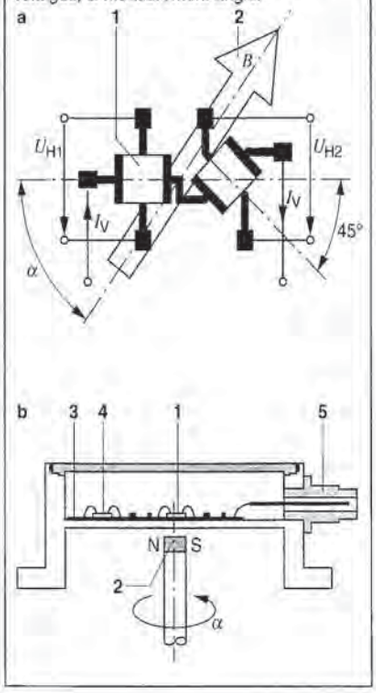
ASIC) with great accuracy over a range of 180°, largely irrespective of fluctuations in temperature and magnetic-field intensity (distance, aging).

The task of measuring various rotations of a rotating part (e.g. steering spindle) is solved with a dual configuration of "pseudo-Hall angle sensors". Here the two associated permanent magnets are moved by the rotating part via a step-up gear train. However, as the two smaller driving gears differ to the tune of one tooth, their mutual phase angle is a clear measure of the absolute angular position. Each individual sensor also offers an indeterminate fine resolution of the angle of rotation. This configuration provides a resolution more precise than 1° for e.g. the entire steering-angle range of four full rotations.

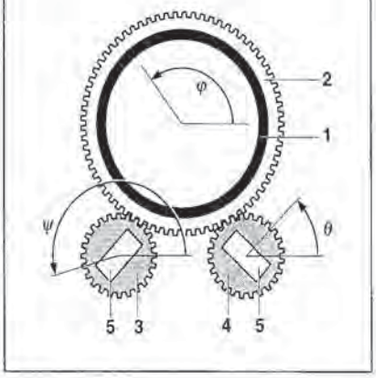
Systems for monitoring vehicle to vehicle distances can use ultrasonic transit-time processes (close-range, 0.5...5 m), as well as processes based on transit-time and triangulation principles using short-range infrared light (lidar: mid-range measurements extending up to 50 m). Another option is electromagnetic radar (long-range operation, up to 150 m).

ACC systems (Adaptive Cruise Control) with just such a long-range radar sensor are vehicle-speed controllers with automatic detection of vehicles which are driving in front in a lane and where braking may be required. A working frequency of 76 GHz (wavelength approx. 3.8 mm) permits the compact design required for automotive applications. A Gunn oscillator (Gunn diode in the cavity resonator) feeds in parallel three adjacently arranged patch antennas which at the same time also serve to receive the reflected signals. A plastic lens (Fresnel) set in front focuses the transmitted beam, referred to the vehicle axle, horizontally at an angle of ±5° and vertically at an angle of ±1.5°. Due to the lateral offset of the antennas, their reception characteristic (6 dB width 4°) points in different directions. As well as the distance of vehicles driving in front

Magnetoresistive angle sensor (pseudo-Hall version)
a) Measurement concept,
b) Sensor structure.
1 Thin NiFe layer (AMR sensor), 2 Pivoting permanent magnet with inductive control B, 3 Hybrid, 4 ASIC, 5 Electrical connection. I_V Supply current, U_{H1}, U_{H2} Measurement voltages, α Measurement angle.



AMR steering-angle sensor
1 Steering spindle, 2 Gear with n teeth, 3 Gear with m teeth, 4 Gear with m+1 teeth, 5 Magnets.
φ, ψ, θ Angle of rotation.

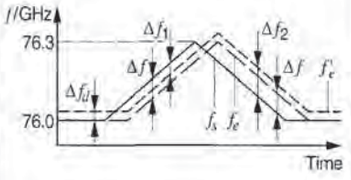


and their relative speed, it is thus also possible to determine the direction under which they are detected. Directional couplers separate transmitted and received reflection signals. Three downstream mixers transpose the received frequency down to virtually zero by admixing the transmit frequency (0...300 kHz). The low-frequency signals are digitized for further evaluation and subjected to a high-speed Fourier analysis to determine the frequency.

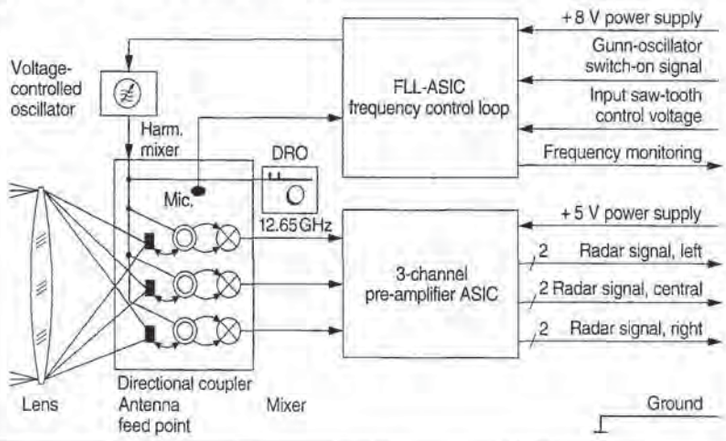
The frequency of the Gunn oscillator is compared continually with that of a stable reference oscillator DRO (Dielectric Resonance Oscillator) and regulated to a prespecified setpoint value. Here the supply voltage to the Gunn diode is modulated until it corresponds again to the setpoint value. This control loop is used for measurement purposes to increase and reduce the Gunn-oscillator frequency every 100 ms briefly in a saw-tooth manner by 300 MHz (FMCW Frequency Modulated Continuous Wave). The signal reflected from the vehicle driving in front is delayed according to the propagation time (i.e. in a rising ramp by a lower frequency and in a falling ramp by a frequency higher by the same amount). The frequency difference Δf is a direct measure of the distance (e.g. 2 kHz/m). If however there is additionally a specific relative speed between the two vehicles, the received frequency f_e is increased on account of the Doppler effect in both the rising and falling ramps by a specific, proportional amount Δf_d (e.g. 512 Hz per m/s), i.e. there are two different difference frequencies Δf_1 and Δf_2. Their addition produces the distance between the vehicles, and their difference the relative speed of the vehicles. This method can be used to detect and track up to 32 vehicles.

Magnetic-field sensors (saturation-core probes) can monitor the vehicle's direction of travel for general orientation and application in navigation systems.

Distance and velocity measurement with FMCW radar
f_s Transmitted frequency, f_e/f'_e Received frequency without/with relative velocity, Δf_d Frequency increase due to Doppler effect (relative velocity), $\Delta f_1/\Delta f_2$ Differential frequency without/with relative velocity.



***ACC-sensor control unit** (block diagram)*



RPM and velocity sensors

A distinction is made between absolute rotating velocity in space and relative rotating velocity between two parts.

An example of absolute rotating velocity is the vehicle's yaw rate about its vertical axis ("yaw velocity"); this is required for vehicle-dynamics control. Examples of relative rotating velocity are the crankshaft and camshaft speeds, the wheel speeds (for ABS/TCS) and the speed of the diesel injection pump. Measurements are mainly taken with the aid of an incremental sensor system comprising a gear and an min^{-1} sensor.

Newer applications:
- Bearing-integrated min^{-1} sensors (wheel bearings, Simmer shaft-seal module on the crankshaft),
- Linear velocity,
- Vehicle yaw rate about the longitudinal axis ("roll velocity" for rollover protection).

Inductive sensors

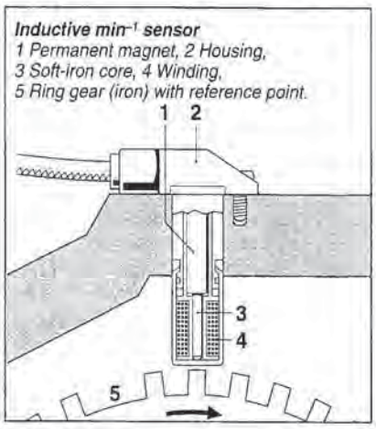
The inductive sensor consists of a bar magnet with a soft-magnetic pole pin supporting an induction coil with two connections. When a ferromagnetic ring gear (or a rotor of similar design) turns past this sensor, it generates a voltage in the coil which is directly proportional to the periodic variation in the magnetic flux. A uniform tooth pattern generates a sinusoidal voltage curve. The rotational speed is reflected in the periodic interval between the voltage's zero transition points, while the amplitude is also proportional to rotating speed.

The air gap and the tooth dimensions are vital factors in defining the (exponential) signal amplitude. Teeth can still be detected without difficulty up to air-gap widths of one half or one third of a tooth interval. Standard gears for crankshaft and ABS wheel-speed sensors cover gaps ranging from 0.8 to 1.5 mm. The reference point for the ignition timing is obtained either by omitting a tooth or by bridging a gap between teeth. The resulting increase in distance between zero transitions is identified as the reference point and is accompanied by a substantial increase in signal voltage (the system registers a larger tooth).

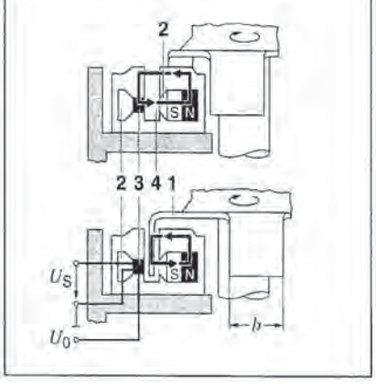
Hall-effect sensors/vane switches

Semiconductor sensors utilize the Hall effect (P. 75) in the form of Hall-effect vane switches, e.g. as ignition triggering sensors in ignition distributors (P. 490). The sensor and the electronic circuitry for supply and signal processing are integrated on the sensor chip.

This "Hall IC" (with bipolar technology for sustained temperatures of up to 150°C and direct connection to the vehicle electrical system) is located within an almost completely insulated magnetic circuit consisting of permanent magnet and pole elements. A soft-magnetic trigger wheel (e.g. camshaft-driven) travels through the



Inductive min⁻¹ sensor
1 Permanent magnet, 2 Housing, 3 Soft-iron core, 4 Winding, 5 Ring gear (iron) with reference point.



Hall-effect vane switch (ignition distributor)
1 Vane with width b, 2 Soft-magnetic conductors, 3 Hall IC, 4 Air gap.
U_0 Supply voltage, U_S Sensor voltage.

gap. The trigger-wheel vane interrupts the magnetic field (that is, it deflects it around the sensor), while the gap in the trigger wheel allows it to travel through the sensor unimpeded.

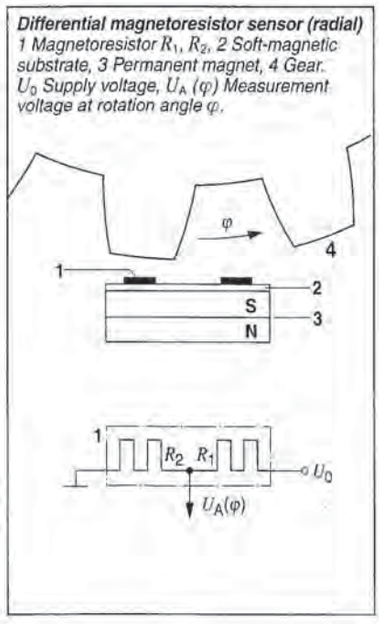
The differential Hall-effect sensor of a system with electronic ignition distribution picks off the camshaft position at a special, soft-magnetic segment disk.

Newer sensors

Sensors of the future should satisfy the following criteria:
- static monitoring (e.g. zero min^{-1}),
- larger air gaps,
- independence from air-gap fluctuations (temperature-resistant ≤200 °C).

Gradient sensors

Gradient sensors (e.g., based on Hall, differential, or differential magnetoresistive sensors) incorporate a permanent magnet on which the pole surface facing the gear is homogenized with a thin ferromagnetic wafer. Two galvanomagnetic elements (generic term for Hall sensors and magnetoresistors) are located on each element's sensor tip, at a distance of roughly one half a tooth interval. Thus one of the elements is always opposite a gap between teeth when the other is adjacent to a tooth. The sensor measures the difference in field intensity at two adjacent locations on the circumference. The output signal is roughly proportional to the diversion of field strength as a function of the angle at the circumference; polarity is therefore independent of the air gap.



Differential magnetoresistor sensor (radial)
1 Magnetoresistor R_1, R_2, 2 Soft-magnetic substrate, 3 Permanent magnet, 4 Gear. U_0 Supply voltage, $U_A(\varphi)$ Measurement voltage at rotation angle φ.

Gauss-effect magnetoresistors are magnetically controlled, bipolar semiconductor resistors (indium antimonide) with a design similar to that of the Hall sensor. In the standard application range their resistance is essentially proportional to the square of the field strength. The two resistors of a differential sensor assume the function of voltage dividers in the electrical circuit; for the most part, they also compensate for temperature sensitivity. The substantial measurement effect makes it possible to dispense with local electronic amplifiers (output signal 0.1...1 V). Magnetoresistors for automotive applications withstand temperatures ≤170 °C (brief peaks ≤200 °C).

Tangential sensors

The tangential sensor differs from its gradient-type counterpart by reacting to variations in polarity and intensity in the components of a magnetic field located tangentially to the periphery of the rotor. Design options include AMR thin-film technology (barber's pole) or single permalloy resistors featuring full- or half-bridge circuitry. Unlike the gradient sensor, the tangential unit does not need to be adapted for variations in tooth distribution patterns, and thus permits semipunctiform configuration. Although the intrinsic measurement effect exceeds that of the silicon-based Hall sensor by a factor of approx. 1...2, local amplification is still required.

In the case of a bearing-integrated crankshaft speed sensor (Simmer shaft-seal module), the AMR thin-film sensor is mounted together with an evaluation IC on a common leadframe. For the purposes of space saving and temperature protection, the evaluation IC is bent at an angle of 90° and also located further away from the sensor tip.

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Oscillation gyrometers

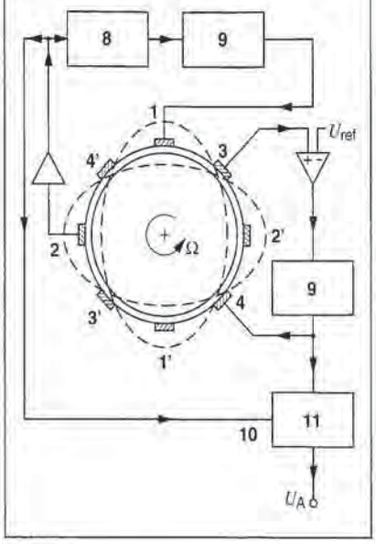
Oscillation gyrometers measure the absolute yaw rate Ω around the vehicle's vertical axis (yaw axis), e.g. in systems for controlling a vehicle's dynamic behavior (ESP, Electronic Stability Program) and for navigation. They are similar in principle to mechanical gyroscopes and for measurement purposes utilize the Coriolis acceleration that occurs during rotational motions in conjunction with an oscillating motion.

Piezoelectric yaw-rate sensors

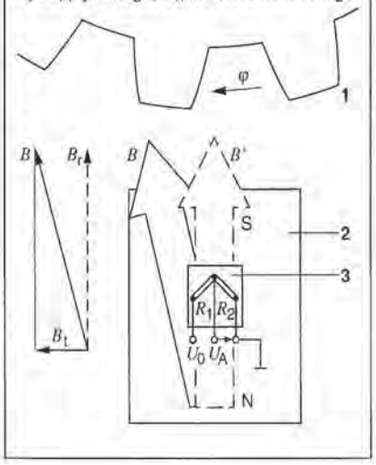
Two diametrically opposed piezo-ceramic elements (1-1') induce radial resonant oscillation in an oscillatory metallic hollow cylinder. A second piezoelectric pair (2-2') governs the cylinder to a constant oscillation amplitude with four axial nodes (45° offset to direction of excitation).

The nodes respond to rotation at the rate Ω about the cylinder axis with a slight peripheral displacement, inducing forces proportional to min^{-1} in the otherwise force-free nodes. This state is detected by a third pair of piezoelectric elements (3-3'). The forces are then processed back to a reference value $U_{ref} = 0$ by a fourth ex-

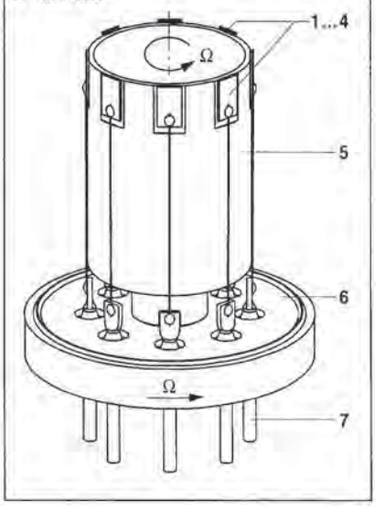
Piezoelectric yaw-rate sensor
Operating concept.
1...4 Piezoelectric elements, 8 Control circuit (fixed phase), 9 Bandpass filter, 10 Phase reference, 11 Rectifier (selective-phase).
U_A Measurement voltage, Ω Yaw rate, $U_{ref} = 0$ (normal operation), $U_{ref} \neq 0$ ("built-in" test).



AMR sensor (tangential)
1 Gear (Fe), 2 Permanent magnet, 3 Sensor. B Control field strength with tangential component B_t and radial component B_r (B' Initial position, $B_t = 0$), R_1, R_2 Permalloy thin-film resistors (AMR), φ Rotation angle, U_0 Supply voltage, U_A Measurement voltage.



Piezoelectric yaw-rate sensor
Structure.
1... 4 Piezoelectric element pairs, 5 Oscillating cylinder, 6 Baseplate, 7 Connection pins. Ω Yaw rate.

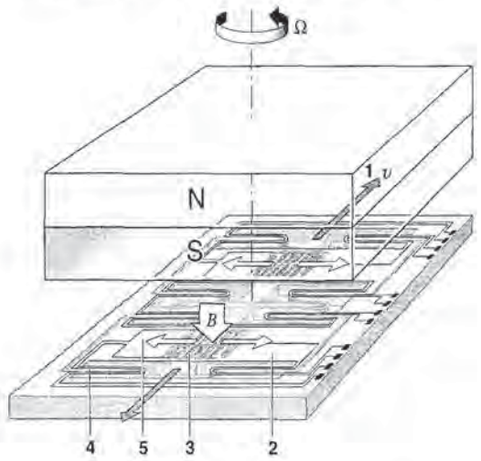


citing pair (4-4') in a closed-loop operation. After careful filtering using synchronized-phase rectification, the required control value provides an extremely precise output signal. A controlled temporary change of the setpoint value to $U_{ref} \neq 0$ provides a simple means of testing the entire sensor system ("built-in" test).

Complex compensation circuitry is required to deal with the temperature sensitivity of this sensor. Because the piezoceramic elements' response characteristics also change with age, careful pretreatment (artificial aging) is also required.

Micromechanical silicon yaw-rate sensors provide an inexpensive and compact alternative to today's intricate mechanical sensors. A combined technology is used to achieve the high precision needed in vehicle-dynamics systems: two thicker mass boards worked from the wafer by means of bulk micromechanics (P. 90) oscillate in push-pull mode at their resonant frequency, which is determined by their mass and their coupling-spring stiffness (> 2 kHz). Each of them is provided with an extremely small surface-micromechanical, capacitive acceleration sensor which measures Coriolis acceleration in the wafer plane vertical to the oscillation direction when the sensor chip rotates about its vertical axis at the yaw rate Ω. They are proportional to the product of the yaw rate and the oscillation velocity which is electronically regulated to a constant value. For drive purposes, there is a simple printed conductor on the relevant oscillation board which is subjected to a Lorentz force in a permanent-magnetic field vertical to the chip surface. A similarly simple, chip-surface-saving conductor is used to measure the oscillation velocity directly and inductively with the same magnetic field. The different physical natures of the drive and sensor systems prevent unwanted crosstalking between the two parts. In order to suppress external accelerations (common-mode signal), the two opposing sensor signals are subtracted from each other (summation however can also be used to measure the external acceleration). The precise micromechanical structure helps to suppress the influence of high oscillation acceleration with regard to the Coriolis acceleration that is lower by several powers

Micromechanical yaw-rate sensor with electrodynamic drive in combined technology form *(bulk and SMM micromechanics)*
1 Oscillation direction, 2 Oscillating body, 3 Coriolis acceleration sensor, 4 Retaining/guide pin, 5 Direction of Coriolis acceleration, Ω Yaw rate, υ Oscillation velocity.



of ten (cross sensitivity well below 40 dB). The drive and measuring systems are mechanically and electrically isolated in rigorous terms here.

If the Si yaw-rate sensor is manufactured completely in accordance with surface micromechanics SMM (P. 90), and the magnetic drive and control system is replaced at the same time by an electrostatic system, this isolation can be realized less consistently: Using "comb" structures, a centrally mounted rotary oscillator is electrostatically driven to oscillate at an amplitude which is constantly regulated by means of a similar capacitive pick-off. Coriolis forces force a simultaneous "out-of-plane" tilting motion whose amplitude is proportional to the yaw rate Ω and which is detected capacitively with electrodes located under the oscillator. To prevent this motion from being excessively damped, it is essential to operate the sensor in a vacuum. The smaller chip size and the simpler manufacturing process do indeed reduce the cost of such a sensor, but the reduction in size also diminishes the already slight measuring effect and thus the attainable accuracy. It places higher demands on the electronics. The influence of external accelerations is already mechanically suppressed here.

Radar sensors

Research focuses on simple (low-cost) Doppler radar systems for measuring the vehicle's linear velocity.

Acceleration/vibration sensors

These sensors are suitable for triggering passenger-protection systems (airbags, seatbelt tensioners, rollover bars), for knock detection and control in internal-combustion engines, and for registering lateral acceleration rates and velocity changes in four-wheel-drive vehicles fitted with ABS.

Hall-effect acceleration sensor

In ABS-equipped vehicles with four-wheel drive and modern cars with vehicle-dynamics control, the wheel-speed sensors are supplemented by a Hall-effect acceleration sensor to monitor lateral and longitudinal acceleration rates. Deflection levels in the spring-mass system used in this application are recorded using a magnet and a Hall-effect sensor (measuring range: 1 g). The sensor is designed for narrow-band operation (several Hz) and features electrodynamic damping.

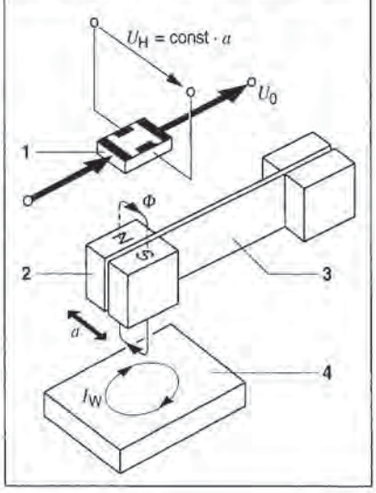
Piezoelectric sensors

Piezoelectric bimorphous spring elements/two-layer piezoceramics, are used in applications such as triggering seatbelt tensioners, airbags and rollover bars.

Typical acceleration rates in automotive applications:

Application	Range
Knock control	1...10 g
Passenger protection	
Airbag, seat-belt tightener	50 g
Rollover bar	4 g
Seatbelt inertia reel	0.4 g
ABS, ESP	0.8...1.2 g
Suspension control	
Structure	1 g
Axle	10 g

Hall acceleration sensor
1 Hall sensor, 2 Permanent magnet (seismic mass), 3 Spring, 4 Damping plate (Cu). a Acceleration, I_W Eddy currents, U_H Hall voltage, U_0 Supply voltage, Φ Magnetic flux.



Their intrinsic inertial mass causes them to deflect under acceleration to provide a dynamic (not DC response pattern) signal with excellent processing characteristics (typical frequency limit of 10 Hz).

The sensor element is located in a sealed housing shared with the initial signal-amplification stage. It is sometimes encased in gel for physical protection.

The sensor's actuating principle can also be inverted: An additional actuator electrode makes it easy to check the sensor (on-board diagnosis).

Longitudinal elements (knock sensors)

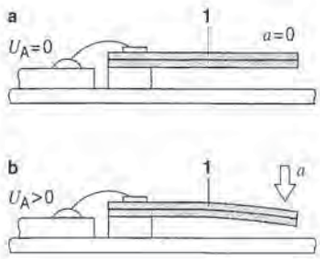
Longitudinal elements are employed as knock sensors (acceleration sensors) for ignition systems that feature knock control (P. 496). They measure (with low directional selectivity) the structure-borne noise at the engine block (measuring range approx. 10 g at a typical vibration frequency of 5...20 kHz). An unencapsulated, annular piezo-ceramic ring element measures the inertial forces exerted upon a seismic mass of the same shape.

New sensor concepts

Capacitive silicon acceleration sensors

The first generation of micromechanical sensors relied on anisotropic and selective etching techniques to fabricate the required spring-mass system from the full wafer (bulk silicon micromechanics) and produce the spring profile.

Piezoelectric sensor
a) At rest, b) During acceleration a.
1 Piezo-ceramic bimorphous spring element, U_A Measurement voltage.



Capacitive pick-offs have proven especially effective for the high-precision measurement of this seismic-mass deflection. This design entails the use of supplementary silicon or glass wafers with counter-electrodes above and below the spring-held seismic mass. This leads to a 3-layer structure, whereby the wafers and their counterelectrodes also provide overload protection.

A precisely metered air cushion in the hermetically-sealed oscillating system provides an extremely compact yet efficient and inexpensive damping unit with good temperature response characteristics. Current designs almost always employ a fusion bonding process to join the three silicon wafers directly.

Due to variations in the thermal expansion rates of the different components, it is necessary to mount them on the casing baseplate. This has a decisive effect upon the desired measuring accuracy. Virtually straight-line mounting is used, with free support in the sensitive range.

This type of sensor is usually employed for low-level accelerations (≤ 2 g) and relies upon a three-chip concept: (sensor chip + CMOS processing chip + bipolar protection IC). Conversion for extended signal evaluation triggers an automatic reset, returning the seismic mass to its base position and supplying the positioning signal as initial value.

For higher acceleration rates (passenger-protection systems), surface-micromechanical sensors with substantially more compact dimensions (typical edge lengths approx. 100 µm) are already in use. An additive process is employed to construct the spring-mass system on the surface of the silicon wafer.

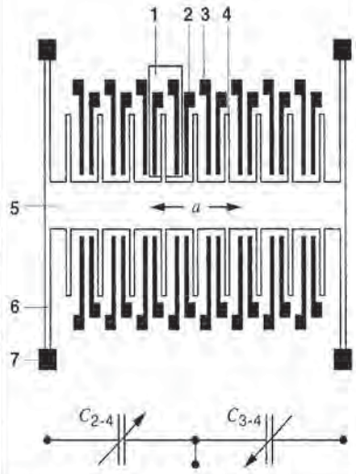
In contrast to the bulk silicon sensors with capacitance levels of 10...20 pF, these sensors only have a typical capacitance of 1 pF. The electronic evaluating circuitry is therefore installed on a single chip along with the sensor (usually position-controlled systems).

Pressure sensors

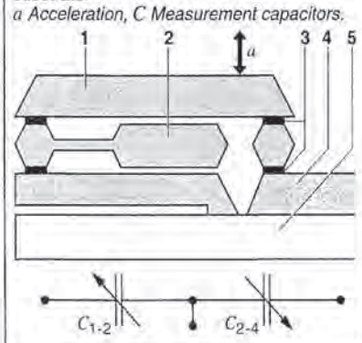
Pressure measurement is direct, by means of diaphragm deflection or force sensor. Typical applications:

- intake-manifold pressure (1...5 bar),
- braking pressure (10 bar), electropneumatic brakes,
- air-spring pressure (16 bar), for vehicles with pneumatic suspension,
- tire pressure (5 bar absolute), for monitoring and/or adjusting tire pressure,
- hydraulic reservoir pressure (approx. 200 bar), ABS, power steering,
- shock-absorber pressure (+ 200 bar), chassis and suspension-control systems,
- refrigerant pressure (35 bar), air-conditioning systems,
- modulator pressure (35 bar), automatic transmissions,
- brake pressure in master- and wheel-brake cylinders (200 bar), automatic yaw-moment compensation, electronically controlled brake,
- positive/vacuum pressure in fuel tank (0.5 bar) for on-board diagnostics (OBD),
- combustion-chamber pressure (100 bar, dynamic) for ignition miss and knock detection,
- diesel pumping-element pressure (1000 bar, dynamic), electronic diesel injection,
- common-rail pressure (1500 to 1800 bar), diesel engines, and
- common-rail pressure (100 bar) for spark-ignition (gasoline) engines.

Micromechanical-surface acceleration sensor
1 Elementary cell, 2, 3 Fixed wafers, 4 Movable wafers, 5 Seismic mass, 6 Spring shoulder, 7 Anchor. a Acceleration, C Measurement capacitors.



Bulk silicon acceleration sensor
1 Si upper wafer, 2 Si center wafer (seismic mass), 3 Si oxide, 4 Si lower wafer, 5 Glass substrate. a Acceleration, C Measurement capacitors.

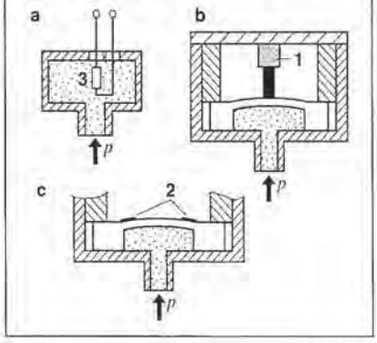


Thick-film pressure sensors

The measurement diaphragm and its strain-gauge resistors (DMS) both use thick-film technology to measure absolute pressures of up to approx. 20 bar with a K factor (relative variation in resistance/expansion) of K = 12...15.

When the respective coefficients of expansion for the ceramic substrate and the ceramic cover film are correct, the diaphragm will form a dome-shaped bubble

Pressure measurement
a) Direct, pressure-sensitive resistor (3), b) with force sensor (1), c) via diaphragm deformation/DMS (2). p Pressure.



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upon cooling after being bonded-on during manufacture. The result is a hollow chamber ("bubble") approx. 100 µm in height, with a diameter of 3...5 mm. After the application of additional thick-film strain-gauge resistors, the unit is hermetically sealed with another ceramic glass coating. The residual gas remaining in the "bubble" provides partial compensation for temperature changes in the sensor.

The signal-amplification and correction components are separate from the measurement medium, but are located directly adjacent to the sensor on the same substrate.

The "bubble sensor" principle is not suitable for extremely high or low pressures; versions for these applications generally incorporate flat ceramic diaphragms.

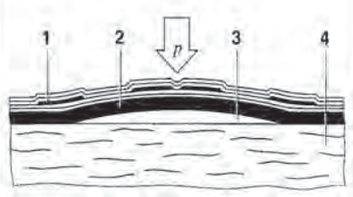
Semiconductor pressure sensors

The pressure is exerted against a Si diaphragm incorporating pressure-sensitive resistors, manufactured using micromechanics technology. The K factor of the resistors diffused into the monocrystalline silicon is especially high, typically K = 100. Up to now the sensor and the hybrid circuitry for signal processing have been located together in a single housing. Sensor calibration and compensation can be continuous or in stages, and are performed either on an ancillary hybrid chip (a second Si chip providing signal amplification and correction) or on the same sensor chip. Recent developments have seen values, e.g. for zero and lead correction, being stored in digital form in a PROM.

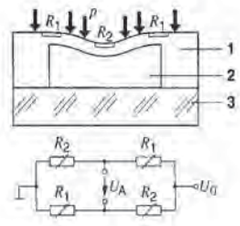
Integrated single-chip sensors with fully electronic calibration are suitable for use as load sensors for electronic ignition and fuel-injection systems. Due to their extremely compact dimensions, they are suitable for the functionally more favorable installation directly on the intake manifold (earlier designs were mounted either in the relevant ECU or at a convenient location in the engine compartment). Frequently applied are reverse assembly techniques in which the measured pressure is conducted to an electronically passive cavity recessed into the side of the sensor chip. For maximum protection, the – much more sensitive – side of the chip with the printed circuits and contacts is enclosed in a reference-vacuum chamber located between the housing's base and the soldered metal cap.

These sensors will also be available for application in tire-pressure monitoring systems. Measurement will be continuous and non-contacting (transformer concept). A virtually identical sensor chip can also be used as a combustion-chamber pressure sensor. This is provided that the Si chip is not directly exposed to high temperatures (max. 600 °C). A metallic insulation diaphragm and a soldered transfer rod of adequate length (several mm) furnish the desired protection. Micromechanical techniques are employed to apply a miniature pedestal to the center of the diaphragm, effectively converting the unit to a force sensor. The rod transmits

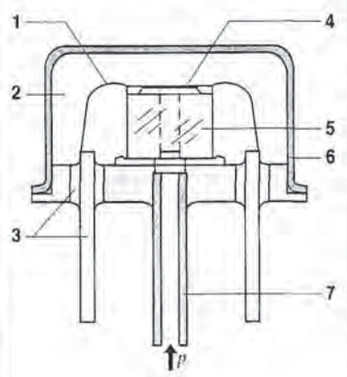
Thick-film pressure sensor
1 Piezoresistive measurement bridge, 2 Thick-film diaphragm, 3 Reference-pressure chamber ("bubble"), 4 Ceramic substrate. p Pressure.



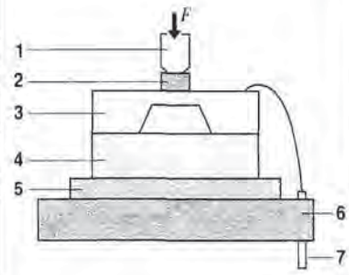
Semiconductor pressure sensor
1 Silicon, 2 Vacuum, 3 Glass (Pyrex). p Pressure, U_0 Supply voltage, U_A Measurement voltage, strain-gauge resistors R_1 (expanded) and R_2 (deflected) in bridge circuit.



Integrated silicon manifold-pressure sensor
1 Bonded connections, 2 Reference vacuum, 3 Glass-enclosed electrical connection path, 4 Sensor chip, 5 Glass pedestal, 6 Cap, 7 Pressure connection. p Pressure.



Integrated silicon combustion-pressure sensor
1 Force-transfer rod, 2 Si pedestal (force input), 3 Integral Si pressure sensor, 4 Pyrex, 5 Ceramic auxiliary subplate, 6 Steel baseplate, 7 Connection pins. F Combustion-chamber pressure force.



the forces registered at the front diaphragm through the pedestal and into the sensor chip with a minimum of distortion. This remote installation position means that the chip is only subjected to operating temperatures below 150 °C.

New sensor concepts

Piezoelectric sensors

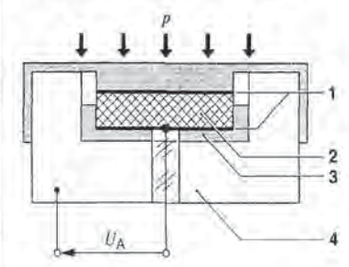
Piezoelectric sensors provide dynamic pressure measurement. On electronically controlled diesel fuel-injection pumps, for determining port opening and port closing (end of pump delivery and start of pump delivery respectively) only changes of pumping-element pressure are registered by the sensor. A thin intermediate diaphragm is employed for direct or indirect pressure transmission to a cylindrical or rectangular piezo-ceramic pellet. Because extreme precision is not required in this application, deviations resulting from hysteresis, temperature and aging are not a major consideration. An amplifier featuring a high-resistance input circuit is frequently installed in the sealed housing. This unit decouples the signal locally to prevent shunts from producing measurement errors.

High-pressure sensors with metal diaphragm

Sensors are also required to monitor extremely high pressures, e.g., in the common rails of diesel injection systems to provide data for closed-loop control. Here, diaphragms made of high-quality spring steel and featuring a DMS pick-up furnish much better performance than systems designed to monitor manifold pressure. These units

- use uncomplicated and inexpensive designs to insulate the measured medium

Piezoelectric pressure sensor
1 Metallic coating, 2 Piezoelectric disk, 3 Insulation, 4 Housing. p Pressure, U_A Measurement voltage.



- differ from silicon in retaining a yield range for enhanced burst resistance, and
- are easy to install in metallic housings.

Insulated sputtered (vacuum-evaporation application) metallic thin-film DMS (K = 2) and also poly-Si DMS (K = 40) units offer permanently high sensor accuracy. Amplification, calibration and compensation elements can be combined in a single ASIC, which is then integrated together with the required EMC protection on a small carrier in the sensor housing.

Force/torque sensors

Applications: Bearing-pin sensors on tractors in systems for controlling plow force.

Magnetoelastic bearing-pin sensors

The bearing-pin sensors are based on the magnetoelastic principle. The hollow coupling pin contains a magnetic field coil. Positioned at a 90° angle to this is a measuring coil to which no magnetic flux is applied when no forces are present. However, when the ferromagnetic material in the pin becomes anisotropic under force, a flux proportional to the force permeates the measuring coil, where it induces electrical voltage. The supply and amplification electronics integrated in a chip are likewise located inside the pin.

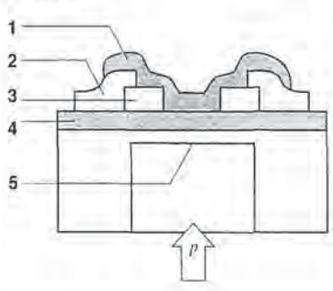
New sensor concepts

- Eddy-current principle: eddy-current torsional-force sensor, radial and axial torsion-measurement spring, radial and axial slotted-disk and coil configuration.
- Measurement with strain-gauge resistors (DMS principle): pressed-in and welded-in sensors, pressed-in elements.
- Magnetoelastic force sensor.
- Force-measurement ring using thick-film technology: force measurement with orthogonally loaded pressure-sensitive resistors.
- Hydrostatic pressure measurement in plunger-loaded hydrostatic cylinders, generally charged with rubber or gum elastic (no leakage risk).
- Microbending effect: fiber-optic compressive-stress sensor.

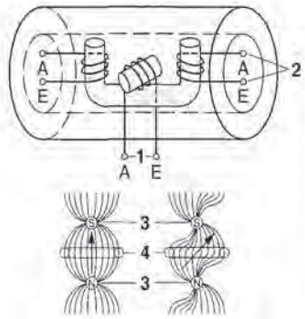
New applications:

- Measuring coupling forces on commercial vehicles between towing vehicle and trailer/semitrailer for controlled, force-free braking.
- Measuring damping forces for electronic chassis and suspension-control systems.
- Measuring axle load for electronically-controlled braking-force distribution on heavy commercial vehicles.
- Measurement of pedal force on electronically-controlled braking systems.

High-pressure sensor with metallic diaphragm (measurement element, nos. 1...4, dimensions exaggerated)
1 SiNx passivation, 2 Gold contact, 3 Poly-Si DMS, 4 SiO_2 insulation, 5 Steel diaphragm. p Pressure.



Magnetoelastic bearing-pin sensors
1 Primary winding (feed), 2 Secondary winding (measurement signal), 3 Primary pole surface, 4 Secondary pole surface.



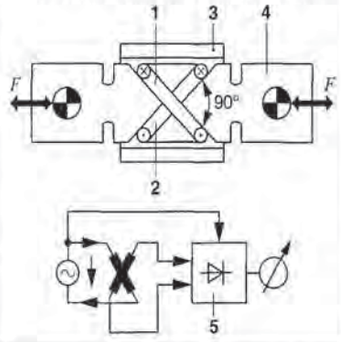
- Measurement of braking force in electrically actuated and electronically controlled braking systems.
- Non-contact measurement of drive and braking torque.
- Non-contact measurement of steering/power-steering torque.
- Finger-protection for electric power windows and sunroofs.

In the case of the cross-ductor principle used in magnetoelastic tension/compressive-force sensors, no voltage is induced in the secondary transformer coil on account of the right-angled offset in the rest state ($F = 0$). A voltage is only established in the coil when under the application of force the relative permeability of the magnetoelastic sensor material used (special steel) becomes anisotropic. This sensor principle can also be applied for higher operating temperatures (up to 300 °C) (e.g. for installation in proximity to the brakes).

Torque measurement:
There are essentially two different ways of measuring torque: angle- and stress-measuring methods. In contrast to stress-measuring methods (DMS, magnetoelastic), angle-measuring methods (e.g. eddy current) require a particular length of torsion shaft over which the torsion angle (approx. 0.4...4 °) can be picked off. The mechanical stress proportional to the torque σ is directed at an angle of under 45° to the shaft axis.

Stress-measuring torque sensor:
The mechanical stress is measured with a strain-gauge bridge. The bridge is powered via a transformer and the supply is air-gap-independent due to rectifier and control electronics accommodated on the shaft. Further local electronic components on the shaft enable the measurement signal to be amplified and converted into an air-gap-invariant alternating-current waveform (e.g. analogous to frequency) which is likewise decoupled by a transformer. For larger quantities, the required electronics can be integrated on the shaft in a single chip. The strain-gauge resistors can be inexpensively accommodated on a premanufactured round steel

Magnetoelastic compression-tension force sensor according to cross-ductor principle
1 Supply coil, 2 Measuring coil, 3 Magnetic yoke, 4 Magnetoelastic force-sensing element, 5 Phase-selective rectifier. F Force.



Basic principles of torque measurement
1 Torsion bar. ϕ Torsion angle, σ Torsional stress, M Torque, r Radius, l Rod length.

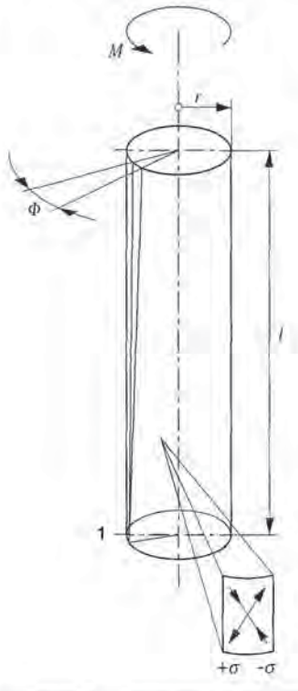


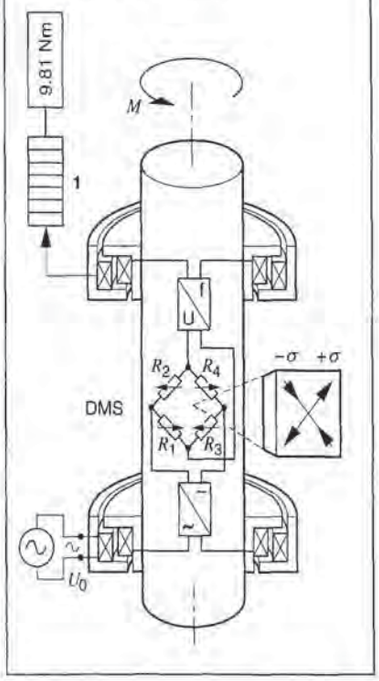
plate (e.g. in thin-film form, P. 87) and then welded with the round plate onto the shaft. High precision levels can be achieved with such a configuration in spite of reasonable manufacturing costs.

Angle-measuring torque sensor:
Concentrically engaged slot sleeves are flanged at each end over a sufficient length of the measurement shaft. The sleeves have two rows of slots which are arranged in such a way that, when the shaft is subjected to torsion, an increasingly larger view of the shaft is exposed in the one row while the view is increasingly blocked off in the other row. Two fixed high-frequency coils (approx. 1 MHz) arranged over each row are thus increasingly or decreasingly damped or varied in terms of their inductance value. In order to achieve sufficient precision, it is essential for the slot sleeves to be manufactured and mounted to exacting standards. The associated electronics are appropriately accommodated very near to the coils.

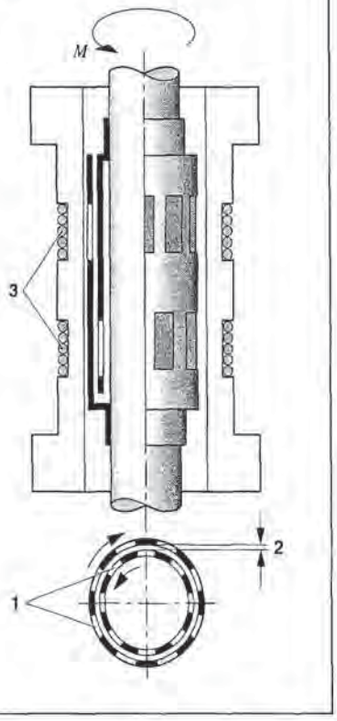
Flow meters
Flow quantities in automotive applications:
- Fuel flow rate, i.e., amount of fuel actually consumed by the engine, is based on the difference between forward and return flow rates.

On spark-ignition engines featuring electronically-controlled fuel-metering systems using air intake as a primary control parameter, this figure is already available in the form of a calculated metering value; thus measurement for control of the combustion process is redundant. However, fuel-flow measurement is re-

Strain-gauge torque sensor with non-contact, transformer pick-off
1 Torque indicator.
σ Torsional stress, U_0 Supply voltage, R_1...R_4 Strain-gauge resistors.



Eddy-current torque sensor
1 Slot sleeves, 2 Air gap, 3 High-frequency coils.



quired to determine and display fuel consumption on engines not equipped with electronic control systems.

– Air flow in the engine's intake manifold: The mass relationships are the salient factors in the chemical process of combustion, thus the actual objective is to measure the mass flow of the intake or charge air, although procedures employing volume and dynamic pressure are also applied.

The maximum air-mass flow to be monitored lies within a range of 400...1000 kg/h, depending upon engine output. As a result of the modest idle requirements of modern engines, the ratio between minimum and maximum air flow is 1:90...1:100.

Flow measurement

A medium of uniform density ϱ at all points flows through a tube with a constant cross-section A at a velocity which is virtually uniform in the tube cross-section ("turbulent" flow):

– Volume flow rate $Q_V = v \cdot A$ and
– Mass flow rate $Q_M = \varrho \cdot v \cdot A$

If an orifice plate is then installed in the duct, forming a restriction, this will result in a pressure differential Δp in accordance with Bernoulli's Law. This differential is an intermediate quantity between the volume and mass flow rates:

$\Delta p = const \cdot \varrho \cdot v^2 = const \cdot Q_V \cdot Q_M$

Fixed-position orifice plates can only cover measurement variables within a range of 1:10; variable flaps are able to monitor variations through a substantially greater ratio range.

Volume flow sensors

According to the principle of the Karman vortex path, whirls and eddies diverge from the air stream at a constant distance behind an obstruction. Their periodicity as measured (e.g., monitoring of pressure or acoustic waves) at their periphery (duct wall) provides an eddy frequency in the form of a signal ratio:

$f = 1/T = \text{const} \cdot Q_V$.

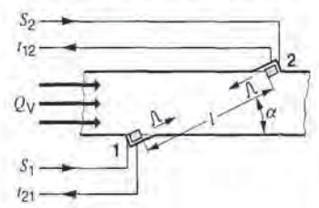
Disadvantage: Pulsation in the flow can result in measuring errors.

The ultrasonic flow-measurement procedure can be employed to monitor the propagation time t of an acoustic pulse as it travels through the medium to be measured (e.g. air) at angle α (see Fig.). One measurement is taken upstream and one downstream using the same measurement path l. The resulting transit-time differential is proportional to the volumetric flow rate.

Pitot-tube air-flow sensors

Pivoting, variable-position pressure flaps leave a variable section of the flow diameter unobstructed, with the size of the free diameter being dependent upon the flow rate. A potentiometer monitors the characteristic flap positions for the respective flow rates. The physical and electrical design of the air-flow sensor, e.g., for

Ultrasonic flow measurement
1, 2 Transmitter/receiver 1 and 2, l Measurement path, S Transmit command, t Transit period, Q_V Volume flow, α Angle.



L-Jetronic (P. 471), is such as to ensure a logarithmic relationship between flow rate and output signal (at very low flow rates the incremental voltage variations referred to the flow-rate variation are substantially greater than at high flow rates). Other types of automotive air-flow sensors are designed for a linear characteristic (KE-Jetronic, P. 469). Measuring errors can occur in cases where the flap's mechanical inertia prevents it from keeping pace with a rapidly pulsating air current (full-load condition at high engine speeds).

Air-mass meters

Air-mass meters operate according to the hot-wire or hot-film principle; the unit contains no moving mechanical parts. The

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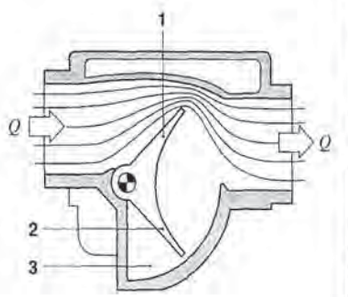
closed-loop control circuit in the meter's housing maintains a constant temperature differential between a fine platinum wire or thin-film resistor and the passing air stream. The current required for heating provides an extremely precise – albeit non-linear – index of mass air flow. The system's ECU generally converts the signals into linear form as well as assuming other signal-processing duties. Due to its closed-loop design, this type of air-mass meter can monitor flow rate variations in the millisecond range. However, the sensor's inability to recognize flow direction can produce substantial measuring errors when strong pulsation occurs in the manifold.

The platinum wire in the hot-wire air-mass meter functions both as the heating element and as the heating element's temperature sensor. To ensure stable and reliable performance throughout an extended service life, the system must burn-off all accumulated deposits from the hot-wire's surface (at approx. 1000 °C) after each phase of active operation (when the ignition is switched off).

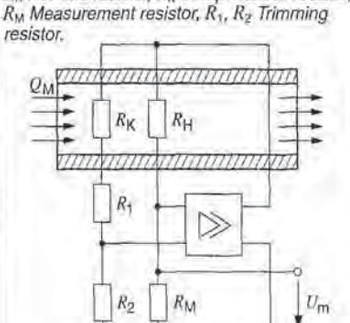
The hot-film air-mass meter combines all measuring elements and the control electronics on a single substrate. In current versions, the heating resistor is located on the back of the base wafer, with the corresponding temperature sensor on the front. This results in somewhat greater response lag than that associated with the hot-wire meter. The temperature-compensation sensor (R_K) and the heating element are thermally decoupled by means of a laser cut in the ceramic substrate. More favorable flow characteristics make it possible to dispense with the hot-wire meter's burn-off decontamination process.

Extremely compact micromechanical hot-film air-mass meters also operate according to thermal principles. Here the heating and measuring resistors are in the form of thin platinum layers sputtered onto the base Si chip. Thermal decoupling from the mounting is obtained by installing the Si chip in the area of the heater resistor H on a micromechanically thinned section of the base (similar to a pressure-sensor diaphragm). The adjacent heater-temperature sensor S_H and the air-temperature sensor S_L (on the thick edge of the Si chip) maintain the heater resistor H at a constant overtemperature. This method differs from earlier techniques in dispensing with the heating current as an output signal. Instead, the signal is derived from the temperature differential in the medium (air) as monitored at the sensors S_1 and S_2. Temperature sensors are located in the flow path upstream and downstream from the heater resistor H. Although (as with the earlier process) the response pattern remains nonlinear, the fact that the resulting signal also indicates the flow direction represents an improvement over the former method using the heating current.

Pitot-tube air-flow sensor
1 Pressure flap, 2 Compensation flap, 3 Compression volume. Q Flow.

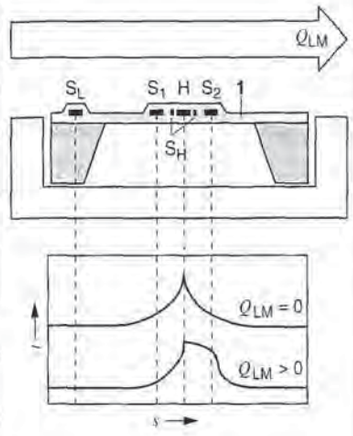


Hot-wire air-mass meter
Q_M Mass flow, U_m Measurement voltage, R_H Hot-wire resistor, R_K Compensation resistor, R_M Measurement resistor, R_1, R_2 Trimming resistor.

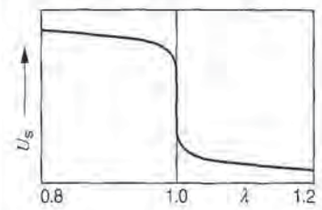


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Micromechanical hot-film air-mass meter
1 Dielectric diaphragm, H Heating resistor, S_H Heater-temperature sensor, S_L Air-temperature sensor, S_1, S_2 Temperature sensors (upstream and downstream), Q_{LM} Mass air flow, s Measurement point, t Temperature.



O_2 sensor response curve
λ Excess-air factor, U_S Sensor voltage.



Concentration sensors

Virtually all chemical concentration sensors run the risk of being poisoned during the necessary direct contact with the measured medium, i.e. irreversibly damaged by harmful foreign substances. For instance, electrolytic oxygen-concentration sensors (lambda oxygen sensors) can be rendered useless by lead that may be present in the fuel or exhaust gas.

Oxygen-concentration sensor (lambda oxygen sensor)

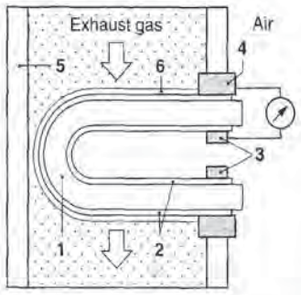
The fuel-metering system employs the exhaust-gas residual-oxygen content as measured by the lambda sensor to very precisely regulate the air-fuel mixture for combustion to the value λ (lambda) = 1 (stoichiometric combustion, P. 458).

The sensor is a solid-state electrolyte made of ZrO ceramic material. At high temperatures, this electrolyte becomes conductive and generates a characteristic galvanic charge at the sensor connections; this voltage is an index of the gas' oxygen content. The maximum variation occurs at λ = 1.

Electrically-heated sensors are especially well-suited for measurements in the lean range, and already come into operation in the warm-up phase.

For the wide lean range, flat and smaller "wafer sensors" of multilayer ceramic design (wide-band lambda sensors) are used; these sensors can also be used in diesel engines. A sensor of this type is essentially a combination of a conventional concentration sensor which acts as a galvanic cell (Nernst sensor) and a limit-current or "pump" cell. A voltage is applied from an external source to the pump cell, which is of the same design as a conventional concentration cell. If the voltage is high enough, a "limit current" sets in which is proportional to the difference in oxygen concentration at both ends of the sensor. Oxygen atoms are transported – depending on the po-

O_2 sensor in exhaust pipe
1 Ceramic sensor, 2 Electrodes, 3 Contact, 4 Housing contacts, 5 Exhaust pipe, 6 Protective ceramic coating (porous).



larity – with the current. An electronic control circuit causes the pump cell to supply the concentration sensor permanently through a very narrow diffusion gap with precisely enough oxygen to maintain a status of $\lambda = 1$ at the sensor. I.e. oxygen is pumped away in the event of excess air in the exhaust gas (lean range); in the event of a low residual-oxygen content in the exhaust gas (rich range), oxygen is pumped in by reversing the pump voltage. The relevant pump current forms the output signal.

Humidity sensors:
Areas of application:
- Monitoring of air drier for pneumatic brakes,
- Monitoring of outside air humidity for slippery-ice warnings,
- Calculation of dew point in vehicle interior (air-quality sensing, climate control, misting over of vehicle windows).

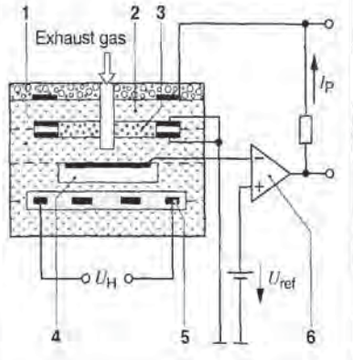
Capacitive sensors are mostly used to determine relative humidity. A sensor of this type is composed of a thin-film polymer with a metal coating on both sides. The capacitance of this capacitor is considerably but reversibly modified by the adsorption of water. The time constant is typically approx. 30 s. The dew point can also be determined by additionally measuring the air temperature (NTC).

When installed e.g. in an air-quality ECU, a Teflon diaphragm protects the sensor against harmful substances. Generally speaking, the air-quality ECU also contains above all CO and NO_X sensors, mostly in the form of thick-film resistors (SnO_x), which modify their electrical resistance in a wide range (e.g. 1...100 kohm) by adsorption of the measured media.

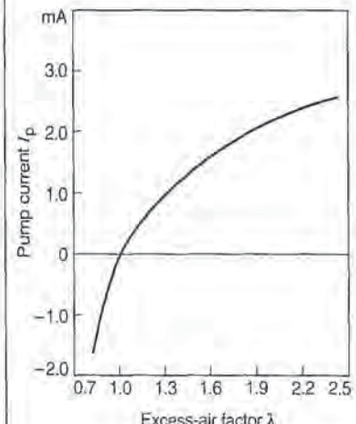
Temperature sensors

Temperature measurements in motor vehicles are conducted almost entirely by exploiting the sensitivity to temperature variation found in electrical resistance materials with a positive (PTC) or negative (NTC) temperature coefficient as contact thermometers. Conversion of the resistance variation into analog voltage is performed predominantly with the aid of supplementary temperature-neutral or inversely-sensitive resistors as voltage dividers (also providing increased linearity). Non-contact (pyrometric) temperature sensing has recently come into consideration for passenger safety (passenger observation for airbag activation) and also for passenger comfort (climate control,

Wide-band O_2 sensor *(structure)*
1 Nernst concentration cell, 2 Oxygen pump cell, 3 Diffusion gap, 4 Reference-air channel, 5 Heater, 6 Control circuit.
I_P Pump current, U_H Heating voltage, U_{ref} Reference voltage.



Sensor signal of wide-band O_2 sensor
(measured current)



prevention of window misting); this has been made economically viable by the introduction of microsystems technology. The following temperatures occur in motor vehicles:

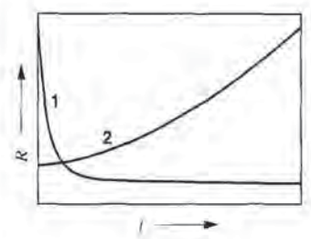
Location	Range	°C
Intake air/charge air	−40 ...	170
Outside atmosphere	−40 ...	60
Passenger compartment	−20 ...	80
Ventilation & heating air	−20 ...	60
Evaporator (AC)	−10 ...	50
Engine coolant	−40 ...	130
Engine oil	−40 ...	170
Battery	−40 ...	100
Fuel	−40 ...	120
Tire air	−40 ...	120
Exhaust gas	100 ...	1000
Brake calipers	−40 ...	2000

At many locations, temperature is also measured in order that it can be compensated for in those cases in which temperature variations trigger faults or act as an undesirable influencing variable.

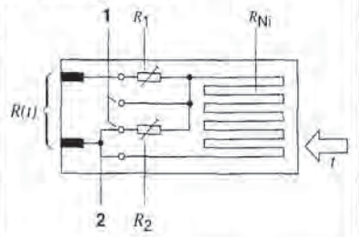
Sintered-ceramic resistors (NTC)
Sintered-ceramic resistors (heat conductors, thermistors) made of heavy-metal oxides and oxidized mixed crystals (sintered in pearl or plate-form) are included among those semiconductive materials which display an inverted exponential response curve. High thermal sensitivity means that applications are restricted to a "window" of approx. 200 K; however, this range can be defined within a latitude of −40 ... approx. 850 °C.

Thin-film metallic resistors (PTC)
Thin-film metallic resistors, integrated on a single substrate wafer together with two supplementary, temperature-neutral trimming resistors, are characterized by extreme precision, as they can be manufactured and then "trimmed" with lasers to maintain exact response-curve tolerances over long periods of time. The use of layer technology makes it possible to adapt the base material (ceramic, glass, plastic foil) and the upper layers (plastic molding or paint, sealed foil, glass and ceramic coatings) to the respective application, and thus provide protection against the monitored medium. Although metallic

Temperature sensors (examples)
1 NTC thermistor, 2 PTC thermistor. t Temperature, R Resistance.



Metallic-film thermistor
1 Auxiliary contacts, 2 Bridge, R_{Ni} Nickel-plated resistor, $R(t)$ Resistance relative to temperature t, R_1, R_2 Temperature-independent trimming resistors.



layers are less sensitive to thermal variations than the ceramic-oxide semiconductor sensors, both linearity and reproducibility are better:

Sensor material	Temperature coefficient TC	Measurement range
Ni	$5.1 \cdot 10^{-3}$/C	−60...320 °C
Cu	$4.1 \cdot 10^{-3}$/C	−50...200 °C
Pt	$3.5 \cdot 10^{-3}$/C	−220...850 °C

With
$TC = [R(100\,°C) - R(0\,°C)] / [R(0\,°C) \cdot 100\,K]$

Thick-film resistors (PTC/NTC)
Thick-film pastes with both high specific resistance (low surface-area requirement) and positive and negative temperature coefficients are generally employed as temperature sensors for compensation purposes. They have non-linear response characteristics (without, however, the extreme variations of the massive NTC re-

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sistor) and can be laser-trimmed. The measurement effect can be enhanced by using NTC and PTC materials to form voltage-divider circuits.

Monocrystalline Si-semiconductor resistors (PTC)

When monocrystalline semiconductor materials such as Si are used to manufacture the temperature sensor, it is possible to integrate additional active and passive circuitry on the sensor chip (allowing initial signal conditioning directly at the measuring point).

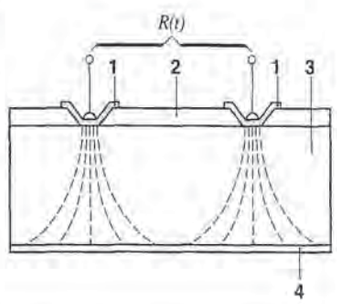
Due to the closer tolerancing which is possible, these are manufactured according to the spreading-resistance principle. The current flows through the measuring resistor and through a surface-point contact before arriving at the Si bulk material. It then proceeds, widely distributed, to a counterelectrode covering the base of the sensor chip. As well as the highly reproducible material constants, the high current density after the contact point (high precision achieved through photolithographic manufacture) almost exclusively determines the sensor's resistance value.

The measurement sensitivity is virtually twice that of the Pt resistor (TC = $7.73 \cdot 10^{-3}$/K). However, the temperature-response curve is less linear than that of a metallic sensor.

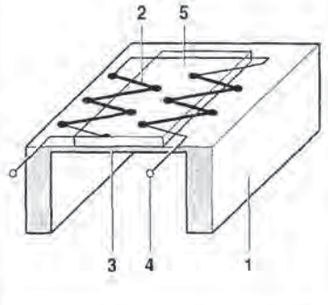
Thermopile sensors

For non-contact measurement of the temperature of a body, the radiation emitted by this body is measured; this radiation is preferably in the infrared (IR) range (wavelength: 5...20 µm). Strictly speaking, the product of the radiated power and the emission coefficient of the body is measured. The latter is material-dependent but mostly close to 1 for materials of technical interest (also for glass). However, for reflective or IR-permeable materials (e.g. air, Si), it is << 1. The measuring point is reproduced on a radiation-sensitive element which thus heats up slightly with respect to its environment (typically 0.01...0.001 °C). This small temperature difference can be effectively measured with thermocouples many of which are connected in succession to increase the measuring effect (thermopile). It is possible to manufacture just such a thermopile sensor at low cost using micromechanical techniques. All the "hot" points are located on a thermally well insulated, thin diaphragm while all the cold points are located on the thicker chip edge (temperature sink). The sensor's settling time is typically approx. 20 ms. A "single-pixel sensor" of this type is ideal for e.g. determining the surface temperature of the windshield so as to prevent it from misting over should the temperature drop below the dew point.

Si semiconductor resistor (spreading-resistance principle)
1 Contacts, 2 Passivation (nitride, oxide), 3 Si substrate, 4 Unconnected counterelectrode. R(t) Temperature-dependent resistor.



Micromechanical thermopile infrared sensor
1 Si chip, 2 Thermocouples connected in series, 3 SiN diaphragm, 4 Thermopile connections, 5 Absorber layer.



If several pixels are arranged on a chip to form an array (e.g. 4 x 4), rough imaging is thus already possible. However, there should not be too much insensitive surface area between the pixels and the pixels themselves must be thermally well insulated against each other. As all the pixels can optionally respond electrically, the chip has a large number of terminals. For a TO5 housing, the ASIC for instance must be located near the sensor to preamplify and serialize the signal. To determine the absolute temperature of the pixels, this ASIC also contains in most cases a reference temperature sensor with which object temperatures can be determined to an accuracy of approx. ±0.5 K.

In order to reproduce a scene thermally on the sensor array, the array requires an IR optical imaging unit. The highly inexpensive arched mirror must mostly be ruled out for reasons of available space. Glass lenses are impervious to IR light and plastic lenses are only adequate for operating temperatures up to approx. 85 °C. Si lenses however are very well suited to heat radiation and can be micromechanically manufactured at low cost as diffraction (Fresnel) or refraction lenses with diameters of up to approx. 4 mm. When inserted into the cover of a TO5 housing, they serve at the same time to protect the sensor against direct damage. Although filling the housing with insert gas increases crosstalk between the pixels somewhat, on the other hand it also reduces their response time.

Sensors for other applications

Dirt sensors

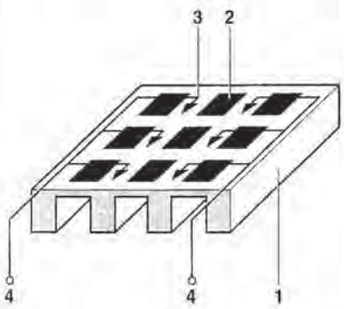
The sensor measures the level of contamination on the headlamp lens to furnish the data required for automatic lens cleaning systems.

The sensor's photoelectric reflected-light barrier consists of a light source (LED) and a light receiver (phototransistor). The source is positioned on the inside of the lens, within the cleansed area, but not directly in the light beam's path. When the lens is clean, or covered with rain droplets, the infrared measurement beam emitted by the unit passes through the lens without being obstructed. Only a minuscule part is reflected back to the light receiver. However, if it encounters dirt particles on the outer surface of the lens, it is reflected back to the receiver at an intensity that is proportional to the degree of contamination and automatically activates the headlamp washer unit once a defined level is reached.

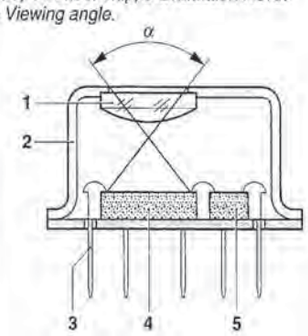
Rain sensors

The rain sensor recognizes rain droplets on the windshield, so that the windshield wipers can be triggered automatically. The unit thus frees the driver to concen-

Micromechanical thermopile array
1 Si chip, 2 Pixel, 3, 4 Pixel connections.



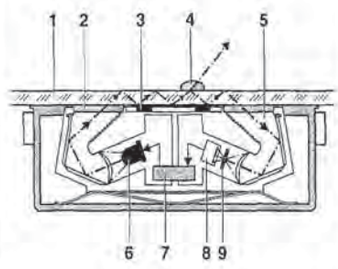
IR imaging sensor
1 Si IR lens, 2 TO5 housing, 3 Connection pins, 4 Sensor chip, 5 Evaluation ASIC. α Viewing angle.



trate on other tasks by making the various control operations used to activate conventional wiper systems redundant. For the time being the driver can still use the manual controls; if desired, the automatic system must be manually selected when the vehicle is started.

The sensor consists of an optical transmission and reception path (similar to the dirt sensor). In this application, the light is directed toward the windshield at an angle. A dry outer surface reflects (total reflection) it back to the receiver, which is also mounted at an angle. When water droplets are present on the outer surface, a substantial amount of the light is refracted outward, thus weakening the return signal. This system also responds to dirt once the activation threshold is exceeded.

Rain sensor
1 Windshield, 2 Optical coupling, 3 Heater, 4 Rain droplets, 5 Light conductor, 6 LED, 7 Electronics, 8 Photodiode, 9 Shield.



Imaging sensors

With imaging sensors, attempts are now being made to reproduce the superior capability of the human eye and the associated mental recognition faculties (albeit at present only to a very modest extent). It is certain that in the foreseeable future the costs of imaging sensors and the high-power processors needed for interpreting a scene will drop to levels that will be viable for automotive applications. In contrast to the human eye, current imaging sensors are also sensitive in the close IR range (wavelength approx. 1 µm). This means that for all the conceivable applications in an automobile, night-time operation becomes possible using invisible IR illumination. Imaging sensors could in future find a variety of uses in motor vehicles for monitoring the passenger compartment (seat position, forward displacement in event of a crash etc.) and the vehicle environment (lateral guidance, collision avoidance, parking and back-up assistance, road-sign recognition etc.).

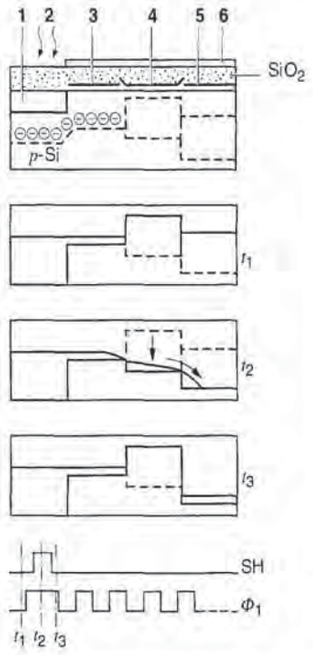
Imaging sensors are a special instance of "multisensor structures" composed of light-sensitive elements (pixels) which are arranged in line or matrix form and receive their light from a conventional optical imaging system. With the Si imaging sensors available today (CCD Charge-Coupled Devices), the incident light through a transparent electrode generates charge carriers in proportion to the intensity and exposure time. These are then collected in a "potential pot" (Si-SiO_2 boundary layer). Using further electrodes, these charges are transferred into an opaque zone and further transported in "analog" shift registers (bucket-brigade principle) in lines into an output register which is serially read out at a higher clock-pulse rate.

While CCD sensors are only of restricted use in motor vehicles on account of their limited light/dark dynamic response (50 dB), their readout time and their temperature range (< 50 °C), newer ("smart") imaging sensors based on CMOS technology are appearing which are fully suitable for automotive applications. The logarithmic brightness/signal characteristic curve possible here corresponds to the human eye and has a dynamic response of 120 dB. This dispenses with the need for e.g. glare control and delivers constant contrast resolution over the entire brightness range. These sensors permit random access to the individual pixels with simultaneously increased sensitivity (higher readout rate). Even the first signal-preprocessing processes are already possible on the imaging-sensor chip.

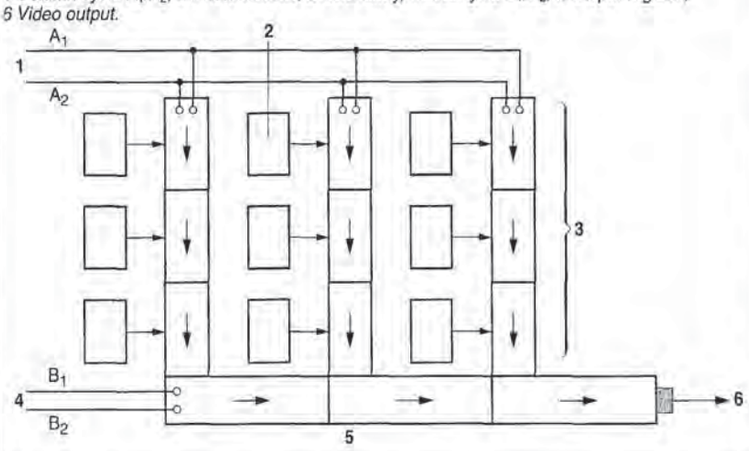
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Future measurement applications:
- Steering-wheel torque sensing (electromotive power steering, "steer-by-wire" system)
- Drive-torque sensing (misfire detection, load signal)
- Passenger safety: AOS (Automotive Occupancy Sensing, Out-of-Position Sensing)
- Measuring wheel forces and friction-coefficient potential
- Fluid sensors
- Sensors for monitoring the vehicle environment (imaging sensors etc.) for autonomous driving and detection of an imminent impact.

CCD principle (charge-coupled devices)
1 Photodiode, 2 Light, 3 Storage electrode, 4 Shift gate, 5 Transfer electrode, 6 Optical cover.



Imaging-sensor structure
1 Column cycle A_1/A_2, 2 Photosensors, 3 CCD array, 4 Line cycle B_1/B_2, 5 Output register, 6 Video output.



Actuators

Quantities and units

Quantity		Unit
A	Pole face; piston surface area	mm^2
B	Magnetic induction or magnetic flux density	T
F	Force	N
I	Electric current	A
l	Length of conductor in field	mm
M	Torque	N · m
p	Pressure	Pa
Q	Volume rate of flow	l/min
Q_{Heat}	Heat flow	W
s	Distance, piston travel	mm
V	Volume	mm^3
V_{th}	Displaced volume per rotation	mm^3
α	Angle between current flow direction and magnetic lines of force	°
δ	Air-gap length	mm
μ_0	Permeability constant	
φ	Rotation angle	°

Actuators (final-control elements) form the junction between the electronic signal processor (data processing) and the actual process (mechanical motion). They convert the low-power signals conveying the positioning information into operating signals of an energy level adequate for process control. Signal converters are combined with amplifier elements to exploit the physical transformation principles governing the interrelationships between various forms of energy (electrical – mechanical – fluid – thermal).

Transistor actuator: Element with electronic circuitry for processing control signals. Includes auxiliary energy input and energy output stages.

Servo component: As above, but with the ability to process nonelectrical control signals. Transistor actuator + servo component = Final-control element.

Converter: Control component without control-signal processing, receives and transfers energy.

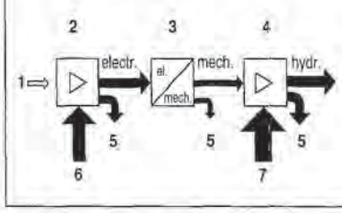
Actuator: Control chain comprising servo component and converter.
The term actuator is also employed as a general-purpose designation for servo components without converters on their own.

Electromechanical actuators

This type of energy conversion represents one option for classifying electromechanical actuators. The energy emanating from the source is transformed into magnetic or electrical field energy, or converted to thermal energy. The individual force-generation principle is determined by these forms of energy, and bases upon either field forces or certain specific material characteristics. Magnetostrictive materials make it possible to design actuators for application in the micropositioning range. This category also includes piezoelectric actuators, which are built according to a multilayer design similar to ceramic capacitors and are potential actuators for fast-acting fuel injectors. Thermal actuators depend exclusively upon the exploitation of characteristics of specific materials.

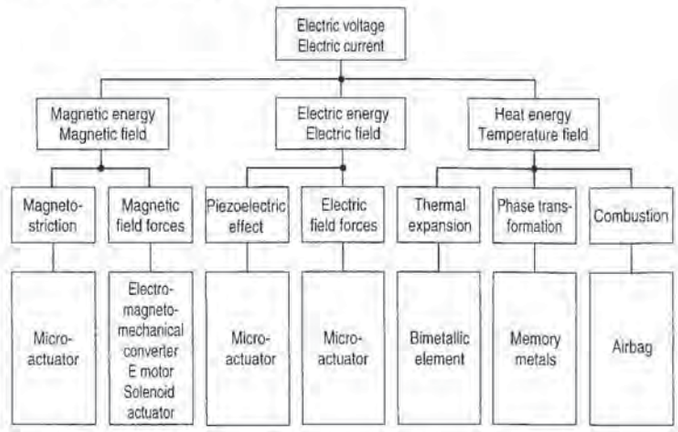
Actuators in a motor vehicle are mostly electro-magneto-mechanical transformers and by extension electrical servomotors (P. 132) and translational and rotational solenoid actuators. An exception is the pyrotechnical airbag system (P. 803). The solenoid actuators can themselves be the servo element, or they can assume a control function by governing a downstream force-amplification device (e.g. mechanical-hydraulic).

Actuator chain
1 Information, 2 Actuator, 3 Transformer, 4 Control element, 5 Losses, 6 External electrical energy, 7 External hydraulic energy.



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Electromechanical actuators (system)



Force generation in the magnetic field

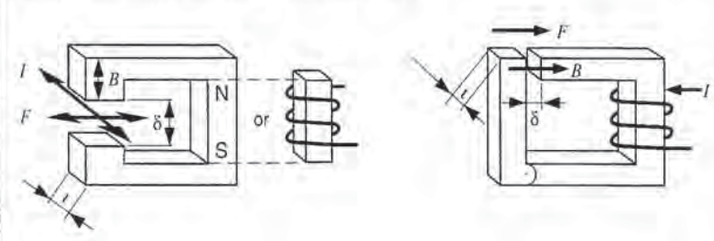
The distinction between the electrodynamic and the electromagnetic actuator principles stems from the manner in which forces are generated in the magnetic field. Common to both principles is the magnetic circuit with soft-magnetic material and the coil for excitation of the magnetic field. A major difference lies in the force which can be extracted from the unit under technically-feasible conditions. Under identical conditions, the force produced through application of the electromagnetic principle is greater by a factor of 40. The electrical time constant for this type of actuator is comparable to the mechanical time constants. Both force-generation principles are applied in linear and rotary drive mechanisms.

Electrodynamic principle

Electrodynamic designs are based on the force exerted on mobile charges or charged conductors within a magnetic field (Lorentz force). An excitation coil or a permanent magnet generates a constant magnetic field. The electrical energy destined for conversion is applied to the moving armature coil (plunger or immersion coil). A high degree of actuator precision is achieved by designing the armature coil with low mass and low inductivity. The two accumulator elements (one on the fixed and one on the moving component) produce two active force directions via current-direction reversal in the armature and excitation coils.

The secondary field produced by the armature current flows in an open mag-

Electrodynamic and electromagnetic transformers



Electrodynamic principle
Force on moving charge $F = B \cdot I \cdot l \cdot \sin \alpha$

Electromagnetic principle
Force between pole faces $F = B^2 \cdot A / 2\mu_0$

netic circuit, thereby diminishing the effects of saturation. Approximately speaking, the force (torque) exerted by an electrodynamic actuator over its setting range is proportional to current and independent of travel.

Electromagnetic principle

The electromagnetic principle exploits the mutual attraction displayed by soft ferrous materials in a magnetic field. The electromagnetic actuator is equipped with only one coil, which generates both the field energy and the energy to be transformed. In accordance with the operating principles, the excitation coil is equipped with an iron core to provide higher inductance. However, as the force is proportional to the square of the density of the magnetic flux, the unit is operative in only one direction. The electromagnetic actuator thus requires a return element (such as a mechanical spring or a magnetic return mechanism).

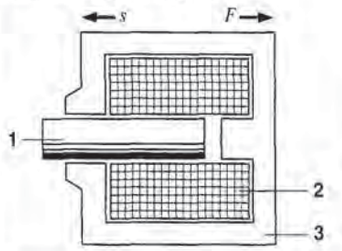
Dynamic response

The dynamic response of an electromechanical actuator, i.e. the activation and deactivation operations, is defined by the equation of mechanical motion, the differential equation of electrical circuits and Maxwell's equations of dynamics. The current- and position-dependent force follows from Maxwell's equations.

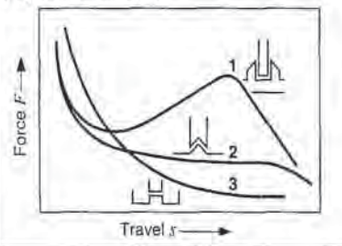
The most basic electrical circuit consists of an inductor with an ohmic resistor. One means of enhancing the dynamic response is through over-excitation at the instant of activation, while deactivation can be accelerated with a Zener diode. In each case, increasing the dynamic response of the electrical circuit involves additional expenditure and increased losses in the actuator's triggering electronics.

Field diffusion is a delay effect which is difficult to influence in actuators with high dynamic response. Rapid switching operations are accompanied by high-frequency field fluctuations in the soft-magnetic material of the actuator's magnetic circuit. These fluctuations, in turn, induce eddy currents, which counteract their cause (build-up and decay of the magnetic field). The resultant delay in the

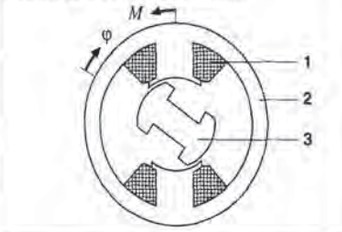
Switching solenoid
1 Armature, 2 Coil, 3 Magnetic yoke.



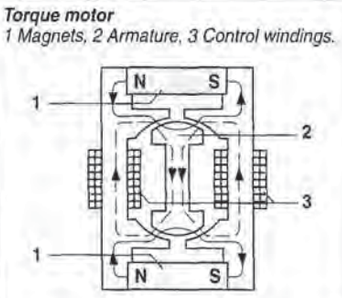
Switching solenoid (characteristic curves)
1 Solenoid plunger, 2 Conical armature, 3 Cylindrical armature.



Electromagnetic single-winding rotary actuator
1 Winding, 2 Stator, 3 Armature.



Torque motor
1 Magnets, 2 Armature, 3 Control windings.



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build-up or reduction of forces can only be reduced by selecting appropriate materials with low electrical conductivity and permeability.

Design

Design selection is essentially determined by operating conditions (e.g., installation space, required force-travel curve and dynamic response).

Electromagnetic actuators

A typical form for translational electromagnetic actuators is the switching solenoid with a force/travel curve which falls as a function of the square of positioning travel. The precise shape of the curve is determined by the type of working gap (e.g., conical or immersion armature).

Rotational electromagnetic actuators are characterized by a defined pole arrangement in stator and rotor. When current is applied to one of the coils, the rotor and stator poles respond with mutual attraction, and in doing so generate a torque.

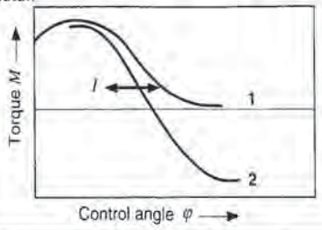
The single-winding rotary actuator incorporates a pair of poles in each of the two main sections, as well as a coil in the stator. Its maximum positioning range is approx. 45°.

The torque motor is a bidirectional electromagnetic rotary actuator featuring a stable working point and without counterforces. The rotor is maintained in a stable position by the excitation field of the permanent magnet in the stator. The magnetic field generated by one or two stator windings produces torque and provides unilateral compensation for the excitation field. This type of layout is suitable for applications in which substantial forces are required over small angles. The relationship between the applied current and the torque motor's force is roughly linear. The torque-motor principle is also employed in translational actuators.

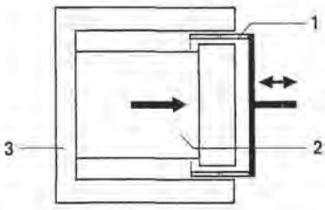
Electrodynamic actuators

In a pot magnet (immersion-coil actuator), a cylindrical immersion coil (armature winding) is set in motion in a working gap.

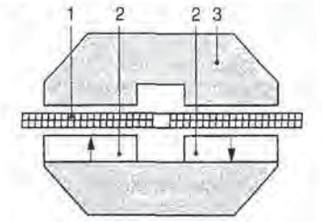
Electromagnetic rotary actuator (characteristic curves)
1 Single-winding rotary actuator, 2 Torque motor.



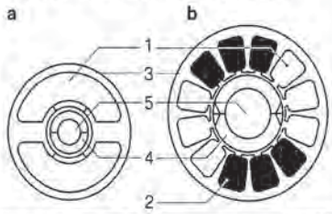
Electrodynamic immersion-coil actuator
1 Immersion coil, 2 Permanent magnet, 3 Magnetic yoke.



Electrodynamic short-stroke linear motor
1 Coil, 2 Permanent magnet, 3 Magnetic yoke.



Electrodynamic rotary actuator
a) Single-winding rotary actuator, b) Dual-winding rotary actuator. 1 Coil 1, 2 Coil 2, 3 Stator, 4 Permanent magnet, 5 Shaft.



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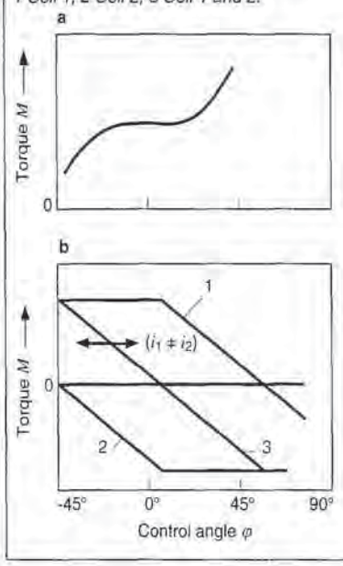
The positioning range is limited by the axial length of the armature winding and by the gap.

The short-stroke linear motor is an actuator with a virtually round disk coil.
A distinction is made between single-winding and dual-winding rotary actuators.

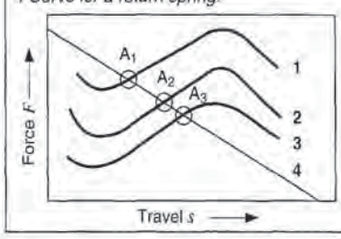
Both types include a permanent magnet within the rotor and one or two stator windings. The rotor magnet is magnetized at both ends to produce magnetic flux in the rotary magnet's working gap, which combines with the armature current to produce a torque. Originating from the position illustrated, the positioning range is less than ±45°. The positioning range of the single-winding rotary actuator also varies according to both the torque requirement and the angle range in which the necessary flux density can be provided.

The dual-winding rotary actuator can be described as a combination of two single-winding rotary actuators with a 90° peripheral offset and designed to produce opposed torque flows. A stable working point is achieved at the zero transition point on the resulting torque curve without auxiliary counteractive forces.

Electrodynamic rotary actuator (characteristic curves)
a) Single-winding rotary actuator, b) Dual-winding rotary actuator. 1 Coil 1, 2 Coil 2, 3 Coil 1 and 2.



Working points (A) of a tractive electromagnet
1, 2, 3 Curves for different currents, 4 Curve for a return spring.



Applications
Electromechanical actuators are direct-action control elements, and without an intermediate ratio-conversion mechanism they convert the energy of the electrical control signal into a mechanical positioning factor/work. Typical applications include positioning of flaps, spools and valves. The described actuators are final-control elements without internal return mechanisms, i.e. without a stable working point. They are only capable of carrying out positioning operations from a stable initial position (working point) when a counterforce is applied (e.g., return spring and electrical control).

A solenoid plunger provides a stable static bias point when its force-travel curve is superimposed upon the characteristic response of a return spring. A variation of the coil current in the solenoid shifts the working point. Simple positioning is achieved by controlling the current. However, particular attention must be paid here to the nonlinearity of the force-current characteristic and the positioning system's sensitivity to interference factors (e.g. mechanical friction, pneumatic and hydraulic forces). The temperature sensitivity of the coil resistance results in positioning errors, making corrective current control necessary. A high-precision positioning system with good dynamic response must incorporate a position sensor and a controller.

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	Hydraulic actuators	Pneumatic actuators
Medium	– Fluid, mostly oil – Supply from tank, oil sump – Virtually incompressible – Self-lubricating – Viscosity heavily temperature-dependent	– Gas, mostly air – Supply from surrounding air – Compressible – Independent lubrication required – Viscosity fluctuations virtually irrelevant
Pressure range	– to approx. 30 MPa (200 MPa for diesel fuel injectors)	– to approx. 1 MPa or greater (approx. 0.05 MPa for vacuum actuators)
Line connections	– Supply and return connection (possible leakage connection)	– Pressure connection only, return directly to environment
Applications	– Positioning applications with high load rigidity, demanding requirements for synchronization and positioning precision in closed-loop control system	– Actuators with lower power requirement, positioning by mechanical stops, in open control loop

Fluid-mechanical actuators

Hydraulic and pneumatic actuators utilize similar principles for the conversion and regulation of energy (see "Automotive hydraulics" P. 816 and "Automotive pneumatics" P. 832). The table shows the differences in characteristics and applications.

In most applications, fluid-mechanical actuator drives are in the form of hydrostatic energy converters. These operate according to the displacement principle, converting the pressure energy of the fluid medium into mechanical work and vice versa.

In contrast, hydrodynamic transformers operate by converting flow energy (kinetic energy of the moving fluid) into mechanical work (example: hydrodynamic coupling, P. 591).

Losses during energy conversion stem from leakage and friction. Fluid-thermal losses are caused by flow resistance, in which throttle action transforms the hydraulic energy into heat. A portion of this heat is dissipated into the environment, and some of it is absorbed and carried away by the fluid medium.

$Q_{Heat} = Q_1 \cdot p_1 - Q_2 \cdot p_2$

With incompressible fluids

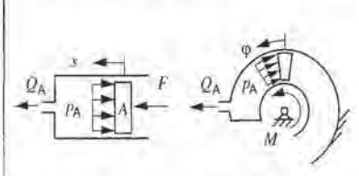
$Q_{Heat} = Q_1 \cdot (p_1 - p_2)$

The flow develops into turbulence at restrictions. The flow rate of the fluid is then largely independent of viscosity. On the other hand, viscosity does play a role in the case of laminar flow in narrow pipes and apertures (see "Automotive hydraulics").

Fluid-mechanical amplifiers control the transition of energy between fluid and mechanical states. The regulating mechanism must be designed for control with only a very small proportion of the energy required for the ultimate positioning operation.

Switching valves open/close the orifice governing the flow to/from a fluid-mechanical energy converter. Provided that the control-element opens suffi-

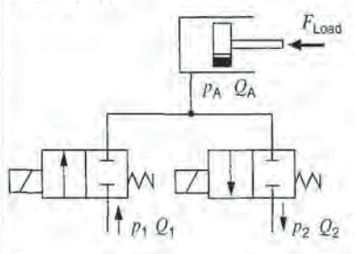
Fluid-mechanical actuators



Linear actuator
$F = p_A \cdot A$
$s = Q_A / A$

Rotary actuator
$M = (p_A \cdot V_{th})/2\pi$
$\varphi = (Q_A / V_{th}) \cdot 2\pi$

Energy regulation with 2/2 directional-control valves



ciently, the throttling losses remain negligible. Pulse-width-modulated opening and closing can be applied to achieve quasicontinuous control of the fluid-mechanical conversion process with virtually no losses. In practice, however, pressure fluctuations and mechanical contact between the valve elements result in undesirable vibration and noise.

Actuator performance data

The table below compares performance data for nine different actuator types.

It contains data based on components with lengths of 50...100 mm and diameters ranging from 20...50 mm.

Comparisons between rotation motors and linear actuators are based on a conversion mechanism consisting of a mechanical spindle with nut (1 mm pitch). Spindle length and motor length are identical.

Expansion
Expansion is the stroke relative to the length of the inner actuator where energy is generated, e.g., piezoelectric-stack length, coil length, internal length of hydraulic cylinder. The effective stroke (70 % of specified spindle length) is assumed as the expansion for rotation motors.

Mechanical stress
Mechanical stress is the lift force relative to the force-generating area, e.g. cross-sectional area of piezoelectric devices, coil gap surface (end face or lateral surface), inner surface of hydraulic cylinder. The peripheral force at the rotor and the rotor lateral surface are used to calculate the shear stress in electric motors.

Velocity
The velocity is defined as the control-stroke travel divided by the control time. On rotating motors, it is the peripheral velocity of the rotor.

Mean control-force density
The mean control-force density is the thermally permissible control force relative to unit volume.

Control-force density per stroke
The control-force density per stroke is the

Performance data

No.	Actuator type	Expansion %	Mechanical stress N/mm²	Velocity m/s	Control-force density per stroke W/cm³	Mean control-force density mW/cm³	Efficiency %
1	Hydraulic cylinder	30	21	0.25	9	3020	92
2	Pneumatic cylinder	76	1	1	3.5	1180	88
3	DC Motor	70	0.007[2])	6[3])	0.8	791	50
4	Ultrasonic motor	70	0.06[2])	0.35[3])	0.13	133	16
5	Piezoeffect actuator	0.09	30	2[4])	15.6	61	7
6	Memory wire	4	50	0.002	0.32	53	0.3
7	Valve solenoid[1])	0.8	2.2	0.5	8	44	5
8	Magnetostriction actuator	0.09	22	1.5	1.6	5.4	5
9	Solenoid 5 % ON	21	0.1	0.16	0.12	4.1	5

[1]) Fuel cooled, [2]) Shear stress in rotor gap/friction gap,
[3]) Rotor peripheral velocity, [4]) Theoretical limit.

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transitional maximum control force for one stroke relative to the unit volume. A spindle (1 mm pitch) with a length equal to the motor length is specified for motors.

Efficiency

The efficiency is the supplied energy divided by the energy transmitted to the actuator, not including losses associated with electronic or other control assemblies. Options for energy recycling (i.e., with piezoelectric actuators) are not considered.

Characteristics

Extremely high performance levels in the areas of expansion, mechanical stress and velocity make hydraulic actuators the preferred design for extended heavy-duty applications.

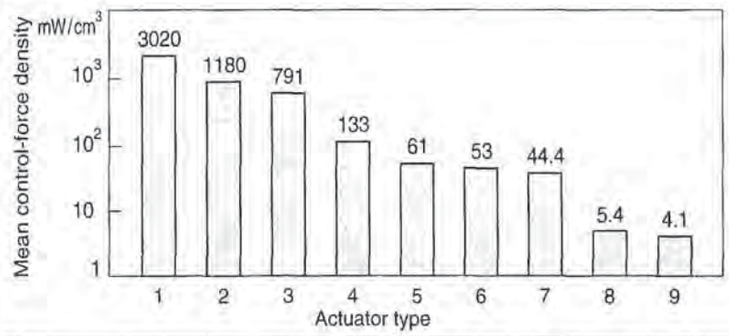
In electric motors, high peripheral velocities compensate for low magnetic-field forces, allowing these motors to provide high levels of force density in continuous operation.

Despite their limited expansion, piezoelectric actuators are capable of generating high force levels and are thus suitable for providing brief bursts of high energy.

Linear solenoids suffer from substantial thermal losses at the coil; with adequate cooling they achieve moderate force-density ratings, comparable to those of solid-body actuators.

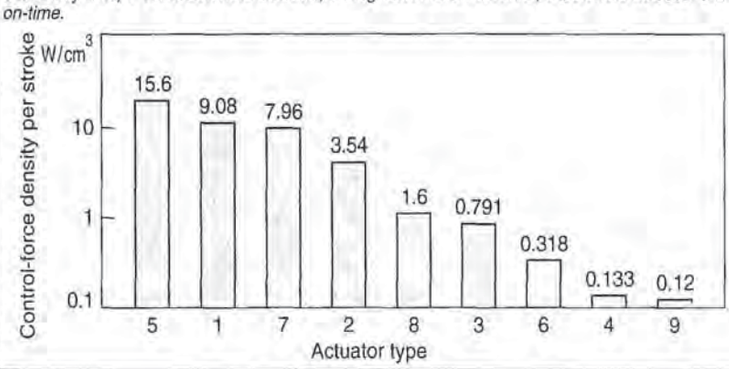
Mean control-force density of selected actuators

1 Hydraulic cylinder, 2 Pneumatic cylinder, 3 DC motor, 4 Ultrasonic motor, 5 Piezoeffect actuator, 6 Memory wire, 7 Valve solenoid actuator, 8 Magnetostriction actuator, 9 Solenoid actuator 5% on-time.



Control-force density per stroke of selected actuators

1 Hydraulic cylinder, 2 Pneumatic cylinder, 3 DC motor, 4 Ultrasonic motor, 5 Piezoeffect actuator, 6 Memory wire, 7 Valve solenoid actuator, 8 Magnetostriction actuator, 9 Solenoid actuator 5% on-time.



Electrical machines

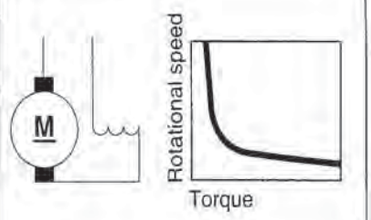
Operating concept

Electrical machines are used to convert electrical and mechanical energy. An electric motor converts electrical energy into mechanical energy, a generator converts energy in the opposite direction. Electrical machines consist of a stationary component (the stator) and a rotating component (the rotor). There are special designs which depart from this configuration such as linear machines which produce linear motion. Permanent magnets or several coils (windings) are used to produce magnetic fields in the stator and rotor which cause torque to develop between these two machine components. Electrical machines have iron stators and rotors in order to control the magnetic fields. Because the magnetic fluxes change over time, stators and rotors must consist of stacks of individual laminations which are insulated with respect to one another. The spatial arrangement of the coils and the type of current used (direct current, alternating current or three-phase current) permit a number of different electrical machine designs. They differ from one another in the way they operate, and therefore have different applications.

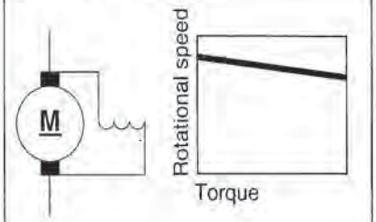
Direct-current machines

The stator of a direct-current machine contains salient poles which are magnetized by the direct-current field windings. In the rotor (here also called the armature), the coils are distributed among slots in the laminated stack and connected to a commutator. Carbon brushes in the stator frame wipe against the commutator as it rotates, thereby transferring direct current to the armature coils. The rotation of the commutator causes a reversal in the direction of current flow in the coils. The different rotational speed vs. torque characteristics result from the method selected for connecting the field winding and armature:

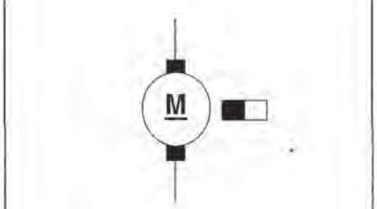
Series-wound machine



Shunt-wound machine



Motor with permanent-magnet excitation



Series connection (series characteristic)
Rotational speed is highly dependent upon load; high starting torque; "racing" of the machine if the load is suddenly removed, therefore load must be rigidly coupled; direction of rotation changed by reversing the direction of current in the armature or field winding; used, among other things, as motor-vehicle drive motor and starter motor for internal-combustion engines.

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Parallel (shunt) connection (shunt characteristic)
Rotational speed remains largely constant regardless of load; direction of rotation is changed by reversing the direction of the current in the armature or field winding; used for instance, as drive motor for machine tools and as direct-current generator. A shunt characteristic can also be obtained by using a separate power supply for the field winding (separate excitation) or by using permanent-magnet excitation in the stator. Applications for permanent-field motors in motor vehicles: starter, wiper, and small-power motors for various drives. If the motor incorporates both series and shunt field windings (compound-wound motor), intermediate levels in the rotational speed/torque characteristic can be obtained; application: e.g. large starters.

All direct-current machines are easily capable of speed control over a wide range. If the machine incorporates a static converter which allows adjustment of the armature voltage, the torque and therefore the rotational speed are infinitely variable. The rotational speed can be further increased by reducing the field current (field weakening) when the rated armature voltage is reached. A disadvantage of direct-current machines is carbon-brush and commutator wear which makes regular maintenance necessary.

Three-phase machines

A three-phase winding is distributed among the stator slots in a three-phase machine. The three phases of current produce a rotating magnetic field. The speed n_0 (in min^{-1}) of this rotating field is calculated as follows:

$$n_0 = 60 \cdot f / p$$

f = frequency (in Hz), p = number of pole pairs.
Three-phase machines are either synchronous or asynchronous, depending upon rotor design.

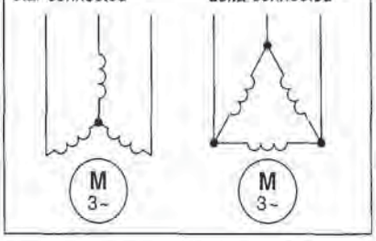
Asynchronous machines
The laminated rotor contains either a three-phase winding, as in the stator, or a bar winding. The three-phase winding is connected to slip rings which are short-circuited either directly or via series resistors. In the case of the bar winding, the bars are connected to one another by two short-circuiting rings (squirrel-cage rotor). As long as the rotational speed of the rotor deviates from n_0, the rotating stator field induces current in the rotor windings, thereby generating torque. Deviation of the rotational speed of the rotor n from n_0 is termed slip s:

$$s = (n_0 - n) / n_0$$

Continuous operation is only economical in the vicinity of n_0 because losses increase as slip increases (nominal slip ≤5%). In this range the asynchronous machine has a shunt characteristic. The machine operates as a motor when $n < n_0$, and as a generator when $n > n_0$. The direction of rotation is changed by reversing two of the phases.

The asynchronous machine is the most frequently used electric motor in the field of drive engineering. With a squirrel-cage rotor it is easy to operate, and requires little maintenance.

Three-phase asynchronous motor with squirrel-cage rotor
Stator winding
star-connected *delta-connected*



Examples of rotating-field speeds

No. of poles ($2p$)	Frequency		
	50 Hz	150 Hz	200 Hz
	Rotating-field speed in min^{-1}		
2	3000	9000	12000
4	1500	4500	6000
6	1000	3000	4000
8	750	2250	3000
10	600	1800	2400
12	500	1500	2000

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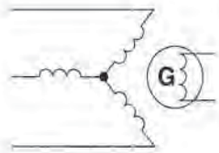
Synchronous machines

In the rotor (here also called the inductor), the poles are magnetized by direct-current coils. The magnetizing current is usually transferred via two slip rings to the rotor. The inductor can be made of solid steel, because the magnetic flux remains constant over time. Constant torque is generated as long as the rotor rotates at a speed of n_0. At other speeds, the torque fluctuates periodically between a positive and a negative maximum value, and excessively high current is produced.

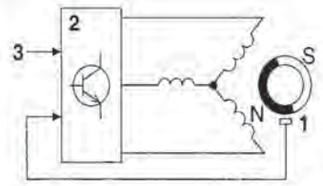
For this reason, a synchronous machine is not self-starting. The synchronous machine also differs from the asynchronous machine in that the reactive power absorption and generation are adjustable. The synchronous machine is most frequently used as a generator in electric power plants. Synchronous motors are used in cases where constant motor speed based on constant line frequency is desired, or where a reactive power demand exists. The automotive three-phase alternator is a special type of synchronous machine.

The rotational speed of all three-phase machines is determined by the stator frequency. Such machines can operate over a wide range of speeds if used in conjunction with static converters which vary the frequency.

Star-connected three-phase synchronous generator
Slip-ring rotor with field winding.



EC motor
1 Electrical machine with rotor-position sensor, 2 Control and power electronics, 3 Input.



EC motors

The "electronically-commutated direct-current" or "EC" motor is becoming increasingly popular. It is essentially a permanent-magnet synchronous machine, and thus dispenses with a slip ring. The EC motor is equipped with a rotor-position sensor, and is connected to the DC power source through its control and power electronics. The electronic transfer circuit switches the current in the stator winding according to rotor position – the magnets which induce the excitation current are attached to the rotor – to provide the interdependence between rotational speed and torque which is normally associated with a separately excited DC machine. The respective magnetic functions of the stator and rotor are the opposite of what they would be in a classical direct-current machine.

The EC motor's potential applications are a result of the advantages which this drive principle provides: Commutator and carbon brushes are replaced by electronic circuitry, dispensing with both brush noise and wear. EC motors are maintenance-free (long service life) and can be constructed to meet high degrees of protection (see below). The electronic control feature makes it easy for drive units with EC motors to incorporate auxiliary functions such as infinitely-variable speed adjustment, direction reversal, gradual starts and lock-up protection.

The main areas of automotive application are in the HVAC (Heating/Ventilation/Air-Conditioning) sectors, and for pumps and servo units. In the area of production machinery, EC motors are chiefly employed as precision drive units for feed-control in machine tools. Here the decisive advantages are freedom from maintenance, favorable dynamic properties and consistent torque output with minimal ripple.

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Single-phase alternating-current machines

Universal motors

The direct-current series-wound motor can be operated on alternating current if a laminated rather than a solid iron stator is used. It is then called a universal motor.

When operated on alternating current, a torque component at twice the frequency of the current is superposed on the constant torque component.

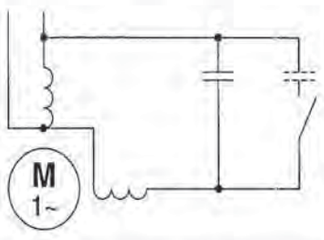
Single-phase asynchronous motors with squirrel-cage rotor

The simplest design of a single-phase asynchronous motor is a three-phase asynchronous machine in which alternating current is supplied to only two stator phases. Although its operation remains largely the same, the power and the maximum torque are reduced. In addition, the single-phase asynchronous machine is not self-starting.

Machines which are intended only for single-phase operation have only a single-phase main winding in the stator, as well as auxiliary starting circuits. The stator also contains an auxiliary winding connected in parallel with the main winding for this purpose. The necessary phase shift of the auxiliary winding current can be achieved through increased winding resistance (low breakaway torque) or by means of a capacitor connected in series with the auxiliary winding (somewhat greater starting torque).

The auxiliary winding is switched off after the motor starts. The direction of rotation of the motor is changed by reversing the two auxiliary or main winding connections. A motor which has a capacitor in series with the auxiliary winding is called a capacitor motor. Capacitor motors with a starting and running capacitor also operate continuously with capacitor and auxiliary winding. Optimum operation for a specific working point can be achieved by correct selection of capacitor. An additional capacitor is often used in order to increase the starting torque; this capacitor is then disconnected after the motor starts.

Two-value capacitor motor



Duty-type ratings for electrical machines

(VDE 0530)

S1: Continuous-running duty

Operation under constant load (rated output) of sufficient duration for thermal equilibrium to be reached.

S2: Short-time duty

Operation under constant load is so brief that thermal equilibrium is not reached. The rest period is so long that the machine is able to cool down to the temperature of the coolant.

Recommended short-time duty periods: 10, 30, 60 and 90 min.

S3 to S5: Intermittent duty

Continuous alternating sequence of load and idle periods. Thermal equilibrium is not reached during the load period or during the cooling period of one duty cycle.
S3 Intermittent duty without influence of starting on temperature.
S4 Intermittent duty with influence of starting on temperature.
S5 Intermittent duty with influence of starting and braking on temperature.

S6: Continuous operation with intermittent loading

Operation with intermittent loading. Continuous alternating sequence of load periods and no-load periods, otherwise as S3.

S7: Uninterrupted duty

Operation with starting and braking.

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S8: Uninterrupted duty
Operation with pole-changing.
For S3 and S6, the duty cycle time is 10 min unless otherwise agreed; and recommended values for cyclic duration factor are 15, 25, 40 and 60 %. For S2, S3 and S6, the operation time or the duty cycle time and the cyclic duration factor are to be specified after the rating; the duty cycle time is only to be specified if it differs from 10 min. Example: S2 – 60 min, S3 – 25 %.

Cyclic duration factor
The cyclic duration factor is the ratio of the loading period, including starting and braking, to the cycle time.

Winding temperature
The mean temperature t_2 of the windings of an electrical machine can be determined by measuring the resistance (R_2) and referring it to an initial resistance R_1 at a temperature t_1:

$$t_2 = \frac{R_2 - R_1}{R_1} (\tau + t_1) + t_1$$

where

$$\tau = \frac{1}{\alpha} - 20\ \text{K}$$

α = Temperature coefficient.

Degrees of protection for electrical machines
(DIN 40 050)

Examples:

Degree of protection IP 00
No protection against accidental contact, no protection against solid bodies, no protection against water.

Degree of protection IP 11
Protection against large-area contact by the hand, protection against large solid bodies, protection against dripping water.

Degree of protection IP 23
Protection against contact by the fingers, protection against medium-size solid bodies, protection against water sprayed vertically and obliquely up to an angle of 60° to the vertical.

Degree of protection IP 44
Protection against contact by tools or the like, protection against small solid bodies, protection against splash water from all directions.

Degree of protection IP 67
Total protection against contact, dustproof, protection against entry of dangerous quantities of water when immersed in water under conditions of defined pressure and for a defined period of time.

Explosion protection Ex
(VDE 0170/0171)

Symbol d:	Explosion-containing enclosure;
Symbol f:	Separate ventilation;
Symbol e:	Increased safety;
Symbol s:	Special protection, e.g. for machines operating in flammable liquids.

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Technical optics

Photometric quantities and units

See P. 18 for names of units

Quantity		Unit
A	Area A_1 Radiating area (surface) A_2 Irradiated area (surface)	m^2
E	Illuminance	lx = lm/m²
I	Luminous intensity	cd
L	Luminance	cd/m²
M	Luminous emittance	lm/m²
P	Power	W
Q	Luminous energy	lm·s
r	Distance	m

Quantity		Unit
t	Time	s
ε_1	Incident angle of radiation (with respect to surface normal)	°
ε_2	Angle of refraction	°
ε_3	Angle of reflection	°
η	Luminous efficiency	lm/W
Φ	Luminous flux	lm
Ω	Solid angle	sr
λ	Wavelength	nm

Electromagnetic radiation

Propagated at speed of light. Wave nature. Not deflected by electric or magnetic fields. Wavelength $\lambda = c/f$, c = light speed ≈ $3 \cdot 10^8$ m/s = 300 000 km/s, f = frequency in Hz.

Designation	Wavelength range	Origin and/or creation	Application examples
Cosmic radiation	< 0.1 pm	Bombardment of Earth's atmosphere by cosmic elementary particles.	Nuclear-physics tests.
Gamma radiation	0.1...10 pm	Radioactive decay.	Nuclear physics, isotope technology.
X-radiation	10 pm...10 nm	X-ray tubes (bombardment of anticathode by high-energy electrons).	Materials tests, medical diagnosis.
Ultraviolet radiation	10...380 nm	Gaseous-discharge lamps, lasers.	Skin therapy, photolithography in IC manufacture.
Visible radiation	380...780 nm	Gaseous-discharge lamps, filament lamps, lasers.	Technical optics, photography, automotive lighting.
Infrared radiation	780 nm...1 mm	Thermal radiators, infrared diodes, lasers.	Therapy, motor-vehicle distance measurement.
EHF waves	1...10 mm	Space-charge-wave tubes, resonant circuits, quartz oscillators.	Satellite communications, microwave heating, traffic radar, television, radio broadcasting, radio.
SHF waves	10...100 mm		
UHF waves	100 mm...1 m		
VHF waves	1...10 m		
HF waves	10...100 m		
MF waves	100 m...1 km		
LF waves	1...10 km		
VLF waves	10...100 km		

Geometrical optics

In many cases, the geometrical dimensions of the media in which optical radiation propagates are large in comparison to the wavelength of the radiation. In such cases, the propagation of radiation can be explained in terms of "light rays", and can be described by simple geometrical laws.

An incident beam of light is split into a refracted beam and a reflected beam at the interface between two media.

The law of refraction applies to the refracted beam:

$$n_1 \cdot \sin \varepsilon_1 = n_2 \cdot \sin \varepsilon_2$$

The indices of refraction n_1 and n_2 of a vacuum and the so-called dielectric media (e.g. air, glass and plastics) are real numbers; for other media they are complex numbers. The indices of refraction of media are a function of the wavelength (dispersion). In most cases, they decrease as the wavelength increases.

The reflected beam behaves according to the following equation:

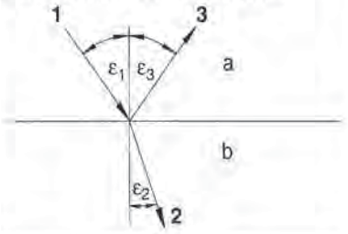
$$\varepsilon_3 = \varepsilon_1$$

The ratio of the intensity of the reflected beam to the intensity of the incident beam (degree of reflection) depends upon the incident angle and the indices of refraction of the adjacent media. In the case of a beam of light passing through air (n_1 = 1.00) into glass (n_2 = 1.52) at an angle of 90° (ε_1 = 0), 4.3% of the energy of the beam is reflected.

If the beam emanates from the optically denser medium ($n_1 > n_2$), total reflection can occur if the angle of incidence ε_1 is equal to or exceeds the limiting angle of total reflection ε_{1max}. According to the law of refraction:

$$\sin \varepsilon_{1max} = n_2/n_1$$

Refraction and reflection
a *Medium 1, Refractive index* n_1, b *Medium 2, Refractive index* n_2. *1 Incident beam, 2 Refracted beam, 3 Reflected beam.*



Indices of refraction n_D (for yellow sodium light, wavelength λ = 589.3 nm).

Medium	n_D
Vacuum, air	1.00
Ice (0 °C)	1.31
Water (+20 °C)	1.33
Silica glass	1.46
Standard glass for optics (BK 7)	1.51673
Window glass, glass used for headlamp lenses	1.52
Polymethyl methacrylate	1.49
Polyvinyl chloride	1.54
Polycarbonate	1.58
Polystyrene	1.59
Epoxy resin	1.60
Gallium arsenide (according to doping level)	approx. 3.5

Components

Cylindrical lenses

Parallel rays are made to converge in a focal line by a cylindrical lens.

Prisms

Prismatic elements are used for the purpose of deflecting a beam of light by a desired angle. Parallel rays remain parallel after deflection by a prism.

In the motor-vehicle headlamp, cylindrical lenses and prismatic elements are used in order to more favorably direct the light emanating from the reflector.

Reflectors

The function of motor-vehicle lamp reflectors is to reflect as much light as possible from the headlamp bulb, to achieve as great a range as possible, and to influence the distribution of light on the road in such a way that the requirements of legislation are met. Additional demands are placed on the headlamps as a result of

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the design (for instance, when fitted into the bumper).

Whereas in the past paraboloids were almost exclusively used as reflectors, the above-mentioned requirements, which are in some cases mutually contradictory, can today only be met by the use of stepped reflectors, free-formed areas or new headlamp designs (PES = Poly-ellipsoid System, see P. 705).

In general, the larger the lens aperture area, the greater the headlamp's range. On the other hand, the greater the solid angle achieved by the reflector, the greater the luminous efficiency.

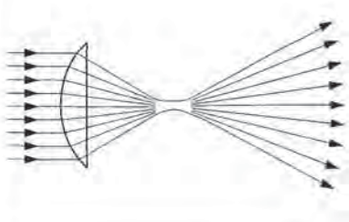
Color filters
Motor-vehicle lamps must meet precise specifications with regard to chromaticity coordinates depending upon their intended functions (turn-signal lamps, stop lamps). These specifications can be met through the use of color filters which weaken the light emitted in certain parts of the visible spectrum.

Light sources

The outer electron shells of atoms of certain materials can absorb varying levels of energy. The transition from higher to lower levels may lead to the emission of electromagnetic wave trains.

The various types of light source can fundamentally be distinguished by the nature of electron excitation (energy supply).

Cylindrical lens element of a headlamp lens



Thermal radiators
In the case of this light source, the energy level is increased by the addition of heat energy. The emission is continuous across a broad wavelength range. The total radiation capacity is proportional to the power of 4 of the absolute temperature (Stephan Boltzmann's Law) and the distribution curve maximum is displaced to shorter wavelengths as the temperature increases (Wien's Displacement Law).

Incandescent lamps
Incandescent lamps, with tungsten glow filament (melting temperature 3660 K), are also thermal radiators. The evaporation of the tungsten and the resulting blackening of the bulb restrict the service life of this type of lamp.

Halogen lamps
The halogen lamp allows the filament temperature to rise to close to the melting point of the tungsten. It has a halogen filler gas (iodine or bromine). Close to the hot bulb wall the evaporated tungsten combines with the filler gas to form tungsten halide. This is gaseous, conductive for light beams and stable in the temperature range 500 K to 1700 K. It reaches the filament by means of convection, decomposes as a result of the high filament temperature, and forms an even tungsten deposit on the filament. In order to maintain this cyclic process, an external bulb temperature of approx. 300 °C is necessary. To achieve this the bulb, made of silica gel, must closely surround the filament. A further advantage of this measure is that higher filling pressure can be used, thereby providing additional resistance to tungsten evaporation. A disadvantage of these lamps is among others their low luminous efficiency.

Gaseous-discharge lamps
Gaseous-discharge lamps are distinguished by their higher luminous efficiency. A gaseous discharge is maintained in an enclosed, gas-filled bulb by applying a voltage between two electrodes. The excitation of the atoms of the emitted gas is effected by collisions between electrons and gas atoms. The atoms excited in the process give off their

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energy in the form of luminous radiation.

Examples of gaseous-discharge lamps are sodium-vapor lamps (street lighting), fluorescent lamps (interior illumination), and motor-vehicle headlamps ("Litronic", P. 744).

Light and the physiology of vision

Because the range of sensitivity to visible radiation varies from person to person, a general brightness sensitivity function has been established for photometric calculations and measurements and is contained, in table form for example, in DIN 5031, Part 3. This function $V(\lambda)$ was determined with test personnel under daylight conditions ("light-adapted eye"), and can be used to calculate unambiguously the photometric values from the objective physical values (see Fig.).

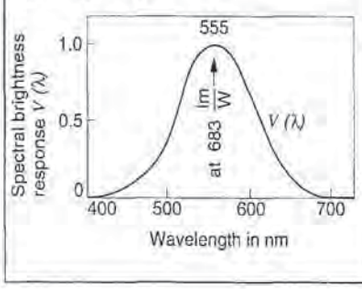
Definition of photometric quantities and units:

Luminous flux Φ
The radiant power emitted by a source of light assessed on the basis of spectral brightness sensitivity.

$$\Phi = K_m \cdot \int P_\lambda \cdot V(\lambda) d\lambda$$

K_m Maximum value of luminous efficacy of radiation for photopic vision $K_m = 683$ lm/W.
$V(\lambda)$ Spectral luminous efficiency for a 2° field of vision according to DIN 5031, Part 3.
P_λ Spectral distribution of radiant energy.

Relative spectral sensitivity $V(\lambda)$ of light-adapted eye



Luminous energy Q
The spectral radiation energy assessed on the basis of $V(\lambda)$. The following equation applies for temporally constant luminous flux:

$$Q = \Phi \cdot t$$

Luminous intensity I
The ratio of luminous flux to a radiation-penetrated solid angle.

$$I = \Phi/\Omega$$

Illuminance E
The ratio of the incident luminous flux to the area of the illuminated surface.

$$E = \Phi/A_2$$

Luminance L
The ratio of the luminous intensity to the apparent (projected) area of the surface from which it is emitted.

$$L = I/(A_1 \cdot \cos\alpha)$$

where α is the angle between the beam direction and the surface normal.

Luminous emittance M
The ratio of the luminous flux emitted by a luminous surface to the area of that surface.

$$M = \Phi/A_1$$

Luminous efficiency η
The ratio of the emitted luminous flux to the power absorbed.

$$\eta = \Phi/P$$

Luminous efficiency can never exceed the maximum value for "luminous efficacy of radiation" $K_m = 683$ lm/W at a wavelength of $\lambda = 555$ nm.

Solid angle Ω
The ratio of the radiation-penetrated portion of the surface of a sphere concentric with the source of radiation to the square of the radius of the sphere. The total solid angle is

$$\Omega = 4\pi \cdot \text{sr} \approx 12.56 \cdot \text{sr}$$

sr Steradian

Contrast
The ratio of the luminance values of two adjacent surfaces.

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Laser technology

Compared to other light sources, the laser has the following characteristic properties:

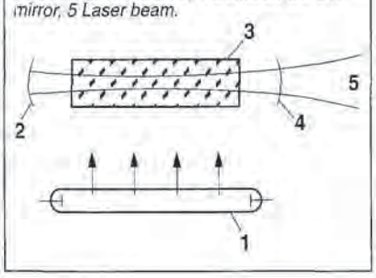
- High luminance, concentration of radiation on a diameter of a few light wavelengths,
- Low beam expansion,
- Monochromatic radiation,
- Can be used for coherent measuring technology (high radiation coherence length),
- High power (in laser tools).

Light generation in the laser is effected by induced emission in a specific laser material, which is brought to a state of excitation by the addition of energy (usually light). A resonator influences the beam geometry as required. The laser radiation emerges at the end of the resonator via a semi-transparent mirror.

Examples of lasers in common use are:

Laser type	Wavelength	Examples of application
Helium-neon laser	633 nm	Measuring technology
CO_2 laser	10.6 µm	Material processing
YAG laser	1064 nm	Material processing
Solid-state laser	e.g. 670 nm e.g. 1300 nm	Measuring technology Telecommunications

Laser principle
1 Pumping light source, 2 Resonator mirror, 3 Laser-active material, 4 Semitransparent mirror, 5 Laser beam.



With laser measuring technology the non-contact, non-interacting testing of production tolerances of precision-machined surfaces (e.g. fuel-injection valves) is possible. With interferometric methods, resolutions in the nm range are achieved. Further laser applications in technology are holography (spatial image information), automatic character recognition (bar-code scanners), information recording (CD scanning), material processing/machining, microsurgery and transmitters for data transfer on optical fibers.

Specific regulations are to be observed when handling laser products. Laser products are classified according to potential hazards. For details, see DIN 0837, "Radiation Safety of Laser Products".

Optical fibers/waveguides

Design

Optical fibers transmit electromagnetic waves in the ultraviolet (UV), visible and infrared (IR) ranges of the spectrum. They are made of quartz, glass or polymers, usually in the form of fibers or in channels created in transparent materials with a core of which the index of refraction is higher than that of the cladding. Thus incident light entering the core zone is retained in that area by means of refraction or total reflection. Depending on the refractive index profile, a distinction is made between three types of fiber (see diagram):

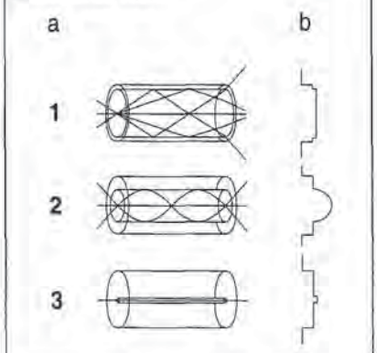
- The step-index optical fiber, with a sharply-defined border between the core and the cladding,
- The graded-index optical fiber, with parabolic refractive index curve form in the core zone,
- The monomode fiber with a very small core diameter.

Step-index and graded-index fibers are multimode fibers, that is, lightwaves can be propagated in them at varying trajectories, generally at an oblique angle to the fiber axis. In the monomode fiber, propagation is only possible in the principal mode.

Polymer fibers are always step-index fibers.

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Light propagation in optical fibers
a Fiber schematic, b Refractive index profile. 1 Step-index fiber, 2 Graded-index fiber, 3 Monomode fiber.



Properties
Glass optical fibers have a high degree of transparency in the range UV to IR. Attenuation is particularly low at the wavelengths 850 nm, 1300 nm and 1550 nm. Synthetic fibers absorb above 850 nm and below 450 nm.

They can only absorb light from a restricted angular range Θ. The numerical aperture NA = SIN (Θ/2) serves as a basis for calculating this range (see table).

The differences in dispersion and propagation time of the various modes cause an increasing widening of light pulses as the length of the fiber increases, and thus restrict the bandwidth.

Optical fibers can be used in the temperature range −40 °C to 135 °C; special versions can be used up to 800 °C.

Areas of application
The main area of application is data transmission. Synthetic fibers are preferred for use in the LAN (Local Area Network) field. Graded-index fibers are the most suitable for medium ranges. Only monomode fibers are used for long-distance data transmission. In fiber-optic networks, optical-fiber structures manufactured according to planar techniques serve as distributors, filters or switches ("integrated optics") and erbium-doped fibers serve as optical amplifiers. Optical fibers are becoming more and more significant in the field of sensor technology. Fiber-optic sensors generate neither stray fields nor sparks, and are themselves non-sensitive to that kind of disturbance. They are currently employed in potentially explosive environments, in medicine and in high-speed trains (ICE).

Energy transport is at the forefront in the area of material processing with laser beams, in microsurgery and in lighting engineering.

Holography

In conventional image recording (photography, video cameras) a three-dimensional image is reduced to a two-dimensional representation. The spatial information contained in the image is lost when the image is stored. Spatial impressions gained when looking at the picture are based on sensory illusions.

With holography, three-dimensional information can be stored and also reproduced. For recording, coherent light-wave trains are necessary. In hologram imaging, a beam splitter divides the laser beam into object and reference beams. The resulting object and reference waves form an interference pattern on the record-

Characteristics of optical fibers (optical waveguides)

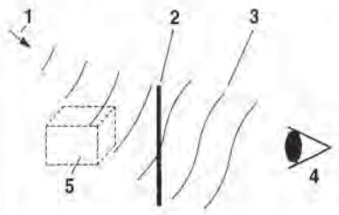
Fiber type	Diameter Core µm	Diameter Cladding µm	Wavelength nm	Numerical aperture NA	Attenuation dB/km	Bandwidth MHz · km
Step-index fiber						
Quartz/glass	50...1000	70...1000	250...1550	0.2...0.87	5...10	10
Polymer	200...>1000	250...2000	450...850	0.2...0.6	100...500	<10
Graded-index fiber	50...150	100...500	450...1550	0.2...0.3	3...5	200...1000
Monomode fiber	3...10	100...500	850...1550	0.12...0.21	0.3...1	2500...15000

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ing medium (hologram plate) where the latter is stored as a diffraction grating.

The expanded beam of a laser illuminates the hologram plate and reconstructs the hologram. The diffraction grating on the hologram deforms the laser wave to such an extent that the observer has the impression that the holographically captured object is present behind the hologram plate.

Hologram reproduction
1 Reconstruction wave, 2 Hologram, 3 Deformed wave, 4 Observer, 5 Virtual image.



Typical applications
- Registration of minute path deviations,
- Measurement of deformations and vibration amplitudes far below the wavelength of light by means of holographic interferometry,
- Holographic measuring and testing methods in precision manufacturing (e.g. fuel-injection components),
- Production of forgery-proof documents,
- Use of holographic elements for illustration purposes.

Display elements

The most important optical information displays are liquid crystal and light-emitting diode displays.

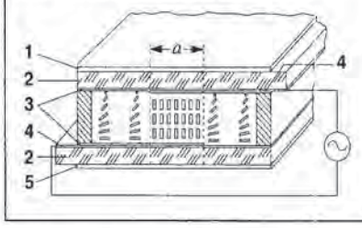
Liquid crystal display

The liquid crystal display, or LCD, is a passive display element. The contrast differences created are made visible by additional illumination. The most widely used type of LCD is the twisted nematic cell, or TN cell.

The liquid crystal substance is held between two glass plates. In the area of the display segments these glass plates are covered with a transparent conducting layer to which a voltage can be applied: an electric field is created between the layers. An additional orientation layer causes the plane of polarization of light passing through the cell to rotate. When polarizers acting at right angles to one another are added to both outside surfaces, the cell is initially transparent. In the area of the two opposed electrodes the liquid crystal molecules are aligned in the direction of the electric field by applying voltage. Rotation of the plane of polarization is now suppressed and the display area becomes opaque.

Numbers, letters and symbols are indicated in separately activated segment areas.

Principle of operation of a liquid crystal display (nematic cell)
1 Polarizer, 2 Glass, 3 Orientation and insulation layer, 4 Electrode, 5 Polarizer (and reflector). a Segment area.



Light-emitting diodes

The light-emitting diode, or LED, display is an active (self-luminous) display. It consists of a semiconductor element with PN junction. The charge carriers (free electrons and holes) recombine during operation in forward direction. With certain semiconductor materials, the energy which is released as a result is converted into electromagnetic radiation energy.

Frequently used semiconductor materials are: gallium arsenide (infrared), gallium arsenide phosphide (red to yellow) and gallium phosphide (green).

Mathematics

Mathematical signs and symbols

≈	Approximately equal to
≪	Much less than
≫	Much greater than
≙	Corresponds to
. . .	and so forth, to
=	Equal to
≠	Not equal to
<	Less than
≤	Less than or equal to
>	Greater than
≥	Greater than or equal to
+	Plus
−	Minus
· or ★ or ×	Multiplied by
− or / or :	Divided by
Σ	Sum of
Π	Product of
~	Proportional to
$\sqrt{}$	Square root of ($\sqrt[n]{}$ n^{th} root of)
$n!$	n factorial (e.g. $3! = 1 \cdot 2 \cdot 3 = 6$)
$\lvert x \rvert$	Absolute value of x
→	Approaches
∞	Infinity
i or j	Imaginary unit, $i^2 = -1$
⊥	Perpendicular to
∥	Parallel to
∢	Angle
△	Triangle
lim	Limiting value
Δ	Delta (difference between two values)
d	Total differential
δ	Partial differential
∫	Integral
ln	Logarithm to base e[1])
lg	Logarithm to base 10

Useful numbers

e	= 2.718282[1])	$\sqrt{\pi}$	= 1.77245
e^2	= 7.389056	$1/\pi$	= 0.31831
1/e	= 0.367879	π^2	= 9.86960
lg e	= 0.434294	$180/\pi$	= 57.29578
$\sqrt{e}$	= 1.648721	$\pi/180$	= 0.017453
1/lg e	= 2.302585	$\sqrt{2}$	= 1.41421
ln 10	= 2.302585	$1/\sqrt{2}$	= 0.70711
1/ln10	= 0.434294	$\sqrt{3}$	= 1.73205
π	= 3.14159		

Number systems

Number systems are employed to form numerals in cases where the number of digits is to be less than the quantity of individual units being described. This type of notation requires the use of a single symbol (digit) for collective representation of more than one element.

Today's denominational number systems differ from former additive systems in employing groups which increase in uniform increments. The position of the digit within the numeral corresponds to the size of the unit (place value). The number at which the first new unit is formed is equal to the base number of a denominational number system; it is equal to the maximum number of individual digits which are available. Most frequently used is the decimal system (base 10). In information technology/computer science, the dual system (base 2) using the digits 0 and 1, and the hexadecimal system (base 16) using the digits 0 through 9 and A through F, are also employed. A real number a is represented in the denominational number system by:

$$a = \pm \sum_{i=-\infty}^{\infty} Z_i \cdot B^i$$

i Position, B Base, Z_i Natural number ($0 \le Z_i < B$) at position i. A comma is inserted between the positions i<0 and i=0.

Roman number system (addition system)	Decimal system (base 10)	Dual system (base 2)
I	1	1
X	10	1010
C	100	1100100
M	1000	1111100110
II	2	10
V	5	101
L	50	110010
D	500	111110010
MIM or MDCCCCLXXXXIX	1999	11111001111

(In the Roman system, a smaller numeral is subtracted from a larger subsequent numeral when it directly precedes it.)

[1]) e = 1 + 1/1! + 1/2! + 1/3! + ... (base of natural logarithms).

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Preferred numbers

Preferred numbers are rounded-off terms in geometric series whose increments (the ratio of a term to its predecessor) are as follows:

Series	R 5	R 10	R 20	R 40
Increment	$\sqrt[5]{10}$	$\sqrt[10]{10}$	$\sqrt[20]{10}$	$\sqrt[40]{10}$

They are used for selecting preferred size and dimension increments.

In addition to the principal series, DIN 323 also contains the exceptional series R 80 as well as series of rounded numbers.

Electrical components such as resistors and capacitors are rated in increments in accordance with the E Series:

Series	E 6	E 12	E 24
Increment	$\sqrt[6]{10}$	$\sqrt[12]{10}$	$\sqrt[24]{10}$

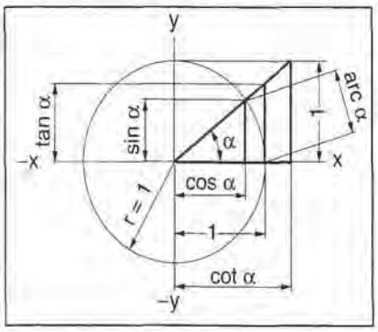
Preferred numbers (DIN 323)

Principal series				Exact values	
R 5	R 10	R 20	R 40		lg
100	1.00	1.00	1.00	1.0000	0.0
			1.06	1.0593	0.025
		1.12	1.12	1.1220	0.05
			1.18	1.1885	0.075
	1.25	1.25	1.25	1.2589	0.1
			1.32	1.3335	0.125
		1.40	1.40	1.4125	0.15
			1.50	1.4962	0.175
1.60	1.60	1.60	1.60	1.5849	0.2
			1.70	1.6788	0.225
		1.80	1.80	1.7783	0.25
			1.90	1.8836	0.275
	2.00	2.00	2.00	1.9953	0.3
			2.12	2.1135	0.325
		2.24	2.24	2.2387	0.35
			2.36	2.3714	0.375
2.50	2.50	2.50	2.50	2.5119	0.4
			2.65	2.6607	0.425
		2.80	2.80	2.8184	0.45
			3.00	2.9854	0.475
	3.15	3.15	3.15	3.1623	0.5
			3.35	3.3497	0.525
		3.55	3.55	3.5481	0.55
			3.75	3.7584	0.575
4.00	4.00	4.00	4.00	3.9811	0.6
			4.25	4.2170	0.625
		4.50	4.50	4.4668	0.65
			4.75	4.7315	0.675
	5.00	5.00	5.00	5.0119	0.7
			5.30	5.3088	0.725
		5.60	5.60	5.6234	0.75
			6.00	5.9566	0.775
6.30	6.30	6.30	6.30	6.3096	0.8
			6.70	6.6834	0.825
		7.10	7.10	7.0795	0.85
			7.50	7.4989	0.875
	8.00	8.00	8.00	7.9433	0.9
			8.50	8.4140	0.925
		9.00	9.00	8.9125	0.95
			9.50	9.4409	0.975
10.0	10.0	10.0	10.0	10.0000	1.0

E series (DIN 41 426)

E 6	E 12	E 24
1.0	1.0	1.0
		1.1
	1.2	1.2
		1.3
1.5	1.5	1.5
		1.6
	1.8	1.8
		2.0
2.2	2.2	2.2
		2.4
	2.7	2.7
		3.0
3.3	3.3	3.3
		3.6
	3.9	3.9
		4.3
4.7	4.7	4.7
		5.1
	5.6	5.6
		6.2
6.8	6.8	6.8
		7.5
	8.2	8.2
		9.1
10.0	10.0	10.0

Trigonometric functions



φ =	$\pm\alpha$	$90 \pm \alpha$	$180 \pm \alpha$	$270 \pm \alpha$
$\sin\varphi$ =	$\pm \sin\alpha$	$\cos\alpha$	$\mp \sin\alpha$	$-\cos\alpha$
$\cos\varphi$ =	$\pm \cos\alpha$	$\mp \sin\alpha$	$-\cos\alpha$	$\pm \sin\alpha$
$\tan\varphi$ =	$\pm \tan\alpha$	$\mp \cot\alpha$	$\pm \tan\alpha$	$\mp \cot\alpha$
$\cot\varphi$ =	$\pm \cot\alpha$	$\mp \tan\alpha$	$\pm \cot\alpha$	$\mp \tan\alpha$

Sine α — side opposite α/hypotenuse
Cosine α — side adjacent to α/hypotenuse
Tangent α — side opposite α/side adjacent to α
Cotangent α — side adjacent to α/side opposite α
Arc $\alpha = \overset{\frown}{\alpha}$ — radian measure of α in circle of radius 1
inv α — involute function

$\sin 0° = \cos 90° = 0$
$\cos 0° = \sin 90° = 1$
$\tan 0° = \cot 90° = 0$
$\cot 0° = \tan 90° = \infty$
$\sin 30° = \cos 60° = 0.5$
$\cos 30° = \sin 60° = 0.5\sqrt{3}$
$\tan 30° = \cot 60° = \sqrt{3}/3$
$\cot 30° = \tan 60° = \sqrt{3}$

$$\overset{\frown}{\alpha} = \text{arc}\,\alpha = \frac{\pi \cdot \alpha}{180°}\,\text{rad} = \frac{\alpha}{57.3°}$$

$$\overset{\frown}{1°} = \text{arc}\,1° = \frac{\pi}{180} = 0.017453$$

$$\text{arc}\,57.3° = 1$$

$$\text{inv}\,\alpha = \tan\alpha - \text{arc}\,\alpha$$

$$\cos^2\alpha + \sin^2\alpha = 1$$

$$\tan\alpha = \frac{\sin\alpha}{\cos\alpha} = \frac{1}{\cot\alpha}$$

$$1 + \tan^2\alpha = \frac{1}{\cos^2\alpha}$$

$$1 + \cot^2\alpha = \frac{1}{\sin^2\alpha}$$

$$\sin\alpha \approx \overset{\frown}{\alpha} - \frac{\overset{\frown}{\alpha^3}}{6}$$

Error < 1 % at $\alpha < 58°$

$$\sin\alpha \approx \overset{\frown}{\alpha}$$

Error < 1 % at $\alpha < 14°$

$$\cos\alpha \approx 1 - \frac{\overset{\frown}{\alpha^2}}{2}$$

Error < 1 % at $\alpha < 37°$

$$\cos\alpha \approx 1$$

Error < 1 % at $\alpha < 8°$

$$\sin 2\alpha = 2 \sin\alpha \cdot \cos\alpha$$
$$\cos 2\alpha = \cos^2\alpha - \sin^2\alpha$$
$$\tan 2\alpha = 2/(\cot\alpha - \tan\alpha)$$
$$\cot 2\alpha = (\cot\alpha - \tan\alpha)/2$$
$$\sin 3\alpha = 3 \sin\alpha - 4 \sin^3\alpha$$
$$\cos 3\alpha = 4 \cos^3\alpha - 3 \cos\alpha$$

$$\sin(\alpha \pm \beta) = \sin\alpha \cdot \cos\beta \pm \cos\alpha \cdot \sin\beta$$
$$\cos(\alpha \pm \beta) = \cos\alpha \cdot \cos\beta \mp \sin\alpha \cdot \sin\beta$$

$$\tan(\alpha \pm \beta) = \frac{\tan\alpha \pm \tan\beta}{1 \mp \tan\alpha \tan\beta}$$

$$\cot(\alpha \pm \beta) = \frac{\cot\alpha \cdot \cot\beta \mp 1}{\cot\beta \pm \cot\alpha}$$

$$\sin\alpha \pm \sin\beta = 2 \sin\frac{\alpha \pm \beta}{2} \cdot \cos\frac{\alpha \mp \beta}{2}$$

$$\cos\alpha + \cos\beta = 2 \cos\frac{\alpha + \beta}{2} \cdot \cos\frac{\alpha - \beta}{2}$$

$$\cos\alpha - \cos\beta = -2 \sin\frac{\alpha + \beta}{2} \cdot \sin\frac{\alpha - \beta}{2}$$

$$\tan\alpha \pm \tan\beta = \frac{\sin(\alpha \pm \beta)}{\cos\alpha \cdot \cos\beta}$$

$$\cot\alpha \pm \cot\beta = \frac{\sin(\beta \pm \alpha)}{\sin\alpha \cdot \sin\beta}$$

Euler's formula
(basis of symbolic calculation):

$$e^{\pm ix} = \cos x \pm i \sin x$$

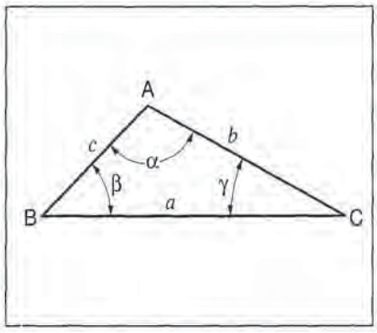
$$\sin x = \frac{e^{ix} - e^{-ix}}{2i}\,;\ \cos x = \frac{e^{ix} + e^{-ix}}{2}$$

where $i = \sqrt{-1}$

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Equations for plane and spherical triangles

Plane triangle

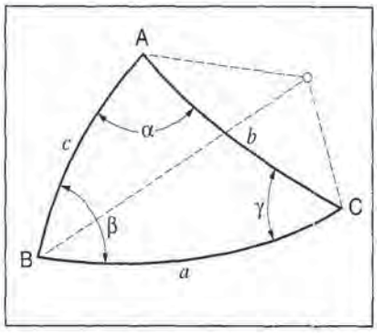


$\alpha + \beta + \gamma = 180°$

Sine law
$a : b : c = \sin\alpha : \sin\beta : \sin\gamma$

Pythagorean theorem (cosine law)
$a^2 = b^2 + c^2 - 2\,bc\cos a$
for right-angle triangle
$a^2 = b^2 + c^2$

Spherical triangle



Sine law
$\sin a : \sin b : \sin c = \sin\alpha : \sin\beta : \sin\gamma$

Cosine law for sides
$\cos a = \cos b\cos c + \sin b\sin c\cos\alpha$

Cosine law for angles
$\cos\alpha = -\cos\beta\cos\gamma + \sin\beta\sin\gamma\cos a$

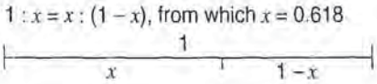
Equations often used

Solution of quadratic equation
$ax^2 + bx + c = 0$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Golden section (continuous division)

$1 : x = x : (1 - x)$, from which $x = 0.618$



Conversion of logarithms

$\lg N = 0.434294 \cdot \ln N$
$\ln N = 2.302585 \cdot \lg N$

Geometric series
$a + aq + aq^2 + aq^3 + \ldots$

n^{th} member $= aq^{n-1}$

for $q > 1$: $\sum_n = a\,(q^n - 1)/(q - 1)$

for $q < 1$: $\sum_n = a\,(1 - q^n)/(1 - q)$

for $n \to \infty$ becomes $q^n = 0$

$$\sum_{n \to \infty} = a/(1 - q)$$

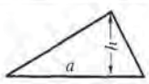
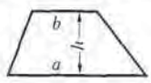
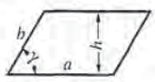
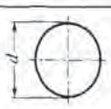
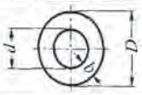
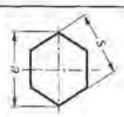
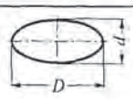
Arithmetic series

$a + (a + d) + (a + 2d) + (a + 3d) + \ldots$
n^{th} member $= a + (n - 1)\,d$

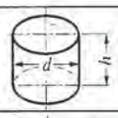
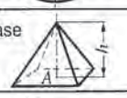
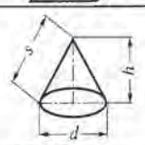
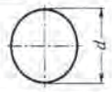
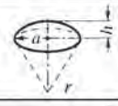
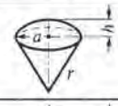
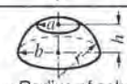
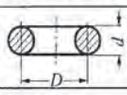
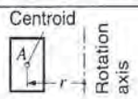
$$\sum_n = \frac{n}{2}\,[2a + (n - 1)\,d]$$

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Areas of plane surfaces

Type of surface	Area A $\pi = 3.1416$
Triangle 	$A = \frac{a \cdot h}{2}$
Trapezoid 	$A = \frac{a+b}{2} h$
Parallelogram 	$A = a \cdot h = a \cdot b \cdot \sin\gamma$
Circle 	$A = \frac{\pi \cdot d^2}{4} = 0.785\, d^2$ Circumference $U = \pi \cdot d$
Annulus 	$A = \frac{\pi}{4}(D^2 - d^2) = \frac{\pi}{2}(D+d)\,b$
Sector  φ in degrees	$A = \frac{\pi \cdot r^2 \cdot \varphi}{360°} = 8.73 \cdot 10^{-3} \cdot r^2 \cdot \varphi$ Arc length $l = \frac{\pi \cdot r \cdot \varphi}{180°} = 1.75 \cdot 10^{-2} \cdot r \cdot \varphi$
Segment  φ in degrees	$A = \frac{r^2}{2}\left(\frac{\pi \cdot \varphi}{180°} - \sin\varphi\right) = h \cdot s\left[0.667 + 0.5\left(\frac{h}{s}\right)^2\right]$ Chord length $s = 2r \cdot \sin\frac{\varphi}{2}$ Arc height $h = r\left(1 - \cos\frac{\varphi}{2}\right) = \frac{s}{2}\tan\frac{\varphi}{4} = 2r \cdot \sin^2\frac{\varphi}{4}$
Hexagon 	$A = \frac{\sqrt{3}}{2}s^2 = 0.866\, s^2$ Width across corners $e = \frac{2s}{\sqrt{3}} = 1.155\, s$
Ellipse 	$A = \pi \cdot D \cdot d/4 = 0.785\, D \cdot d$ Circumference $U = 0.75\,\pi\,(D+d) - 0.5\,\pi\sqrt{D \cdot d}$
Pappus theorem for surfaces of revolution Centroid  Axis of rotation	The area of a surface of revolution is equal to the length l of the generatrix line multiplied by the distance traveled by the centroid $A = 2\pi \cdot r \cdot l$

Volume and surface area of solids

Type of solid	Volume V, surface S, lateral area M $\pi = 3.1416$
Regular cylinder 	$V = \frac{\pi \cdot d^2}{4} h = 0.785\, d^2 \cdot h$ $M = \pi \cdot d \cdot h,\ S = \pi \cdot d\,(d/2 + h)$
Pyramid A Area of base h Height 	$V = \frac{1}{3} A \cdot h$
Circular cone 	$V = \frac{\pi \cdot d^2 \cdot h}{12} = 0.262\, d^2 \cdot h$ $M = \frac{\pi \cdot d \cdot s}{2} = \frac{\pi \cdot d}{4} \sqrt{d^2 + 4h^2} = 0.785\, d \cdot \sqrt{d^2 + 4h^2}$
Truncated cone 	$V = \frac{\pi \cdot h}{12} (D^2 + D \cdot d + d^2) = 0.262\, h\, (D^2 + D \cdot d + d^2)$ $M = \frac{\pi\,(D + d)\, s}{2} \quad s = \sqrt{\frac{(D - d)^2}{4} + h^2}$
Sphere 	$V = \frac{\pi \cdot d^3}{6} = 0.524\, d^3$ $S = \pi \cdot d^2$
Spherical segment (spherical cap) 	$V = \frac{\pi \cdot h}{6} (3a^2 + h^2) = \frac{\pi \cdot h^2}{3} (3r - h)$ $M = 2\pi \cdot r \cdot h = \pi (a^2 + h^2)$
Spherical sector 	$V = \frac{2\pi \cdot r^2 \cdot h}{3} = 2.094\, r^2 \cdot h$ $S = \pi \cdot r\,(2h + a)$
Spherical segment of two bases  r Radius of sphere	$V = \frac{\pi \cdot h}{6} (3a^2 + 3b^2 + h^2)$ $M = 2\pi \cdot r \cdot h$
Torus ring 	$V = \frac{\pi^2}{4} D \cdot d^2 = 2.467\, D \cdot d^2$ $S = \pi^2 \cdot D \cdot d = 9.870\, D \cdot d$
Ellipsoid d_1, d_2, d_3 Length of axes	$V = \frac{\pi}{6} d_1 \cdot d_2 \cdot d_3 = 0.524\, d_1 \cdot d_2 \cdot d_3$
Circular cask D Diameter at bung d Diameter at base h Distance between bases	$V = \frac{\pi \cdot h}{12} (2D^2 + d^2) = 0.26\, h\, (2D^2 + d^2)$
Pappus theorem for solids of revolution 	The volume of a body of revolution is equal to the generatrix area A multiplied by the distance traveled by the centroid $V = 2\pi \cdot r \cdot A$

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Quality

Quality is defined as the extent to which the customer expectations are fulfilled or even exceeded. The desired quality is determined by the customer. With his demands and expectations, he determines what quality is – in both products and services. Because competition leads to increased customer expectations, quality remains a dynamic quantity. Quality is defined through product- and service-related factors which are susceptible to quantitative or qualitative analysis. The preconditions for achieving high quality are:
Quality policy: The company commitment to quality as a top-priority corporate objective,
Leadership: Employee-motivation measures,
Quality assurance.

Quality management

Quality system
All elements in a quality system and all quality-assurance measures must be systematically planned. The individual assignments and the areas of competence and responsibility are to be defined in writing (Quality-Assurance Handbook). Quality systems are also described in international standards, such as DIN ISO 9001 – 9004.

Increased requirements for defect-free products (zero-defect target) and economic considerations (defect prevention in place of sorting and reworking, or scrapping) make it imperative that preventive quality-assurance measures be applied. These serve the following objectives:
- To develop products that are insensitive to production fluctuations.
- To establish production processes to ensure that quality requirements are maintained within the specified limits.
- To apply methods which identify the sources of defects at an early stage, and which can be applied to rectify the manufacturing process in good time.

Three types of "audit" are employed in the regular monitoring of all elements in a quality system:
- System audit: Evaluation of the effectiveness of the quality system regarding its comprehensiveness and the practical application of the individual elements.
- Process audit: Evaluation of the effectiveness of the quality-management (QM) elements, confirmation of quality capability, of adherence to and suitability of particular processes, and the determination of specific measures for improvement.
- Product audit: Evaluation of the effectiveness of the QM elements performed by examining the final products or their components.

Quality management in development
At the outset, every new product which must fulfill the customer's quality and reliability demands is allocated a project specifications manual.

As early as the definition phase, its contents serve as the basis for the planning of all sample and endurance tests required to verify the new product's serviceability and reliability.

Quality assessment
At the conclusion of specific development stages, all the available data regarding quality and reliability are subjected to a quality-assessment procedure, leading to initiation of the required corrective measures. Responsible for the quality assessment are staff members from development, production engineering, and quality assurance; these, in turn, receive support from the specialists in the specialist departments.

Failure Mode and Effects Analysis (FMEA)
This cost-reduction and risk-prevention procedure is suitable for investigating the types of defects which can occur in system components and their effects on the system (for details, see "Reliability", P. 165).

Quality management during procurement
This aspect must extend beyond the receiving inspection; it must comprise an entire system. This system must ensure that the components purchased from suppliers contribute to the reliable fulfillment of the Technical Specifications defined for the finished product.

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Example of application of Failure Mode and Effects Analysis (FMEA)

BOSCH QUALITY ASSURANCE	FMEA Actuator 9 319 150 342 Part 6: Parts production and assembly of bushing holder						DEPT. FMEA PAGE DATE				FVB 75 1289940001 10 10.10.88	
NO.	COMPONENT PROCESS	FUNCTION PURPOSE	DEFECT TYPE	DEFECT EFFECT	DEFECT CAUSES	DEFECT PREVENTION	DEFECT DETECTION	S S	– A	E E	SxE RZ	MEASURES V/T:
1110	Assemble bushing holder	Prepare parts for soldering process	Damaged sealing surfaces	Actuator leaking to surroundings → gasoline vapors in engine compartment	Swarf in assembly device	Wash before assembly, clean tools regularly	100 % visual inspection of soldering; surface check; 100 % visual inspection prior to packing	10	2	1	20	
1130	Solder bushing holder	Hold parts together	Part not soldered		No solder	Scan solder feed	100 % visual inspection of soldering; 100 % visual inspection of surface; 100 % leak test	10 (10	2 2	2 1	40 20)	100 % leak test of bushing-holder assembly V: FVB2 T: 01.89
		Ensure leak-tightness	Part leaking (bubbles)		Insufficient solder	Scan solder feed	100 % visual inspection of soldering	10 (10	4 3	6 2	240 60)	100 % leak test V: FVB2 T: 01.89 + Design improvement at soldering joint V: EVA3 T: 03.89

S = Severity of fault
V = Department responsible
A = Probability of occurrence
T = Deadline for introduction
E = Probability of detection
RZ = Risk number = S x A x E

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It is imperative that suppliers' quality capabilities be supported by modern, preventive quality-assurance techniques (e.g. SPC Statistical Process Control or FMEA). All individual requirements for the product must be specified in a clear and unambiguous manner in order to allow the subcontractor to achieve and competently evaluate comprehensive compliance with the individual quality requirements for the product. These guidelines generally are in the form of drawings, order specifications, standards, formulas, etc.

For example, the actual manufacturer of the supplied product performs the first initial sample inspection. This inspection must be reproduced by the purchaser when the product is received (with particular emphasis on the interrelationships involving manufacturing processes and the finished product), and confirmed by means of an incoming inspection.

The supplier's final or shipping inspection can take the place of the purchaser's incoming inspection in those cases where the subcontractor possesses special knowledge and/or the technical equipment necessary for carrying out specific forms of quality testing. The supplier confirms the relevant quality inspections on the products in quality certificates in accordance with DIN 55 350 or material test certificates in accordance with DIN 50049. The test results obtained must be forwarded to the purchaser.

Quality management in production engineering

The preconditions for supplying assured quality are established in the production-planning phase. Compliance with the following conditions is required:

- Planning of the production process and material flow.
- Planning of resources requirements.
- Selection and acquisition of suitable production methods and production equipment, as well as the requisite test stands (e.g. for SPC).
- Examination of manufacturing methods, production equipment and machines to determine machine and process capability.
- Documentation of the production procedure in the production-sequence plan.
- Determination of the necessary level of employee qualification.
- Preparation of technical drawings and parts lists.

The Process FMEA provides a means of methodically anticipating potential faults in the manufacturing process and of assessing their effects on the quality of the attribute or the product. The Process FMEA is employed to discover the sources of defects, and to avoid the defects or minimize their effects. This makes it possible to initiate the necessary production and test-engineering procedures required for defect prevention.

FMEA working group

Area of operation	Product FMEA	Process FMEA	FMEA contribution
FMEA moderator			Coordination Methods
Construction (Ⓥ = Responsibility)	Ⓥ		Construction
Testing			Functionality
Endurance testing			Durability Climate resistance
Technical marketing			Project specifications
Customer service			Customer service
Pre-production (Ⓥ = Responsibility)		Ⓥ	Manufacturing verifiability procedures
Quality services			Quality and reliability assurance
Production			Production
Materials			Subcontractor supply
Miscellaneous			

Inspection planning comprises the following points:
- Analysis of the functions to be tested.
- Determination of the test criteria.
- Selection of suitable inspection methods and measuring and inspection equipment.
- Determination of the extent and frequency of the inspection.
- Documentation of the test procedure in the inspection plan.
- Planning of recording and documentation of quality data (e.g. in quality-control charts for SPC).
- Planning for control of inspection, measuring, and test equipment.
- Possible planning of quality-data documentation.

The specified inspection criteria must always include all essential characteristics of the finished products.

Suitable means for compilation and evaluation of the inspection results are to be specified for assessing the quality of products and their components, and for controlling production processes. Test results are to be processed in such a manner as to be suitable for application in open-loop and closed-loop process-control systems, fault analysis and fault rectification.

Machine and process capability

The evaluation of machine capability is to confirm performance potential in the following two areas:
- The machine under examination must operate with verifiable consistency. If necessary, this consistency must be formulated with the aid of statistical quantities, e.g. as normal distribution with mean value $\bar{x}$ and standard deviation s.
- The machine must be able to maintain production within specified tolerances. This can only be confirmed using the quantification of consistency indicated above.

Testing of machine capability is restricted to a limited period, and to the investigation of the equipment-related effects on the production process. However, it should be noted that equipment-related and non-equipment-related factors (e.g. effects of material or procedures) cannot usually be separated completely. Individual tests are designed to determine whether:
- unusual process results are recognized,
- mean values and scatter range remain stable within the measurement series (the verification limits of statistical process control are employed for this examination).

If no unusual process results are present, and the mean and the scatter range are stable, then the process is considered to be fully controlled; the suitability of the equipment is then described using the familiar statistics c_m and c_{mk}. The value for c_m only reflects the scatter range for the machine; it is calculated with the following equation:

$$c_m = (OGW - UGW)/(6 \cdot \hat{\sigma})$$

On the other hand, the value for c_{mk} reflects not only the machine's scatter range, but also the position of the mean within the tolerance range. It is essential that it be calculated for the production machinery on which adjustments are either imprecise or impossible. It is calculated as follows:

$$c_{mk} = (\bar{\bar{x}} - UGW)/(3 \cdot \hat{\sigma}) \text{ or}$$
$$c_{mk} = (OGW - \bar{\bar{x}})/(3 \cdot \hat{\sigma})$$

with the lesser value being valid. The definitions are:

$\bar{\bar{x}}$ Total mean value
UGW Lower tolerance-range limit
OGW Upper tolerance-range limit
$\hat{\sigma}$ Estimate for process control

Bosch only designates production equipment as capable of ensuring that manufacture will result in the required product attributes when c_{mk} is at least 1.67.

Unusual process results, or an unstable mean or scatter range indicate that the process is not fully controlled. In this case, non-random influences (interference factors) are affecting the process. These must be eliminated or compensated for. The examination of machine capability is then repeated.

If the result of the machine-capability test is positive, it is followed by an examination of the process capability. This is intended to ensure that the production process is capable of consistently meeting the quality requirements placed upon it.

The examination of process capability extends over a longer period of time. All changes to the process (e.g. material

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changes, tool changes or method changes) are taken into account when the scope and intervals of sample testing are determined, and then included in the examination procedure.

Once compiled, the data are subjected to a statistical analysis comparable to that employed for determining equipment performance potentials. Particular attention is devoted to ascertaining whether the process mean and process control are stable, i.e., whether the process is fully controlled. If the process is fully controlled, then the process capability is confirmed using the known statistics c_p and c_{pk}. These statistics are calculated in the same way as those for c_m and c_{mk} where the values $\bar{\bar{x}}$ and $\hat{\sigma}$ from the process examination are used.

If the process is not fully controlled, calculation of c_p and c_{pk} is not permitted. In this case, the causes of the instability in the process must be either eliminated or compensated for. The process-capability analysis is then repeated.

Bosch designates a process as capable of ensuring the required product attributes only in cases where c_{pk} is at least 1.33.

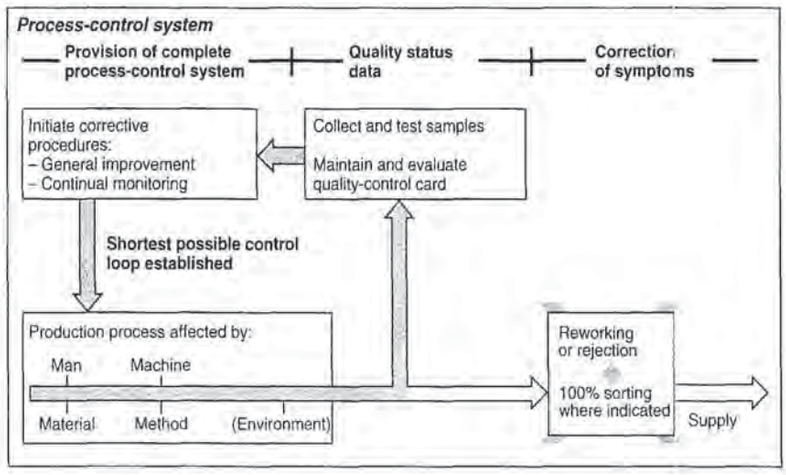
Machine- and process-capability analysis are necessary preliminary checks prior to introduction of SPC. However, both investigations are also important for processes which are not controlled by SPC, as the required potential must be confirmed for each type of process.

Statistical Process Control (SPC)
SPC is a process-control system intended to assist in the prevention of errors and their associated costs. SPC is employed in production, being applied for attributes which are vital to operation (for details, see "Technical Statistics", P. 160).

Measuring and inspection equipment

The measuring and inspection equipment must be able to demonstrate whether the inspection features of the finished product conform to the prescribed specifications. Measuring and inspection equipment must be monitored, calibrated and maintained. Uncertainty of measurement is to be considered when using measuring and inspection equipment. It must be minimal relative to the tolerance range for the attribute being tested. With measuring and inspection equipment, attention is to be paid to:

- Defining the measurements to be performed, the required precision and the suitable measuring and inspection equipment.
- Ensuring that the measuring and inspection equipment meets precision requirements, i.e. the uncertainty of measurement is generally not to exceed 10 % of the tolerance range.
- All measuring and inspection equipment and measurement systems used for



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product quality-assurance are to be specified in an inspection plan; they must be labeled, and are to be calibrated and adjusted at prescribed intervals.
- Calibration procedures must be specified. These must comprise individual data on the type of unit, its identification, application area and calibration intervals, and are also to include the steps to be taken in case of unsatisfactory results.
- Measuring and inspection equipment must be provided with appropriate identification verifying their calibration status.
- Calibration records (histories) are to be maintained.
- The appropriate environmental conditions for calibrating, testing and measurement must be maintained.
- Measuring and inspection equipment is to be carefully stored and protected against contamination in order to maintain consistent levels of precision and suitability for use.
- The measuring and inspection equipment and the software are to be protected against any influences which might invalidate their calibration.

Control of inspection, measuring, and test equipment: Type and extent

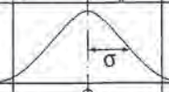
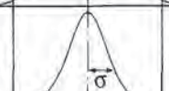
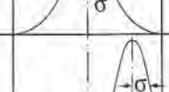
Satisfactory arrangements for monitoring test equipment embrace all measuring devices employed in development, production, assembly and in customer service. This category includes calipers, unit standards, instruments, recording devices, and special test equipment along with its ancillary computer software. In addition, the equipment, mounts and clamps, and instruments employed for process control are also monitored.

Procedures which extend to include the equipment and the abilities of the operator are employed in evaluating whether a test process is controlled. Measurement errors are compared with the quality specifications. Appropriate corrective actions are to be introduced when the requirements for precision and function in measuring and inspection equipment are no longer satisfied.

Measuring instruments subject to calibration

German legal requirements on weights and measures stipulate that calibration of measuring devices which are for use in "business transactions" be officially certified in those cases where the results of their measurements are employed to determine the price of goods or energy. This category includes equipment for measuring length, surface area, volume and mass, and thermal and electrical energy. If these conditions apply, then the calibration of the measuring instruments concerned must be officially certified. Continuing compliance must then be monitored by an official or an officially approved agency.

Relationship between measurement results, statistical analysis and process capability

Process	←Tolerance T→	Status	Process capability
Individual values		Unsure	Not calculated
Statistical analysis		Result negative due to excessive variance	$C_p = \frac{T}{6\sigma} = 0.67$ Outside T by 4.6%
Minimum requirement		Result positive, low variance Mean value maintained	$C_p = 1.33$ Outside T by 63 ppm
Mean tolerance value displaced		Result negative despite low variance	$C_p = 2.0$ but $C_{pk} = \frac{D}{3\sigma} = 0.67$ i.e. outside T by 2.3%

Technical statistics

Purpose of statistics

Descriptive statistics
To describe sets of similar units with specific, different characteristic values using statistical characteristics which allow objective comparisons and evaluations.

Rating statistics
To provide information on the statistical characteristics of larger sets (populations) based on relatively few individual data (samples).

Because such statements are based on the laws of chance and the theory of probability, their validity is always subject to a certain level of confidence, usually 95 % in the field of engineering.

Examples of populations:
- All products of the same type produced under constant manufacturing conditions.
- Set of all the possible results of a measurement under unchanging conditions.

There are two different types of characteristics:
- Quantitative characteristics, e.g., physical quantities (referred to as "measured values"),
- Attribute characteristics, e.g. "OK" or "Defective" etc. (referred to as "test results" in the following).

Statistical analysis methods provide valuable assistance for ensuring and improving quality standards in industrial products. Today's levels of vehicle reliability would be impossible without it.

Presentation of measured values

N Population size: the number of all items which form the basis of statistical analysis
n Number of measured values in the sample
P_A Confidence level
x Individual measured value
R Range: $R = x_{max} - x_{min}$
k Number of classes into which R is divided. $k = \sqrt{n}$ (at least 5)
w Class width
i Ordinal number of measured values (as subscript)
j Ordinal number of classes (as subscript)
x_j Midpoint of class no. j
n_j Absolute frequency of class no. j: number of measured values in class no. j
h_j Frequency in class no. j, $h_j = n_j/n$
h_j/w Frequency density
G_j Cumulative absolute frequency: absolute frequency summed up to a particular class

$$G_j = \sum_{r=1}^{j} n_r$$

H_j Cumulative frequency = G_j/n
$F(x)$ Distribution function: probability for values $\leq x$
$f(x)$ Frequency-density function $\frac{d\,F(x)}{d\,x}$

μ Arithmetic mean of population
$\bar{x}$ Arithmetic mean of a sample

$$\bar{x} = \sum_{i=1}^{n} x_i/n$$

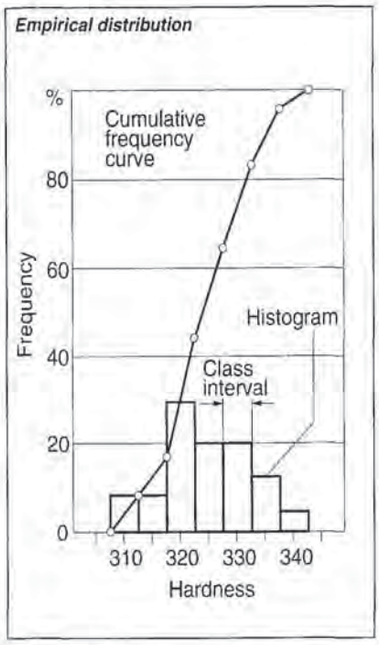
$\bar{\bar{x}}$ Arithmetic mean of several $\bar{x}$ values
σ Standard deviation of population
s Standard deviation of sample

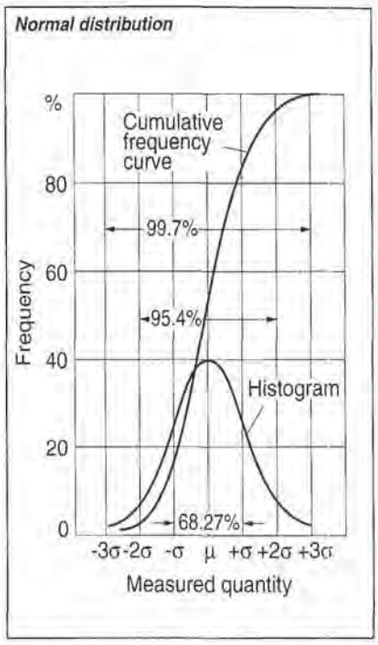
$$s = \sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 / (n-1)}$$

V Variation coefficient $V = s/\bar{x}$
u Dispersion factor
X, Y, Random variable
Z

Histogram and cumulative frequency curve of an empirical distribution
The simplest way of clearly presenting a larger number of characteristic values is the histogram (frequency diagram). In the case of attributes or variables with few discrete values, bars are drawn over the characteristic values whose height is proportional to the relative frequency of the values, i.e. the frequency h_j of the attribute j in proportion from the total number of all the values $\sum_j h_j$.

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In the case of variable attributes with a continuous range of values, the range is divided into k classes and the bars entered over the class midpoints. If the classes are not all the same size, the bars become rectangles whose areas are proportional to the relative frequencies of the classes. Thus, in these cases, the heights of the rectangles are also proportional to the frequency density.

If conclusions are to be drawn from the sample presentation described concerning the population, it is essential to define the classes in such a way that there are at least five values in each class.

Another way of presenting the distribution of attributes is the cumulative frequency curve. The advantage of this curve for variable attributes is that for each value or each interval the percentage of measured values below or above can easily be read off (estimate of fraction defectives outside the tolerance). The cumulative curve can be determined from the histogram by summing the relative frequencies up to the relevant value or interval. For the population, it thus represents the integral over the density function.

Distributions and statistical parameters

A random variable X is characterized by its distribution. The distribution function $F(x)$ describes the relationship between the variable value x and the cumulative frequency or probability for values $\leq x$. In empirical distributions, this function corresponds to the cumulative frequency curve. The histogram corresponds to the density function $f(x)$.

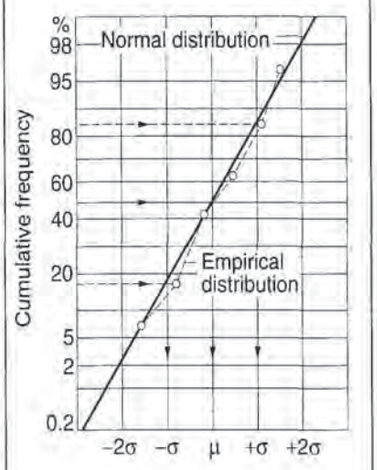
The most important parameters of a distribution are the arithmetic mean μ and the standard deviation σ.

Normal distribution

Normal, or Gaussian, distribution is the mathematically idealized limit case which always results when many mutually independent random effects are added together. The probability-density function of the Gaussian distribution clearly defined by μ and σ forms a symmetrical bell-shaped curve.

The total area under the bell-shaped curve corresponds to 1 = 100%. The standard deviation σ and its multiples allow the delimitation of specific areas with the boundaries $\mu \pm u\sigma$ in which P% of the

Probability grid



values fall (Table 1). The percentages $\alpha = (100 - P)/2$ lie outside these areas on either side.

Empirical and normal distribution in probability grid

In a "probability grid", the ordinate is distorted in such a way that the S-shaped cumulative frequency curve is transformed into a straight line.

Determination of μ and σ from the probability grid:

1. Read off μ at 50 % cumulative frequency.
2. Read off abscissa values at 16 % and 84 %.

The difference corresponds to 2σ.

Sums of random variables

For the mean and standard deviation of a random variable $Z = a \cdot X + b \cdot Y$, created by the linear combination of 2 independently distributed random variables X and Y, the following apply:

$$\mu_z = a \cdot \mu_x + b \cdot \mu_y$$
$$\sigma_z^2 = a^2 \cdot \sigma_x^2 + b^2 \cdot \sigma_y^2$$

Typical applications

1. Fits.
Hole diameter: x.
Shaft diameter: y.
Clearance: $z = x - y$.
For $\sigma_x = \sigma_y$ the following applies: $\sigma_z^2 = 2 \cdot \sigma_x^2$

2. Combined dimension.
If the individual dimensions are statistically independently distributed about their mean tolerances, the tolerance for the combined dimension can be calculated by quadratic addition (cf. DIN 7186).

Evaluation of series of measurements

Random interval for $\bar{x}$ and s
(direct conclusion)

If many samples each containing n values are taken from one and the same population with the mean μ and the standard deviation σ, the mean values $\bar{x}_1, \bar{x}_2, \ldots$ of the samples are dispersed with the standard deviation

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$$ about the true value μ.

In a similar way, random intervals can be defined for s and R.

Table 1. Value frequency P within and α outside $\pm u\sigma$

u	1.00	1.28	1.64	1.96	2.00	2.33	2.58	3.00	3.29
P%	68.27	80	90	95	95.4	98	99	99.7	99.9
α%	15.86	10	5	2.5	2.3	1	0.5	0.15	0.05

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Quantity	Random interval Lower limit	Upper limit
$\bar{x}$	$\mu - u\frac{\sigma}{\sqrt{n}}$	$\mu + u\frac{\sigma}{\sqrt{n}}$
S	$D_u \cdot \sigma$	$D_o \cdot \sigma$
R	$D_u \cdot \sigma \cdot d_n$	$D_o \cdot \sigma \cdot d_n$

D_u and D_o as functions of n and P from Tables 1 and 2.

Table 2. Auxiliary constants for evaluation of measurement series

n	d_n	t values for P = 90%	95%	99%	D_u for P = 95%	D_o
2	1.13	6.31	12.7	63.7	0.03	2.24
3	1.69	2.92	4.30	9.92	0.16	1.92
5	2.33	2.13	2.78	4.60	0.35	1.67
10	3.08	1.83	2.26	3.25	0.55	1.45
20	3.74	1.73	2.09	2.86	0.68	1.32
50	–	1.68	2.01	2.68	0.80	1.20
∞	–	1.65	1.96	2.58	1.00	1.00

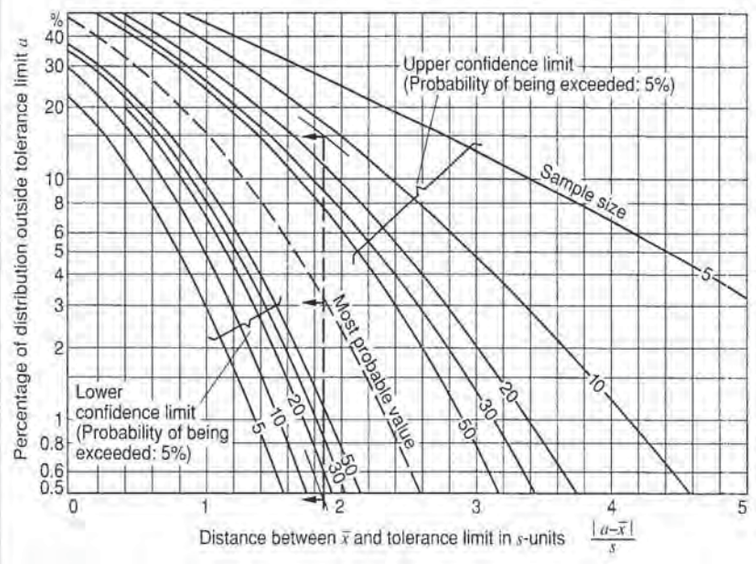
Confidence intervals for μ and σ (conclusion)

If only samples with x and s are known and a statement is to be made on the true mean value μ resulting from an infinite number of measurements, a so-called confidence interval can be specified which features μ with a probability of P_A%. The same holds true for σ.

Quantity	Confidence interval Lower limit	Upper limit
μ	$\bar{x} - t\frac{s}{\sqrt{n}}$	$\bar{x} + t\frac{s}{\sqrt{n}}$
σ	$\frac{s}{D_o}$	$\frac{s}{D_u}$

t, D_o and D_u from Table 2.

Confidence limits for fraction of defectives



Comparison of mean values
Two samples with values of n_1 and n_2 have the same standard deviations $s_1 = s_2$ but different mean values $\bar{x}_1 \neq \bar{x}_2$. The confidence interval for the difference $\mu_1 - \mu_2 = 0$ is:

$\pm t \cdot s_A \cdot \sqrt{1/n_1 + 1/n_2}$ with

$s_A^2 = \left((n_1 - 1)\, s_1^2 + (n_2 - 1)\, s_2^2\right)/(n' - 1)$

$n' = n_1 + n_2 - 1$ determines t in Table 2.

If the difference $x_1 - x_2$ is outside this confidence interval, the two samples come with confidence level P from different populations (e.g. different manufacturing conditions).

Estimation of nonconforming fractions
The percentage of parts lying outside the tolerance limit a is to be estimated based on $\bar{x}$ and s from a sample series.

Calculation procedure:
If μ and σ are known, then the percentage outside a in Table 1 or in the Figure "Confidence limits for nonconforming fractions" ("most probable value" curve) is determined by:

$$u = |a - \mu| / \sigma.$$

A value of e.g. $u = 1.65$ corresponds to a percentage of 5%. But now only $\bar{x}$ and s of the sample are known, not the values μ and σ of the population. As these values are random, the nonconforming fraction can only be specified in terms of the confidence range in which it lies with a particular probability.

In the figure, the confidence limits can be read off as a function of $|a - \bar{x}|/s$ which are exceeded only with a probability of 5%. Separate analyses are required for each of the two tolerance limits.

Example:
Prescribed tolerance for ground rollers $14^{-0.016}_{-0.043}$ mm.

Tested are 14 parts of 13.961 to 13.983 mm. $\bar{x}$ = 13.972 mm; R = 0.022 mm.

Estimated value for s from R with d_n from Table 2:
$s = 0.022/3.5 = 0.0063$

Upper tolerance limit exceeded:

$$\frac{|a - \bar{x}|}{s} = \frac{13.984 - 13.972}{0.0063} = \frac{0.012}{0.0063} = 1.9$$

Referring to the figure:
Upper confidence limit ≈15 %
Most probable value ≈ 3.1%
Lowest confidence limit ≈ 0.5%

Lower tolerance limit exceeded:

$$\frac{|a - \bar{x}|}{s} = \frac{|13.957 - 13.972|}{0.0063} = \frac{0.015}{0.0063} = 2.38$$

Referring to the figure:
Upper confidence limit ≈ 9 %
Most probable value ≈ 1 %
Lowest confidence limit < 0.5%

Statistical Process Control (SPC)
Quality-control charts are employed to ensure consistent quality in manufacturing processes. Small samples are tested at specified intervals; the values $\bar{x}$ and R are entered for test results while the defects are entered for attribute testing.
T_{lo}, T_{up} Lower/upper tolerance limits,
T Difference between upper and lower tolerance limit (tolerance range),
$T = T_{lo} - T_{up}$, $T_m = (T_{lo} + T_{up})/2$,
$\bar{\bar{x}}$, $\bar{R}$ Values from ≥ 20 samples,
$\sigma = \bar{R}/d_n$ = Standard deviation,
$c_p = T/(6 \times \sigma)$ = Process capability.

A process is considered to be "controlled" if 1) $c_p > 1$ (better: $c_p \geq 1.33$),
2) the curve displays no unusual variations (no trends, etc.),
3) $\bar{x}$ and R lie within the "action limits" of the corresponding random intervals.

Table 3 shows the approximate values for action limits as a percentage of T. The calculation is based upon the assumptions that values are:
99.7% random intervals and $c_p = 1$.

Table 3. Action limits as % of T

n	3	4	5	6	7	8	10	12	15
$R/T <$ %	72	78	82	84	86	88	91	93	95
$(\bar{x} - T_m) <$ %	29	25	22	20	19	18	16	14	13

Weibull distribution of service lives

Weibull distribution has gained acceptance as the standard in the investigation of the service lives of technical products. Its distribution function (probability for service lives $\leq t$) is:

$F(t) = 1 - e^{-(t/T)^b}$

Survival probability (reliability function)

$R(t) = 1 - F(t)$

Failure rate (failures per unit time referred to remaining products)

$\lambda(t) = f(t) / R(t)$

where

T Characteristic service life, corresponding sum of failures 63.2 %.

b Failure steepness (Weibull slope),
$b < 1$: falling (early failures)
$b = 1$: constant (random failures)
$b > 1$: rising (wear)

In the Weibull grid with abscissa ln t and ordinate ln (–ln $R[t]$), $F(t)$ becomes a straight line.

Evaluation of an endurance test involving n test specimens:

The diagram shows the evaluation of an endurance test involving $n = 19$ switches, of which $r = 12$ have failed. Against the service lives t ordered according to length in cycles, the sum of failures is plotted as

$H = (i - 0.5)/n$.

The result is:

$T = 83 \cdot 10^3$ cycles
$b = 3.2$ (wear).

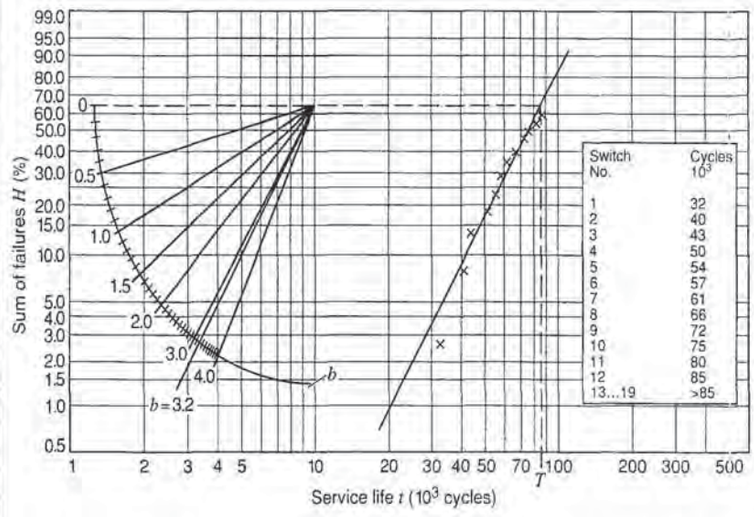
T and b are random values like $\bar{x}$ and s. Approximate confidence intervals ($n \geq 50$) for the "true values" are provided by the formulae:

$T \pm (u/\sqrt{n}) \cdot (T/b)$

$b - 0.5 \cdot (u/\sqrt{n}) \cdot b \ldots b + (u/\sqrt{n}) \cdot b$

u from Table 1.

Evaluation of an endurance test involving $n = 19$ switches in Weibull grid



For incomplete observations ($r < n$):

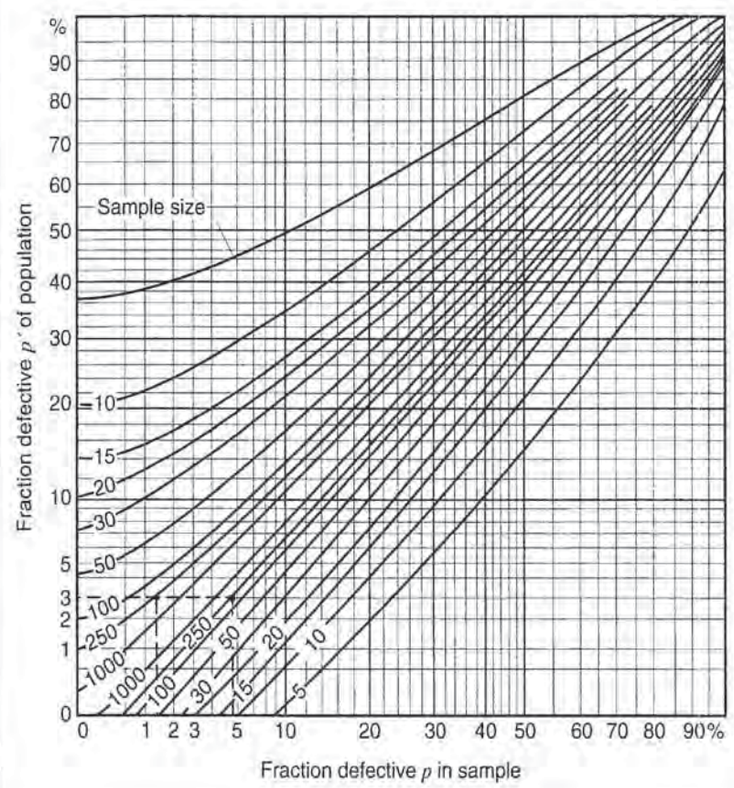
$$n' \approx r \cdot \left(1 + (r/n)\right)/2$$

T, b are therefore less precisely defined by r failures at $r < n$ than at $r = n$. The proportion exceeding a specific life expectancy is estimated in the following section.

Statistical evaluation of test results

N Size of population (batch). An attribute divides the batch into two classes, e.g. "failed" and "OK".
n Number of sample units
I Number of defects in batch
i Number of defects in sample
p Defective fraction in sample
$p = i/n$
p' Defective fraction in batch
$p' = I/N$.

Random and confidence limits for fractions defective *(binomial distribution)*
Probability of each limit being exceeded $\alpha = 10\%$.



Distribution of defective fraction p in random samples

The number of defectives i within the sample is a random variable. Larger batches ($N > 10 \cdot n$) are characterized by binomial distribution, expected value: $E(i) = n \cdot p'$,

Standard deviation:
$\sigma_i = \sqrt{n \cdot p' (1 - p')}$.

Random ranges for p (p' known) and confidence intervals for p' (p known) dependent on n are provided by the diagram on P. 162 with an exceeding probability of $\alpha = 10\,\%$ for each limit.

For the range $p' < 5\,\%$, frequently encountered in practice, binomial distribution is replaced by Poisson's law of infrequent events which is exclusively dependent on $n \cdot p'$ with $E(i) = n \cdot p'$, $\sigma_i = \sqrt{n \cdot p'}$.

Examples:

1. Binomial distribution (diagram P. 162)
In endurance testing with $n = 20$ units, $i = 2$ units have failed after extended usage.

What percentage p' of the series will not achieve the corresponding service life T?

Percentage in random sample $p = {}^{2}/_{20} = 10\,\%$.
At $p = 10\%$, $n = 20$, the diagram provides the following figures:
$p_u' = 2.8\,\%$, $p_o' = 24\,\%$.
With constant quality, the percentage with a service life $< T$ will lie within this range.

2. Poisson distribution (Table 4)
During receiving inspection, a random sampling of $n = 500$ parts found $i = 1$ part which was out of tolerance.

What is the maximum percentage of defective parts in the batch as expressed with 90 % probability?
At $i = 1$, $\alpha = 10\,\%$, Table 4 provides:
$np_o' = 3.89$
$p_o' = 3.89/500 = 7.78\,‰$.

Approximation formula for Poisson distribution

The approximate value for $i > 10$ can be derived using:

$n \cdot p' = i + u \cdot \sqrt{i} + k$
(see Table 4 for u, k).

Example for Poisson approximation:

In a preproduction series consisting of $n = 10\,000$ units, there were $i = 17$ warranty claims. With 97.5 % probability, what is the limit for warranty claims which will not be exceeded in normal series production if identical conditions are maintained?

Inserting the values from Table 4 into the approximation formula given above provides the following:
$np_o' = 17 + 1.96 \cdot \sqrt{17} + 2 = 27.08$
$p_o' = 27.08/10\,000 = 2.7\,‰$.

Table 4. Confidence limits for infrequent events

Obs. no. i	Lower limit np_u' Probability of being exceeded 2.5 %	10 %	Upper limit np_o' 10 %	2.5 %
0	—	—	2.30	3.69
1	0.025	0.105	3.89	5.57
2	0.242	0.532	5.32	7.22
3	0.619	1.10	6.68	8.77
4	1.09	1.74	8.00	10.24
5	1.62	2.43	9.27	11.67
6	2.20	3.15	10.53	13.06
7	2.81	3.89	11.77	14.42
8	3.45	4.66	12.99	15.76
9	4.12	5.43	14.21	17.08
10	4.80	6.22	15.41	18.39
u	− 1.96	− 1.28	+ 1.28	+ 1.96
k	+ 1.0	+ 0.2	+ 1.2	+ 2.0

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Measurement: basic terms

Measurements can only be used as the basis for responsible decisions if their limits of error are known. Here, statistical terms are used.

Definition of terms (as per DIN 1319):

Measured variable
Physical variable which is measured (length, density, etc.).

Measured value
Particular value of the measured variables, e.g. 3 m.

Measurement result
Value calculated from one or more measured values, e.g. mean $\bar{x}$.

Measurement error $F = x_a - x_r$
x_a indicated measured value;
x_r "correct" measured value.
Causes: measured object, measurement equipment, measurement procedure, environment, observer.

Relative measurement error
Normally: F/x_r
For designation of measuring devices F/x_e, where x_e = full-scale deflection of measuring device.

Systematic measurement errors
Measurement errors which, under the same conditions, have the same magnitude and sign.

Those systematic errors which can be detected are to be corrected $B = -F$, otherwise the measurement result is incorrect. Systematic errors which cannot be detected are to be estimated (f).

Random measurement errors
Measurement errors whose magnitudes and signs are randomly dispersed. Estimated using the standard deviation s.

Result of a series of measurements
If n measured values x_i are measured under the same conditions, the following should be specified as the measurement result:

$y = \bar{x}_E \pm u$ Confidence limits for correct measured value, where:
$\bar{x}_E = \bar{x} + B$ Corrected mean value
$u = t \cdot s/\sqrt{n} + |f|$ Measurement uncertainty.
Calculation of s P. 156,
for t, see Table 2 P. 159,
f Non-detected systematic errors.

Separation of measurement and manufacturing accuracy
On each of n products, a characteristic x_i is measured twice with measurement error f_{ik}:

$$y_{ik} = x_i + f_{ik} \; (i = 1, \ldots n;\; k = 1.2)$$

The differences between the 2 measured values on the same product contain 2 measurement errors:

$$z_i = y_{i1} - y_{i2} = f_{i1} - f_{i2}$$
$$\sigma_z^2 = 2\,\sigma_f^2$$
$$\sigma_y^2 = \sigma_x^2 + \sigma_f^2$$

The last two relationships can be used to determine the standard deviation σ_f of the measurement errors and the corrected standard deviation σ_x of the product characteristic x.

Standards
DIN 55 303 Statistical assessment of data
DIN 53 804 Statistical assessments
DIN 55 350 Quality assurance and statistics terms
DIN 40 080 Regulations and tables for attributive sampling
DIN 7186 Statistical tolerances
DIN/ISO 9000 Quality systems
DGQ-11-04 Quality-assurance terms and formulas (Beuth)

Literature
Graf, Henning, Stange: Formeln und Tabellen der Statistik (Formulas and tables for statistics) Springer-Verlag, Berlin, 1956;
Rauhut: Berechnung der Lebensdauerverteilung (Calculation of service life distribution) Glückauf-Verlag, Essen, 1982.

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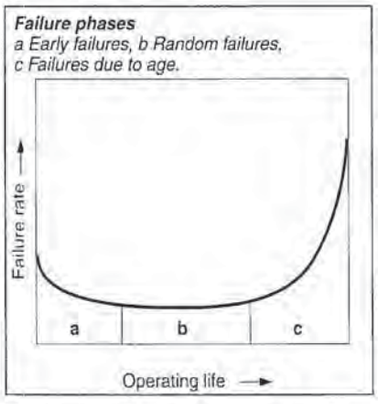
Reliability

According to DIN 40041, reliability is the sum total of those characteristics in the unit under investigation which exert an effect on the unit's ability to achieve specified requirements under given conditions during a specified period of time. Reliability is a constituent element of quality ("reliability is quality based on time").

The essential concept here is the word dependability. Dependability comprises the terms reliability, availability, safety, security and maintainability. Dependability therefore equates to the confidence placed in a service which is to be provided by a system.

Reliability quantifies availability; it is the probability that at any given time a system will prove to be fully operational. The failure rate is the conditional probability density of a component failing before time $t+dt$ provided it has survived beyond time t. The failure rate generally has the shape of a "bathtub curve", which can be described as the superimposition of three Weibull distributions with varying failure steepness components (see Chapter "Technical statistics").

Failure in electronic components is generally spontaneous, with no advance indication of impending defects. This condition is described by a constant failure rate (middle section of the curve). Neither quality control nor preventive maintenance can prevent such failures. Failures caused by incorrect component selection, excessive loads or abuse or manufacturing defects show a "burn-in behavior", described by a failure rate that falls with time while ageing of a component is represented by a rising failure rate (left or right section of the curve).



Failure phases
a Early failures, b Random failures, c Failures due to age.

Reliability analysis and prediction

Mutually supplementary analysis methods are applied to determine the potential failure risk associated with a product, i.e. to discover all possible effects of operational and internal failure, as well as external interference factors (e.g. operator error); these methods are used in different phases of the product's life cycle. Mainly FMEA and fault-tree analysis are used in the development of motor vehicles.

FMEA (DIN 25448, IEC 812)

FMEA (Failure Mode and Effects Analysis) is a "bottom-up" analysis. Starting from faults at the lowest level of the system hierarchy (generally components in design FMEA, function blocks in system FMEA, work steps in process FMEA), the analysis examines the way in which they spread to higher levels. In this way, all those critical system states caused by individual failures are detected and also evaluated in relation to each other. FMEA can be used in various stages of development and production.

Design FMEA: Under the precondition that the parts are manufactured in accordance with their drawings, products/components are examined for conformity between design and specifications in order to avoid errors in system design and to facilitate detection of field risks.

Process FMEA: Under the precondition that the specifications are correct, the process of product manufacture is examined for conformity with the drawings in order to avoid manufacturing errors.

System FMEA: The system components are examined as to their correct combined operation in order to avoid errors in system design and to facilitate detection of field risks.

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Fault-tree analysis (DIN 25 424)
Fault-tree analysis (FTA) is a "top-down" analysis procedure, which permits quantitative assessment of probabilities. Starting from the undesirable event (top event), all the conceivable causes are enumerated, even combinations of individual failures. When the occurrence probabilities of individual failures are known, it is possible to calculate the probability of the undesirable event occurring. For this purpose, above all for electrical components, there are data collections of failure rates such as Mil Hdbk 217E or SAE 870 050. However, their suitability for use with motor vehicles must be critically checked in individual cases.

Reliability enhancement

System reliability can always be improved by avoiding errors or narrowing tolerances. Preventive measures include e.g. selecting more reliable components with higher permissible loads; or (for electronic systems), since the availability of systems declines markedly as the number of components increases, reducing the number of components and thus connections through increased integration. As a rule of thumb, purely electronic components such as transistors or integrated circuits are responsible for 10 % of failures and sensors and final controlling elements for 30 %; however the connections between components and with the outside world are responsible for 60 % of failures. If preventive measures do not prove sufficient, then fault-tolerance measures (e.g. multichannel circuitry, self-monitoring) must be implemented in order to mask the effects of a defect.

Reliability planning
In the case of products to be newly developed, the reliability growth management procedure (RG, Mil Hdbk 189) provides a planning basis for the extent of testing work required to achieve a reliability target depending on the reliability initially available.
In the course of the development of a product, its reliability improves thanks to the causes of observed failures being analyzed and eliminated as far as possible. Strictly speaking, a statistical evaluation of the reliability of a product in its final version can only be started at the end of its development. However, in the case of the service lives demanded in the automobile industry, any such evaluation requires so much time as to delay the series launch. Under certain preconditions, the RG method allows engineers to assess the reliability of a product at any stage in its development. This assessment is based on the data of earlier product versions and the effectiveness of the failure-correction measures introduced. In this way, this procedure on the one hand reduces the time needed until series launch and on the other hand increases the available data volume and thus the confidence level.
If the current average service life MTTF (Mean Time To Failure) is plotted on a log-log scale against the cumulated operating time (total test time of all the test specimens), experience shows that on average this MTTF value increases in a straight line. Depending on the product and the effort expended, the upwards gradient of this line will be between 0.35 and 0.5. This empirical relationship between testing effort and achieved reliability can be used for planning.
A comparison between planning and current status can be made at any time. As the RG program progresses, intermediate reliability targets, specified in advance, must also be met. When planning the test program, it is essential to strike an acceptable balance between testing time, testing effort and available resources, and also to make a realistic estimate of the possible reliability gains.

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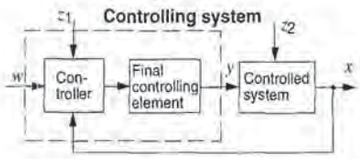
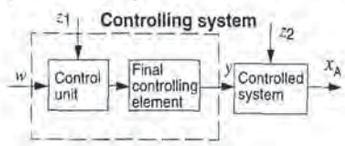
Control engineering

Terms and definitions (in accordance with DIN 19226)

Closed-loop control	Open-loop control
Closed-loop control Closed-loop control is a process by which a variable, the variable to be controlled (controlled variable x), is continuously recorded, compared with another variable, the reference variable w, and influenced according to the result of this comparison in the sense of an adaptation to the reference variable. The ensuing action takes place in a closed control loop. The function of closed-loop control is to adapt the value of the controlled variable to the value specified by the reference variable in spite of disturbances even if the given conditions do not allow for a perfect match.	**Open-loop control** Open-loop control is the process in a system in which one or more variables as input variables influence other variables as output variables on account of the rules characteristic of that system. This type of control is characterized by the open action via the individual transfer element or the open control loop. The term "control" is often used not only to denote the control process itself but also the entire system in which the control function takes place.
Closed control loop The closed control loop is formed by all the elements which take part in the closed action of the control operation. The control loop is a closed path of action which acts in one direction. The controlled variable x acts in a circular structure in the form of negative feedback back on itself. **In contrast to open-loop control, closed-loop control takes into account the influence of all the disturbances (z_1, z_2) in the control loop.** The closed control loop is subdivided into controlled system and controlling system.	**Open control loop** An open control loop is an arrangement of elements (systems) which act on each other in a chain structure. An open control loop as a whole can be part of a higher-level system and interact in any fashion with other systems. An open control loop can only counter the effect of the disturbance which is measured by the control unit (e.g. z_1); other disturbances (e.g. z_2) are unaffected. The open control loop is subdivided into controlled system and controlling system.

Controlling system (open and closed loops)
The open-loop or closed-loop controlling system is that part of the control loop which acts on the controlled system via the final-controlling element as determined by the control parameters.

System boundaries
The open-loop and closed-loop controlling systems include all those devices and elements which act directly to produce the desired condition within the control circuit.

Closed control loop	*Open control loop*
	
Input variables and output variable of closed-loop controlling system The input variables to the controlling system are the controlled variable x, the reference variable w and the disturbance(s) z_1. The output variable from the controlling system is the manipulated variable y.	**Input variables and output variable of open-loop controlling system** The input variables to the controlling system are the reference variable w and the disturbance(s) z_1. The output variable from the controlling system is the manipulated variable y.

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Closed-loop control	Open-loop control

Controlled system (open and closed loops)
The open-loop or closed-loop controlled system is that part of the control loop which represents the area of the system to be influenced according to the function.

Input variables and output variable of closed-loop controlled system	Input variable and output variable of open-loop controlled system
The input variables to the controlled system are the manipulated variable y and the disturbances z_2. The output variable from the controlled system is the controlled variable x.	The input variable is the manipulated variable y. The output variable is the object variable x_A or an output variable which influences the object variable in a predetermined manner.

Transfer elements and system elements
Open- and closed-loop controls can be subdivided into elements along the control loop.

In terms of equipment design and function these are called system elements and transfer elements, respectively.

In terms of closed- or open-loop control function, only the relationship between the variables and their values which act upon one another in the system are described.

Loop, direction of control action
Both the open control loop and the closed control loop comprise individual elements (or systems) which are connected together to form a loop.

The loop is that path along which open- or closed-loop control takes place. The direction of control action is the direction in which the control function operates.

The loop and the direction of control action need not necessarily coincide with the path and the direction of corresponding energy and mass flows.

Final controlling element, control point
The final controlling element is that element which is located at the upstream end of the controlled system, and which directly affects the flow of mass or energy. The location at which this action takes place is called the control point.

Disturbance point
The disturbance point is the location at which a variable not controlled by the system acts on the loop, thereby adversely affecting the condition which the control is designed to maintain.

Manipulated variable y, manipulating range Y_h
The manipulated variable y is both the output variable of the controlling system and the input variable of the controlled system. It transfers the action of the controlling system to the controlled system.

The manipulating range Y_h is the range within which the manipulated variable can be adjusted.

Reference variable w, reference-variable range W_h
The reference variable w of an open- or closed-loop control is a variable which is not acted on directly by the control; it is input to the loop from outside the control, and is that variable whose value is to be reflected by the output variable in accordance with the control parameters.

The reference-variable range W_h is that range within which the reference variable w of an open- or closed-loop control may lie.

Disturbances z, disturbance range Z_h
Disturbances z in open- and closed-loop controls are all variables acting from outside the control which adversely affect the action of the control. In many cases, the most important disturbance is the load or the throughput through the system. The disturbance range Z_h is that range within which the disturbance may lie without adversely affecting the operation of the control.

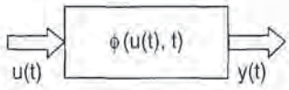
Object variable x_A, object range X_{Ah}
The object variable x_A of an open- or closed-loop control is that variable which the control is intended to influence.

The object range X_{Ah} of an open- or closed-loop control is that range within which the object variable may lie, with full functional capability of the control.

Control methods

Transfer elements

Transfer elements are the basic modules and core elements for the control-engineering analysis and synthesis of dynamic systems. They each contain an illustration specification which allows an output variable to be clearly assigned to each input variable that is permitted for the corresponding transfer element. The general graphical representation of a transfer element is the block diagram (see illustration).



The illustration specification ϕ is often termed the operator. With the operator ϕ, the functional relationship between the input and output variables of a transfer element can be described by

$$y(t) = \phi(u(t), t).$$

A summary of the simplest transfer elements can be found in the accompanying table.

A particular position among the general transfer elements is taken up by linear time-invariant transfer elements. For these elements, the following superposition principle applies

$$\phi(u_1(t) + u_2(t)) = \phi(u_1(t)) + \phi(u_2(t))$$

together with the condition of time invariance

$$y(t) = \phi(u(t)) \rightarrow y(t\text{-}T) = \phi(u(t\text{-}T)),\ T>0.$$

With the transfer elements connected to each other by the action lines, it is possible to depict complex dynamic systems such as e.g. a DC motor, hydraulic systems, mechatronic servo-systems etc.

Controller design

A series of analytical and synthesizing processes are available for application in control engineering. Control engineers distinguish here between time-range and frequency-range procedures. A classical and effective example of the frequency-range approach is the design of controllers using Bode diagrams. An efficient time-range procedure is the design of a state controller by means of pole specification or the Riccati controller.

Many of the problems posed by the requirements of control engineering are solved by using certain controller types which are composed as far as possible of the following four transfer elements:

- *P* element (proportional-action transfer element),
- *I* element (integral-action transfer element),
- *D* element (derivative-action transfer element),
- P-T_1 element (1st order time-delay element).

Parallel connection on the input side, addition of the output variables from the three transfer elements *P*, *I*, *D* and downstream connection of the P-T_1 element can be used to create the controller types *P*, *I*, *PI*, *PP*, *PD*, *PID*, *PPD*. See DIN 19226 for characteristics and system performance.

Subdivision of control modes

In control-engineering practice, distinctions are made between the individual control modes according to the following attributes: continuous-time/continuous-value, continuous-time/discrete-value, discrete-time/continuous-value and discrete-time/discrete-value. Of these four attributes, only the instances of continuous-time/continuous-value and discrete-time/discrete-value control are of significance.

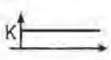
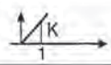
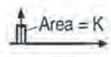
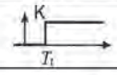
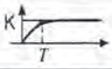
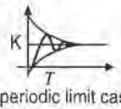
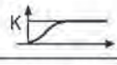
Continuous-time/
continuous-value control

In continuous-time/continuous-value control, the controlled variable is recorded in an uninterrupted process and compared with the reference variable. This comparison provides the basis for continuous-time and continuous-value generation of the manipulated variable.

Continuous-time/continuous-value control is also referred to as analog control.

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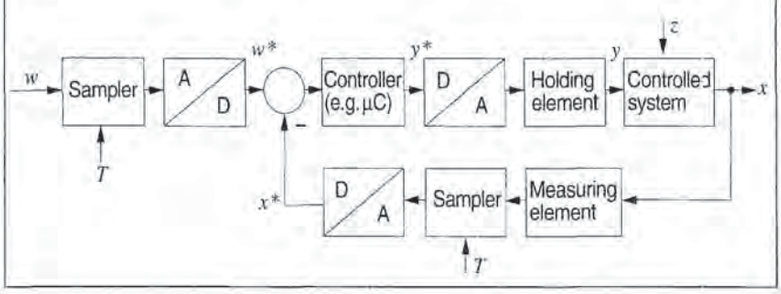
Table: Summary of some transfer elements

Designation	Functional relationship	Transfer function	Course of step response	Symbol
P element	$y = Ku$	K		
I element	$y = K\int_0^t u(\tau)\,d\tau$	$\frac{K}{s}$		
D element	$y = K\dot{u}$	Ks		
TZ element T_t element	$y(t) = Ku(t-T_t)$	$Ke^{-T_t s}$		
S element	$y = u_1 \pm \ldots \pm u_n$			
P-T_1 element VZ_1 element	$T\dot{y} + y = Ku$	$\frac{K}{1+Ts}$		
P-T_2 element VZ_2 element	$T^2\ddot{y} + 2dT\dot{y} + y = Ku$	$\frac{K}{1+2dTs+T^2s^2}$	Periodic case: d < 1  Aperiodic limit case: d ≧ 1 	

Discrete-time/discrete-value control

In discrete-time/discrete-value control, the controlled variable is recorded, quantified and subtracted from the quantified reference variable only at the sampling instants. The manipulated variable is calculated on the basis of the control difference thus created. For this purpose, an algorithm is generally used which is implemented in the form of a software program on a microcontroller. A/D and D/A converters are used as process interfaces. Discrete-time/discrete-value control is also referred to as digital control.

Block diagram of digital control
*T Sampling time, * Digital signal values*



Examples of closed-loop control systems in motor vehicles (simplified)

Control system	Object variable (x_A)	Variables: Controlled variable (x)	Variables: Reference variable (w)	Manipulated variable (y)	Disturbances (z)	Controlling system	Elements: Final controlling element	Controlled system
Lambda closed-loop control	Air/fuel ratio (λ)	O_2 content of exhaust gas	$\lambda = 1.0$ (fixed-command control)	Injected fuel quantity	Inexact pilot control, leaks, crankcase ventilation	Lambda control unit and lambda sensor	Fuel injectors	Combustion chamber; part of intake system and exhaust system up to λ sensor
Rotational-speed control in diesel engines	Engine speed		Setpoint speed (follow-up control)	Injected fuel quantity	Load	Governor	Fuel-injection pump	Mixture-formation area in engine
Antilock braking system (ABS control)	Wheel slip	Wheel slip	Slip limit (adaptive)	Braking pressure	Road and driving conditions	Controller in ABS control unit	Pressure-control valve	Tires, road
Temperature control (passenger compartment)	Interior temperature	Interior, discharge, outside-air temperatures	Setpoint temperature (follow-up control)	Hot-water flow rate or hot-/cold-air mixture ratio	Engine temp., outside temp.; heat radiation; driving speed; engine speed	Temperature regulator and temperature sensor	Electromagnetic heating valve or air flap	Passenger compartment

Examples of open-loop control systems in engines

Control system	Object variables (x_A)	Variables: Reference variables (w)	Variables: Input variables of controlling system	Disturbances (z)	Manipulated variable (y)	Controlling system	Elements: Final controlling element	Controlled system
Jetronic gasoline injection	Air/fuel ratio	Air/fuel ratio (setpoint)	Engine speed, engine temperature, vehicle system voltage, air quantity, air temperature, throttle-valve position	Fuel temperature, manifold-wall fuel condensation	Duration of injection	Jetronic control unit with various measuring elements	Fuel injectors	Mixture-formation area
Electronic ignition systems	Ignition point	Ignition point (setpoint)	Engine speed, crankshaft position, intake-manifold pressure, throttle-valve position, engine temperature, vehicle system voltage	Condition of spark plugs, air/fuel ratio, fuel quality, mechanical tolerances	Ignition point	Ignition control unit	Ignition output stage	Combustion chamber in engine

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Data processing in motor vehicles

Requirements

Highly sophisticated state-of-the-art open-loop and closed-loop control concepts are essential for meeting the demands for function, safety, environmental compatibility and comfort associated with the wide range of automotive subsystems installed in modern-day vehicles. Sensors monitor reference and controlled variables, which an electronic control unit (ECU) then converts into the signals required to adjust the final controlling elements/actuators. The input signals can be analog (e.g. voltage characteristic at pressure sensor), digital (e.g. switch position) or pulse-shaped (i.e. information content as a function of time; e.g. engine-speed signal). These signals are processed after being conditioned (filtering, amplification, pulse shaping) and converted (analog/digital); digital signal-processing methods are preferred.

Thanks to modern semiconductor technology, powerful computer units, with their accompanying program and data memories, and special peripheral circuitry, designed specifically for real-time applications, can all be integrated on a limited number of chips.

Modern vehicles are equipped with numerous digital control units (ECUs), e.g. for engine management, ABS and transmission-shift control. Improved performance and additional functions are obtained by synchronizing the processes controlled by the individual control units and by mutual real-time adaptation of the respective parameters. An example of this type of function is traction control (TCS), which reduces the driving torque when the drive wheels spin.

Up to now, data between the control units (in the example cited above, ABS/TCS and engine management) have been exchanged mostly through separate individual circuits. However, this type of point-to-point connection is only suitable for a limited number of signals. The data-transmission potential between the individual ECUs can be enhanced by using a simple network topology designed specifically for serial data transmission in automotive applications.

Microcomputer

The microcomputer comprises both the central processing unit (CPU) for processing arithmetic operations and logical relationships, and special function modules to monitor external signals and to generate the control signals for external servo elements. These peripheral modules are largely capable of assuming complete control of real-time operations. The program-controlled CPU could only discharge these at the price of both additional complication and curtailment in the number of functions (e.g. determining the moment at which an event occurred).

Computing capacity

Apart from the architecture (e.g. accumulator, register machine) and the word length (4...32 bits), the product of the internal clock frequency and the average number of clock pulses required per instruction determines the capacity of a CPU:

- Clock frequency: 1...40 MHz (typical),
- Clock pulses per instruction: 1...32 pulses (typical), depending on the CPU's architecture and the instruction (e.g. 6 pulses for addition, 32 pulses for multiplication).

Electronic control unit (ECU)

Digital input signals

Register a switch position or digital sensor signals (e.g. rotational-speed pulses from a Hall-effect sensor).
Voltage range: 0 V to battery voltage

Analog input signals

Signals from analog sensors (lambda sensor, pressure sensor, potentiometer).
Voltage range: several mV up to 5 V.

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Microcomputer
Microcomputer
Microprocessor (CPU)
Central processing unit
ALU
Arithmetic and logic unit
4, 8, 16, 32 bit
Volatile read/write memory (RAM) for variable data
Memory capacity:
64 bytes ... 32 kbytes
Read-only memory (ROM, EPROM, flash EPROM) for programs and permanent data records
Memory capacity:
2 kbytes ... 512 kbytes
Non-volatile read/write memory (EEPROM)
Memory capacity:
32 bytes ... 1kbyte
Internal clock (oscillator)
Bus 4, 8, 16, 32 bit data circuit
Interrupt controller
Watchdog
Event counter
(Counter)
Counter
8 ... 64 bit
Signal acquisition and output with time reference
(Timer, Time Processing Unit, input-capture, output-compare register)
Resolution
≥ 50 ns
Timing range
50 ns ... 1s
Analog/ digital (A/D) converter
(A/D converter)
Resolution
8 ...10 bit
4 ... 32 channels
Digital I/O (inputs/ outputs)
(Digital I/O)
8 ... 32 channels
Serial interface
(UART, SPI, CAN)
Data rate
200 bit/s ... 1 Mbit/s
Bus controller
(Bus controller)
Communication with external chips via address/data bus

Pulse-shaped input signals
Signals from inductive min^{-1} sensors. After signal conditioning, they are processed further as digital signals.
Voltage range: 0.5 V to 100 V.

Initial conditioning of input signals
Protective circuits (passive: R and RC circuits; active: special surge-proof semiconductor elements) are used to limit the voltage of the input signals to acceptable levels (operating voltage of the microcomputer). Filters remove most of the superimposed noise from the transmitted signals, which are then amplified to the microprocessor's input voltage.
Voltage range: 0 V to 5 V.

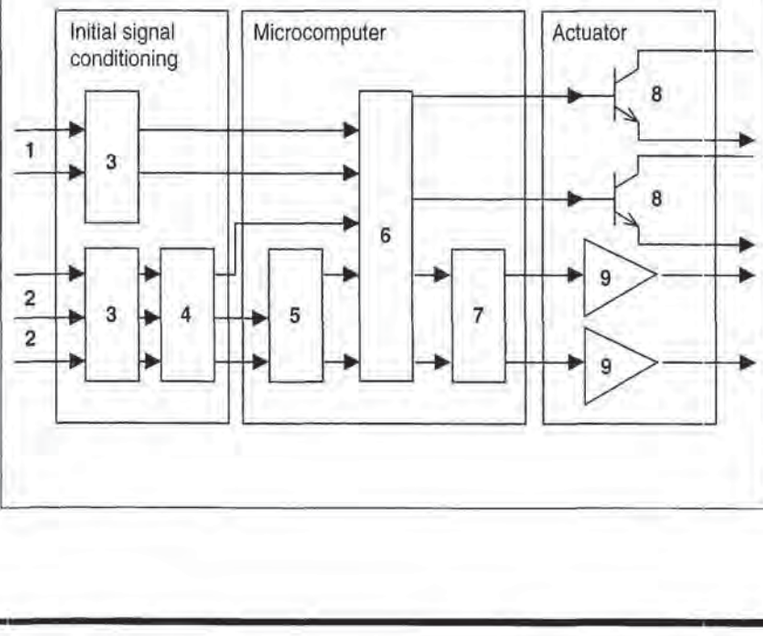
Signal processing
ECUs generally process signals in digital form. Rapid, periodic, real-time signals are processed in hardware modules specifically designed for the particular function. Results, e.g. a counter reading or the time of an event, are transmitted in registers to the CPU for further processing. This procedure substantially reduces the CPU's interrupt-response requirements (µs range).

The amount of time available for calculations is determined by the open-loop or closed-loop control system (ms range).

The software contains the actual control algorithms. Depending on the data, an almost unlimited number of logic operations can be established and data records stored and processed in the form of parameters, characteristic curves and multidimensional program maps.

Output signals
Power switches and power-gain circuits amplify the microprocessor's output signals (0 to 5 V, several mA) to the levels required by the various final-controlling elements/actuators (battery voltage, several A).

Signal processing in ECU
1 Digital input signals, 2 Analog input signals, 3 Protective circuit, 4 Amplifier, filter, 5 A/D converter, 6 Digital signal processing, 7 D/A converter, 8 Circuit-breaker, 9 Power amplifier.



Complete system

Logistical concept (CARTRONIC)
The concept divides the total automotive electrical system into conveniently-dimensioned subsystems. Units with closely-related functions (units with a high rate of mutual data exchange) are combined in a sub-network. This logistical concept results in sub-networks with varying requirements for transmission capacity, while data transmission remains compatible.

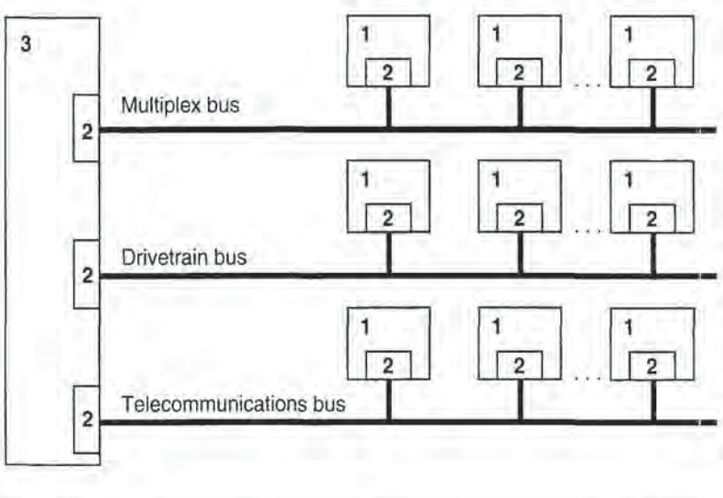
Topology
At the logical level, all of the known communications systems developed for automotive applications are based on a single serial connection of the ECUs. The physical layout employs one-wire or differential two-wire interfaces in bus form to connect the control units with one another.

Protocol
The protocol consists of a specific collection of execution statements which are used to control data communications between the individual control units. Procedures have been laid down for bus access, message structure, bit and data coding, error recognition and response and the identification of faulty bus users (CAN, P. 884).

Transmission speed
Multiplex bus: 10 kbit/s...125 kbit/s
Drivetrain bus: 125 kbit/s...1 Mbit/s
Telecommunications bus:
10 kbit/s...125 kbit/s.

Latency time
The period that elapses between the transmitter's send request and the target station's receipt of the error-free message.
Multiplex bus: 5 ms...100 ms
Drivetrain bus: 0.5 ms...10 ms
Telecommunications bus:
5 ms...100 ms.

Interfacing of bus systems
1 ECU, 2 Bus controller, 3 Gateway.



Chemical elements

Element	Symbol	Type[1]	Atomic number	Relative atomic mass	Valence	Year discovered	Discoverer(s)
Actinium	Ac	m	89	227	3	1899	Debierne
Aluminum	Al	m	13	26.9815	3	1825	Oersted
Americium[2]	Am	m	95	243	2; 3; 4; 5; 6	1944	Seaborg et al
Antimony	Sb	m	51	121.760	3; 5	Antiquity	
Argon	Ar	g	18	39.948	0	1894	Ramsay, Rayleigh
Arsenic	As	n	33	74.9216	3; 5	C13	Magnus
Astatine	At	n	85	210	1; 3	1940	Corson, MacKenzie, Segré
Barium	Ba	m	56	137.327	2	1808	Davy
Berkelium[2]	Bk	m	97	247	3; 4	1949	Seaborg et al
Beryllium	Be	m	4	9.0122	2	1797	Vauquelin
Bismuth	Bi	m	83	208.9804	1; 3; 5	C15	Unknown
Bohrium[2]	Bh	m[3]	107	262	–[4]	1981	Armbruster, Münzenberg et al
Boron	B	n	5	10.811	3	1808	Gay-Lussac, Thénard, Davy
Bromine	Br	n	35	79.904	1; 3; 4; 5; 7	1826	Balard
Cadmium	Cd	m	48	112.411	1; 2	1817	Strohmeyer
Caesium	Cs	m	55	132.9054	1	1860	Bunsen, Kirchhoff
Calcium	Ca	m	20	40.078	2	1808	Davy
Californium[2]	Cf	m	98	251	2; 3; 4	1950	Seaborg et al
Carbon	C	n	6	12.011	2; 4	Antiquity	
Cer	Ce	m	58	140.116	3; 4	1803	Berzelius et al
Chlorine	Cl	g	17	35.4527	1; 3; 4; 5; 6; 7	1774	Scheele
Chromium	Cr	m	24	51.9961	1; 2; 3; 4; 5; 6	1780	Vauquelin
Cobalt	Co	m	27	58.9332	1; 2; 3; 4; 5	1735	Brandt
Copper	Cu	m	29	63.546	1; 2; 3	Antiquity	
Curium[2]	Cm	m	96	247	2; 3; 4	1944	Seaborg et al
Dubnium[2]	Db	m[3]	105	262	5 (?)	1967/70	Disputed (Flerov or Ghiorso)
Dysprosium	Dy	m	66	162.50	2; 3; 4	1886	Lecoq de Boisbaudran
Einsteinium[2]	Es	m	99	252	3	1952	Ghiorso et al
Erbium	Er	m	68	167.26	3	1842	Mosander
Europium	Eu	m	63	151.964	2; 3	1901	Demarcay
Fermium[2]	Fm	m[3]	100	257	3	1952	Ghiorso et al
Fluorine	F	g	9	18.998	1	1887	Moissan
Francium	Fr	m	87	223	1	1939	Perey
Gadolinium	Gd	m	64	157.25	2; 3	1880	de Marignac
Gallium	Ga	m	31	69.723	1; 2; 3	1875	Lecoq de Boisbaudran
Germanium	Ge	m	32	72.61	2; 4	1886	Winkler
Gold	Au	m	79	196.9665	1; 3; 5; 7	Antiquity	

[1]) m Metal, n Nonmetal, g Gas.
[2]) Artificially produced; does not occur naturally.
[3]) Unknown. The elements are presumably 100...112 metals.
[4]) Unknown.

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Element	Symbol	Type[1]	Atomic number	Relative atomic mass	Valence	Year discovered	Discoverer(s)
Hafnium	Hf	m	72	178.49	4	1923	Hevesey, Coster
Hassium[2]	Hs	m[3]	108	265	–[4]	1984	Armbruster, Münzenberg et al
Helium	He	g	2	4.003	0	1895	Ramsay, Cleve, Langlet
Holmium	Ho	m	67	164.9303	3	1878	Cleve, Delafontaine, Soret
Hydrogen	H	g	1	1.0079	1	1766	Cavendish
Indium	In	m	49	114.818	1; 2; 3	1863	Reich, Richter
Iodine	I	n	53	126.9045	1; 3; 5; 7	1811	Courtois
Iridium	Ir	m	77	192.217	3; 4	1803	Tennant
Iron	Fe	m	26	55.845	2; 3; 6	Antiquity	
Krypton	Kr	g	36	83.80	0; 2	1898	Ramsay
Lanthanum	La	m	57	138.9055	3	1839	Mosander
Lawrencium[2]	Lr	m[3]	103	262	3	1961	Ghiorso et al
Lead	Pb	m	82	207.2	2; 4	Antiquity	
Lithium	Li	m	3	6.941	1	1817	Arfvedson
Lutetium	Lu	m	71	174.967	3	1907	Urbain, James
Magnesium	Mg	m	12	24.3050	2	1755	Black
Manganese	Mn	m	25	54.9380	2; 3; 4; 6; 7	1774	Grahn
Meitnerium	Mt	m[3]	109	266	–[4]	1982	Armbruster, Münzenberg et al
Mendelevium[2]	Md	m[3]	101	258	2; 3	1955	Seaborg, Ghiorso et al
Mercury	Hg	m	80	200.59	1; 2	Antiquity	
Molybdenum	Mo	m	42	95.94	2; 3; 4; 5; 6	1781	Hjelm
Neodymium	Nd	m	60	144.24	2; 3; 4	1885	Auer von Welsbach
Neon	Ne	g	10	20.1797	0	1898	Ramsay, Travers
Neptunium[2]	Np	m	93	237	3; 4; 5; 6	1940	McMillan, Abelson
Nickel	Ni	m	28	58.6934	2; 3	1751	Cronstedt
Niobium	Nb	m	41	92.9064	3; 4; 5	1801	Hatchett
Nitrogen	N	g	7	14.0067	2; 3; 4; 5	1772	Rutherford
Nobelium[2]	No	m[3]	102	259	2; 3	1958	Ghiorso, Seaborg
Osmium	Os	m	76	190.23	2; 3; 4; 5; 7; 8	1803	Tennant
Oxygen	O	g	8	15.9994	1; 2	1774	Priestley, Scheele
Palladium	Pd	m	46	106.42	2; 4	1803	Wollaston
Phosphorus	P	n	15	30.9738	3; 5	1669	Brandt
Platinum	Pt	m	78	195.078	2; 4; 5; 6	Antiquity	(Mayas)
Plutonium[2]	Pu	m	94	244	3; 4; 5; 6	1940	Seaborg et al
Polonium	Po	m	84	209	2; 4; 6	1898	M. Curie
Potassium	K	m	19	39.0983	1	1807	Davy
Praseodymium	Pr	m	59	140.9076	3; 4	1885	Auer von Welsbach
Promethium	Pm	m	61	145	3	1945	Marinsky et al
Protactinium	Pa	m	91	231.0359	4; 5	1917	Hahn, Meitner, Fajans

[1] m Metal, n Nonmetal, g Gas.
[2] Artificially produced; does not occur naturally.
[3] Unknown. The elements are presumably 100...112 metals.
[4] Unknown.

Chemical elements (continued)

Element	Symbol	Type[1]	Atomic number	Relative atomic mass	Valence	Year discovered	Discoverer(s)
Radium	Ra	m	88	226	2	1898	P. & M. Curie
Radon	Rn	g	86	222	0; 2	1900	Dorn
Rhenium	Re	m	75	186.207	1; 2; 3; 4; 5; 6; 7	1925	Noddack
Rhodium	Rh	m	45	102.9055	1; 2; 3; 4; 5; 6	1803	Wollaston
Rubidium	Rb	m	37	85.4678	1	1861	Bunsen, Kirchhoff
Ruthenium	Ru	m	44	101.07	1; 2; 3; 4; 5; 6; 7; 8	1808	Klaus
Rutherfordium[2]	Rf	m[3]	104	261	4 (?)	1964/69	Disputed (Flerov or Ghiorso)
Samarium	Sm	m	62	150.36	2; 3	1879	Lecoq de Boisbaudran
Scandium	Sc	m	21	44.9559	3	1879	Nilson
Seaborgium[2]	Sg	m[3]	106	263	–[4]	1974	Ghiorso et al
Selenium	Se	n	34	78.96	2; 4; 6	1817	Berzelius
Silver	Ag	m	47	107.8682	1; 2	Antiquity	
Silicon	Si	n	14	28.0855	2; 4	1824	Berzelius
Strontium	Sr	m	38	87.62	2	1790	Crawford
Sodium	Na	m	11	22.9898	1	1807	Davy
Sulfur	S	n	16	32.066	1; 2; 3; 4; 5; 6	Antiquity	
Tantalum	Ta	m	73	180.9479	1; 3; 4; 5	1802	Eckeberg
Technetium	Tc	m	43	98	4; 5; 6; 7	1937	Perrier, Segrè
Tellurium	Te	m	52	127.60	2; 4; 6	1783	Müller
Terbium	Tb	m	65	158.9253	3; 4	1843	Mosander
Thallium	Tl	m	81	204.3833	1; 3	1861	Crookes
Thorium	Th	m	90	232.0381	2; 3; 4	1829	Berzelius
Thulium	Tm	m	69	168.9342	2; 3	1879	Cleve
Tin	Sn	m	50	118.710	2; 4	Antiquity	
Titanium	Ti	m	22	47.87	2; 3; 4	1791	Gregor
Tungsten	W	m	74	183.84	2; 3; 4; 5; 6	1783	Elhuijar
Ununbium[2][5]	Uub	m[3]	112	277	–[4]	1996	Armbruster, Hofmann
Ununnilium[2][5]	Uun	m[3]	110	270	–[4]	1994	Armbruster, Hofmann
Unununium[2][5]	Uuu	m[3]	111	272	–[4]	1994	Armbruster, Hofmann
Uranium	U	m	92	238.0289	3; 4; 5; 6	1789	Klaproth
Vanadium	V	m	23	50.9415	2; 3; 4; 5	1801	del Rio
Xenon	Xe	g	54	131.29	0; 2; 4; 6; 8	1898	Ramsay, Travers
Ytterbium	Yb	m	70	173.04	2; 3	1878	de Marignac
Yttrium	Y	m	39	88.9059	3	1794	Gadolin
Zinc	Zn	m	30	65.39	2	Antiquity	
Zirconium	Zr	m	40	91.224	3; 4	1789	Klaproth

[1] m Metal, n Nonmetal, g Gas.
[2] Artificially produced; does not occur naturally.
[3] Unknown. The elements are presumably 100...112 metals.
[4] Unknown.
[5] Provisional IUPAC designation.

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Periodic table of elements

Ia	IIa	IIIa	IVa	Va	VIa	VIIa	VIIIa
1 H 1.008							2 He 4.003
3 Li 6.941	4 Be 9.012	5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
11 Na 22.990	12 Mg 24.305	13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.066	17 Cl 35.453	18 Ar 39.948
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.87	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845
37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07
55 Cs 132.905	56 Ba 137.327	57 La* 138.906	72 Hf 178.49	73 Ta 180.948	74 W 183.84	75 Re 186.207	76 Os 190.23
87 Fr (223)	88 Ra (226)	89 Ac** (227)	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (262)	108 Hs (265)

VIIIb	Ib	IIb
27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.39
45 Rh 102.906	46 Pd 106.42	47 Ag 107.868	48 Cd 112.411
77 Ir 192.217	78 Pt 195.078	79 Au 196.967	80 Hg 200.59
109 Mt (266)	110 Uun (269)	111 Uuu (272)	112 Uub (277)

*	58 Ce 140.116	59 Pr 140.908	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.964	64 Gd 157.25	65 Tb 158.925	66 Dy 162.50	67 Ho 164.930	68 Er 167.26	69 Tm 168.934	70 Yb 173.04	71 Lu 174.967
**	90 Th 232.038	91 Pa 231.036	92 U 238.029	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

All elements are arranged sequentially according to atomic number (proton number). The horizontal rows represent the periods (or shells), while the various element groups are divided into vertical columns. The relative atomic masses are indicated below the element symbols. The values given in parentheses are the mass numbers (nucleon numbers) of the stablest isotopes of artificially produced radioactive elements.

Material terminology[1])

State of aggregation
There are three classical states of aggregation depending upon the arrangement of the elementary particles (atoms, molecules, ions): solid, liquid and gaseous. Plasma (ionized gas which has high electrical conductivity) is often considered as a fourth state of aggregation.

Solution
A solution is a homogeneous mixture of different materials which are distributed at the atomic or molecular level.

Compound
A compound is the union of two or more chemical elements whose masses are always in the same ratio with respect to one another. Compounds which have metallic characteristics are called intermetallic compounds.

Dispersion
A dispersion or disperse system consists of at least two materials; one material, called the disperse phase, is finely distributed in the other material, called the dispersion medium.

Suspension
A suspension is a disperse system in which solid particles are distributed in a liquid. Examples: graphite in oil, clay in water.

Emulsion
An emulsion is a disperse system in which droplets of one liquid are distributed in a second liquid. Examples: drilling oil, butterfat in milk.

Colloid
A colloid is a disperse system in which the particles of the disperse phase have linear dimensions ranging from roughly 10^{-9} to 10^{-6} m. Examples: smoke, latex, gold-ruby glass.

[1]) The following is a list of the most important material terms and parameters which appear in subsequent materials tables and are not defined elsewhere.

Material parameters[1])

Density
Density is the ratio of the mass to the volume of a specific amount of substance.

See DIN 1306, 1984 edition, for special density terms.

Radial crushing strength
Radial crushing strength is a strength parameter which is specified in particular for the sintered metals used for plain bearings. It is determined from the pressure test when a hollow cylinder is crushed.

For additional information see "Technical Conditions of Delivery for PM Parts (Sint. 03)", Aug. 1981 edition.

Yield strength (0.2%)
The 0.2% yield strength is that tensile stress which causes permanent (plastic) elongation of 0.2% in a solid body; it is determined from the σ-ε curve of a tensile test with a defined stress-increase rate.

Cyclic loading of a test specimen by tensile/compressive stresses with increasing amplitude yields the cyclic σ-ε curve and from this the cyclic 0.2% yield strength. When compared with the monotonic 0.2% yield strength, this value is a measure of possible softening or hardening brought about by cyclic over-stressing.

The yield strength ratio is the ratio of the cyclic to the monotonic 0.2% yield strength. $\gamma > 1$ signifies cyclic hardening, $\gamma < 1$ cyclic softening.

Fracture toughness
Fracture toughness, or K_{Ic} factor, is a material parameter of fracture mechanics. The K_{Ic} factor is that stress intensity ahead of a crack tip which leads to unstable crack propagation, and therefore to the fracture of the structural part. If the K_{Ic} factor of a material is known, the critical fracture load can be determined from crack length, or critical crack length can be determined from the given external loading value.

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Specific heat capacity
Specific heat capacity (specific heat) is the quantity of heat in J required to raise the temperature of 1 kg of a substance by 1 K. It is dependent on temperature.

In the case of gases, it is necessary to differentiate between specific heat capacity at constant pressure and at constant volume (symbols: c_p and c_v, respectively). This difference is usually negligible in the case of solid and liquid substances.

Specific heat of fusion
The specific heat of fusion of a solid is the quantity of heat in J required to transform 1 kg of a substance at fusion temperature from the solid to the liquid state.

Specific heat of evaporation
The specific heat of evaporation of a liquid is the quantity of heat in J required to evaporate 1 kg of this liquid at boiling temperature. The specific heat of evaporation is highly dependent upon pressure.

Thermal conductivity
Thermal conductivity is the quantity of heat in J which flows in 1 s through a material sample which has a surface area of 1 m² and a thickness of 1 m if the temperatures of the two end surfaces of the sample differ by 1 K.

In the case of liquids and gases, thermal conductivity is often highly dependent upon temperature, whereas temperature is generally not significant in the case of solids.

Coefficient of thermal expansion
The coefficient of linear (or longitudinal) expansion indicates the relative change in length of a material caused by a change in temperature of 1 K. For a temperature variation ΔT, the change in length is defined as $\Delta l = l \cdot \alpha \cdot \Delta T$. The cubic or volume coefficient of expansion is defined in the same way. The volume coefficient of expansion for gases is roughly 1/273. For solids, it is roughly three times as large as the coefficient of linear expansion.

Permeability
Permeability μ or relative permeability μ_r describes the dependence of magnetic induction on the applied field:

$$B = \mu_r \cdot \mu_0 \cdot H$$

Depending on the application in which the magnetic material is used, there are roughly 15 types of permeability. These are defined according to modulation range and type of loading (direct-current or alternating-current field loading). Examples:

Initial permeability μ_a
Slope of the virgin curve for $H \rightarrow 0$. In most cases, however, the slope for a specific field strength (in mA/cm) is specified rather than this limit value. Example: μ_4 is the slope of the virgin curve for $H = 4$ mA/cm.

Maximum permeability μ_{max}
Maximum slope of the virgin curve.

Permanent permeability μ_p or μ_{rec}
Average slope of a retrograde magnetic hysteresis loop whose lowest point usually lies on the demagnetization curve.

$$\mu_p = \Delta B/(\Delta H \cdot \mu_0)$$

Temperature coefficient of magnetic polarization $TK(J_s)$
This temperature coefficient indicates the relative change in saturation polarization as the temperature changes, it is given in % per kelvin.

Temperature coefficient of coercive field strength $TK(H_c)$
This temperature coefficient indicates the relative change, in % per kelvin, of coercive field strength as the temperature changes.

Curie point (Curie temperature) T_c
The Curie point is the temperature at which the magnetization of ferromagnetic and ferrimagnetic materials becomes zero and at which they behave like paramagnetic materials (sometimes defined differently, see characteristic values of soft ferrites on P. 208).

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Material groups

The materials in current industrial use can be classified according to one of four categories. Each of these, in turn, includes various subclassifications:

- Metals: wrought, rolled, cast etc. metals, sintered metals,
- Nonmetallic inorganic materials: ceramic materials, glass,
- Nonmetallic organic materials: natural materials, plastics and elastomers
- Composite materials.

Magnetic materials form an important material group with special characteristics, and will be described separately.

Metals

Metals generally exhibit a crystalline structure. Their atoms are arranged in a regular crystal lattice. The valence electrons of the atoms are not bound to a special atom, but rather are able to move freely within the metal lattice (metallic bond).

This special metal-lattice structure explains the characteristic properties of metals: high electrical conductivity which decreases as temperature increases; good thermal conductivity; low transparency to light; high optical reflectivity (metallic luster); ductility and the resulting high degree of formability. Alloys are metals which consist of two or more components, of which at least one is a metal.

Wrought, rolled, cast etc. metals

Apart from small flaws such as shrink-holes and nonmetallic inclusions, such metals contain no voids. Components are produced by casting, either directly (e.g. gray cast iron, diecast aluminum) or from wrought products (machined with or without cutting).

Sintered metals

Sintered metals are usually produced by pressing powder or by the injection-molding of mixtures composed of metallic powder and plastic. Following the removal of parting agents and plasticizers, the parts are then sintered to give them their characteristic properties. Sintering is a type of heat treatment in a range from 800 to 1300 °C. In addition to its chemical composition, the sintered part's properties and application are to a large extent determined by its degree of porosity. Components with complicated shapes can often be made particularly cheaply from sintered metals, either ready-to-install or requiring only little finishing.

Nonmetallic inorganic materials

These materials are characterized by ion bonds (e.g., ceramic materials), mixed (heteropolar/homopolar) bonds (e.g., glass) or homopolar bonds (e.g., carbon). These kinds of bonds, in turn, are responsible for several characteristic properties: generally poor thermal and electric conductivity (the latter increases with temperature), poor luminous reflectance, brittleness and thus almost complete unsuitability for cold forming.

Ceramics

Ceramics are at least 30 % crystalline in nature; most ceramics also contain amorphous components and pores. Their manufacture is similar to that of sintered metals, however nonmetallic powders or powder mixtures are used; sintering at temperatures generally higher than 1000 °C gives ceramics their characteristic properties. Ceramic structural parts are sometimes also shaped at high temperatures or even by a melting process, with subsequent crystallization.

Glass

Glass is viewed as under-cooled, frozen liquid. Its atoms are only in a short-range order. It is regarded as amorphous. Molten glass turns to solid glass at the transformation temperature T_g (T_g is derived from the former designation "glass formation temperature"). T_g is dependent on a variety of parameters and therefore not clearly determined (better: transformation range).

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Nonmetallic organic materials

These materials consist mainly of compounds of the elements carbon and hydrogen, whereby nitrogen, oxygen and other elements are also often included in the structure. In general, these materials exhibit low thermal and electric conductivity, and are combustible.

Natural materials

The best-known natural materials are wood, leather, resin, natural rubber, and fibers made of wool, cotton, flax, hemp and silk. Most natural materials are used in processed or refined form, or serve as raw materials in the manufacture of plastics.

Plastics

A significant characteristic of plastics is their macromolecular structure. There are three different types of plastics: thermoplastics, thermosets (sometimes also called thermosetting plastics) and elastomers. The transformation temperature T_E for thermoplastics and thermosets lies above the temperature of application; the reverse is true for elastomers. T_E (comparable with the transformation temperature T_g of glass) is understood to mean that temperature below which intrinsic molecular motion ceases. The major importance of thermoplastics and thermosets lies in the fact that they can be shaped and molded without machining.

Thermoplastics

Thermoplastics soften and lose their dimensional stability at temperatures above T_E. Their physical properties are highly temperature-dependent. The effect of temperature can be somewhat reduced by using mixtures of thermoplastic polymers.

Thermosets

Thermosets retain their dimensional stability up to temperatures almost as high as the processing temperature due to closely-spaced cross-linking. Their mechanical properties are less temperature-dependent than those of thermoplastics. Fillers are usually added to thermosetting resins to counteract their inherent brittleness.

Elastomers

Elastomers are useful in many applications because of their elasticity, which is only present at temperatures above T_E. Elastomers are vulcanized (widely-spaced cross-linking) in order to stabilize their molecular bonds.

Composite materials

Composite materials consist of at least two physically or chemically different components. These components must be tightly bound together at a defined interface. The formation of the interface must have no negative effect on any of the bound components. Under these two conditions it is possible to bond many materials together. Composite materials exhibit combinations of properties which none of the components alone possesses. Different classes of composite materials are:

Particle composite materials (e.g., powder-filled resins, hard metals, plastic-bonded magnets, cermets),

Laminated composite materials (e.g., composite or sandwich panels, resin-bonded fabric),

Fiber composite materials (e.g., with fiberglass, carbon-fiber, and cotton-fiber-reinforced plastics).

Magnetic materials

Materials which have ferromagnetic or ferrimagnetic properties are called magnetic materials and belong to one of two groups: metals or nonmetallic inorganic materials. They are characterized by their ability to store magnetic energy (permanent magnets), or by their good magnetic flux conductivity (soft magnets). In addition to ferromagnets and ferrimagnets, diamagnetic, paramagnetic and antiferromagnetic materials also exist. They differ from each other in terms of their permeability μ (P. 68) or the temperature-dependence of their susceptibility $\varkappa$.[1])

$$\mu_r = 1 + \varkappa$$

[1]) Ratio of the magnetization of a substance to the magnetic field strength or excitation.

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Diamagnets: Susceptibility $\varkappa_{Dia}$ is independent of temperature.
See P. 68 for examples.
Paramagnets: Susceptibility $\varkappa_{para}$ drops as temperature increases. Curie's law: $\varkappa_{para} = C/T$

C Curie constant, T Temperature in K.
See P. 68 for examples.
Ferromagnets and ferrimagnets: Both types exhibit spontaneous magnetization which disappears at the Curie point (Curie temperature T_c). At temperatures above the Curie temperature, they behave like paramagnets. For $T > Tc$, the Curie-Weiss law is applicable to susceptibility: $\varkappa = C/(T-T_c)$

The saturation induction of ferromagnets is higher than it is for ferrimagnets, because all magnetic moments are aligned in parallel. In the case of ferrimagnets, on the other hand, the magnetic moments of the two sublattices are aligned antiparallel to one another. These materials are nevertheless magnetic, because the magnetic moments of the two sublattices have different magnitudes.

Antiferromagnets: Examples: MnO, MnS, $FeCl_2$, FeO, NiO, Cr, V_2O_3, V_2O_4.
As in the case of ferrimagnets, adjacent magnetic moments are aligned antiparallel with respect to one another. Because they are of equal magnitude, the effective magnetization of the material is zero.

At temperatures above the Néel point (Néel temperature T_N), they behave like paramagnets. For $T>T_N$, the following is applicable to susceptibility: $\varkappa = C/(T+\Theta)$
Θ Asymptotic Curie temperature

Soft magnetic materials
The following figures are from the applicable DIN Standards. Soft-magnetic metallic materials (DIN-IEC 60404-8-6).

Many material qualities defined in this standard relate to the materials in DIN 17 405 (DC relays) and DIN-IEC 740-2 (transformers and reactors).
Designation comprises a letter and number combination:
Code letter, Number 1, Number 2, – Number 3. The "code letter" indicates the main alloy constituent:
"A" pure iron, "C" silicon, "E" nickel, "F" cobalt.

Number 1 indicates the concentration of the main alloy element.

Number 2 defines the different curves: 1: round hysteresis loop, 2: rectangular hysteresis loop.

The significance of the Number 3 following the hyphen varies according to the individual alloy. It indicates the minimum initial permeability μ_a/1000 in nickel alloys; with other alloys it designates the maximum coercive field strength in A/m. The properties of these materials are strongly geometry-dependent and highly application-specific. The material data quoted in extracts from the standard can therefore only provide an extremely general overview of the properties of these materials. Refer to P. 203 for material data.

Magnetic sheet steel and strip (formerly in DIN 46 400)
Designation: Code letter 1 Number 1 – Number 2 Code letter 2.

The first code letter is "M" for all varieties (indicates metallic materials). Number 1 is one hundred times the maximum magnetic reversal loss at 1.5 or 1.7 Tesla and 50 Hz in W/kg. Number 2 is the product's nominal depth in mm times one hundred.
Code letter 2 provides type data:
"A" cold-rolled electric sheets, no granular orientation, finish-annealed (DIN-EN 10 106).
Grain-oriented electric sheet, finish-annealed (DIN-EN 10 107): "N" standard magnetic reversal loss, "S" limited magnetic reversal loss, "P" low magnetic reversal loss, "D" cold-rolled electric sheet of unalloyed steel, not finish-annealed (DIN-EN 10 126), "E" cold-rolled steel-alloy electric sheet, not finish-annealed (DIN-EN 10 165). Materials data, P. 204.

Materials for transformers and reactors (DIN-IEC 740-2).
These materials comprise the alloy classes C21, C22, E11, E31 and E41 from the standard for soft-magnetic materials (DIN-IEC 60404-8-6). The standard essentially contains the minimum values for core-sheet permeability for

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specified core-sheet sections (YEI, YED, YEE, YEL, YUI and YM). See P. 205 for material properties.

Materials for DC relays
(DIN 17 405); see P. 206 for material properties.
Designation:
a) Code letter "R" (relay material).
b) Code letters for identifying alloy constituents:
Fe = unalloyed, Si = silicon steels
Ni = nickel steels or alloys.
c) Code number for maximum coercive field strength.
d) Code letter for stipulated delivery state: "U" = untreated, "GB" = malleable pre-annealed, "GT" = pre-annealed for deep-drawing, "GF" = final-annealed.

DIN-IEC 60404-8-10 essentially contains the limit deviations for magnetic relay materials based on iron and steel. The designation code defined in this standard is as follows:
- Code letter "M".
- Permitted maximum value for coercive field strength in A/m.
- Code letter for material composition: "F" = pure ferric material, "T" = steel alloy, "U" = unalloyed steel.
- Code letter for delivery state: "H" = hot-rolled, "C" = cold-rolled or cold-drawn.
  Example: M 80 TH.

Sintered metals for soft-magnetic components (DIN-IEC 60404-8-9)
Designation:
- Code letter "S": for sintered materials.
- Hyphen, followed by the identifying alloy elements, i.e. Fe plus if necessary P, Si, Ni or Co.
- The maximum coercive field strength in A/m follows the second hyphen. Refer to P. 207 for material data.

Soft-magnetic ferrite cores
(DIN 41 280)
Soft-magnetic ferrites are formed parts made of a sintered material with the general formula $MO \cdot Fe_2O_3$ where M is one or more of the bivalent metals Cd, Co, Ca, Mg, Mn, Ni, Zn.
Designation: The various types of magnetically soft ferrites are classified in groups according to nominal initial permeability, and are designated by capital letters. Additional numbers may be used to further subdivide them into subgroups; these numbers have no bearing on material quality.

The coercive field strength H_c of soft ferrites is usually in the range 4...500 A/m. Based on a field strength of 3000 A/m, the induction B is in the range 350...470 mT. Refer to P. 208 for material data.

Permanent-magnet materials
(DIN 17410, replaced by DIN-IEC 60404-8-1)
If chemical symbols are used in the abbreviated names of the materials, they refer to the primary alloying constituents of the materials. The numbers before the forward slash denote the $(BH)_{max}$ value in kJ/m³ and those after the slash denote one tenth of the H_{cJ} value in kA/m (rounded values). Permanent magnets with binders are indicated by a final p.

Designation by abbreviated name or material number[1])
DIN: Material number as defined in DIN 17 007, Parts 2 and 4.
IEC: Structure of material numbers;
Code letters:
R – Metallic permanent-magnet materials
S – Ceramic permanent-magnet materials
1st number:
indicates type of material, e.g.:
1 AlNiCo, 5 RECo
2nd number:
0: isotropic material
1: anisotropic material
2: isotropic material with binder
3: anisotropic material with binder.
3rd number:
indicates quality level.
Refer to P. 209 for material data.

[1]) The designation system for permanent-magnet materials is currently undergoing extensive revision. Because the discussions were still in progress at the editorial deadline, no data or comments could be provided.

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Properties of solids[8])

Substance		Density	Melting point[1])	Boiling point[1])	Thermal conductivity[2])	Mean specific heat capacity[3])	Melting enthalpy ΔH[4])	Coefficient of linear expansion[3])
		g/cm³	°C	°C	W/(m·K)	kJ/(kg·K)	kJ/kg	$\times 10^{-6}$/K
Aluminum	Al	2.70	660	2467	237	0.90	395	23.0
Aluminum alloys		2.60...2.85	480...655	–	70...240	–	–	21...24
Amber		1.0...1.1	≈300	Decomposes	–	–	–	–
Antimony	Sb	6.69	630.8	1635	24.3	0.21	172	8.5
Arsenic	As	5.73	–	613[5])	50.0	0.34	370	4.7
Asbestos		2.1...2.8	≈1300	–	–	0.81	–	–
Asphalt		1.1...1.4	80...100	≈300	0.70	0.92	–	–
Barium	Ba	3.50	729	1637	18.4	0.28	55.8	18.1...21.0
Barium chloride		3.86	963	1560	–	0.38	108	–
Basalt		2.6...3.3	–	–	1.67	0.86	–	–
Beef tallow		0.9...0.97	40...50	≈350	–	0.87	–	–
Beryllium	Be	1.85	1278	2970	200	1.88	1087	11.5
Bismuth	Bi	9.75	271	1551	8.1	0.13	59	12.1
Bitumen		1.05	≈90	–	0.17	1.78	–	–
Boiler scale		≈2.5	≈1200	–	0.12...2.3	0.80	–	–
Borax		1.72	740	–	–	1.00	–	–
Boron	B	2.34	2027	3802	27.0	1.30	2053	5
Brass CuZn37		8.4	900	1110	113	0.38	167	18.5
Brickwork		>1.9	–	–	1.0	0.9	–	–
Bronze CuSn 6		8.8	910	2300	64	0.37	–	17.5
Cadmium	Cd	8.65	321.1	765	96.8	0.23	54.4	29.8
Calcium	Ca	1.54	839	1492	200	0.62	233	22
Calcium chloride		2.15	782	>1600	–	0.69	–	–
Cellulose acetate		1.3	–	–	0.26	1.47	–	100...160
Cement, set		2...2.2	–	–	0.9...1.2	1.13	–	–
Chalk		1.8...2.6	Decomposes into CaO and CO_2		0.92	0.84	–	–
Chamotte (fireclay)		1.7...2.4	≈2000	–	1.4	0.80	–	–
Charcoal		0.3...0.5	–	–	0.084	1.0	–	–
Chromium	Cr	7.19	1875	2482	93.7	0.45	294	6.2
Chromium oxide	Cr_2O_3	5.21	2435	4000	0.42[6])	0.75	–	–
Clay, dry		1.5...1.8	≈1600	–	0.9...1.3	0.88	–	–
Cobalt	Co	8.9	1495	2956	69.1	0.44	268	12.4
Coke		1.6...1.9	–	–	0.18	0.83	–	–
Colophonium (rosin)		1.08	100...130	Decomposes	0.32	1.21	–	–
Common salt		2.15	802	1440	–	0.92	–	–
Concrete		1.8...2.2	–	–	≈1.0	0.88	–	–
Copper	Cu	8.96	1084.9	2582	401	0.38	205	–
Cork		0.1...0.3	–	–	0.04...0.06	1.7...2.1	–	–
Corundum, sintered		–	–	–	–	–	–	6.5[7])
Cotton wadding		0.01	–	–	0.04		–	–
Diamond	C	3.5	3820	–	–	0.52	–	1.1
Foam rubber		0.06...0.25	–	–	0.04...0.06	–	–	–
Germanium	Ge	5.32	937	2830	59.9	0.31	478	5.6
Glass (window glass)		2.4...2.7	≈700	–	0.81	0.83	–	≈8
Glass (quartz glass)		–	–	–	–	–	–	0.5
Gold	Au	19.32	1064	2967	317	0.13	64.5	14.2
Granite		2.7	–	–	3.49	0.83	–	–

[1]) At 1.013 bar. [2]) At 20 °C. ΔH of chemical elements at 27 °C (300 K). [3]) At 0...100 °C, see also P. 181. [4]) At the melting point and 1.013 bar. [5]) Sublimed. [6]) Powder form. [7]) At 20...1000 °C. [8]) Materials, PP. 193...227.

Substance		Density	Melting point[1]	Boiling point[1]	Thermal conductivity[2]	Mean specific heat capacity[3]	Melting enthalpy ΔH[4]	Coefficient of linear expansion[3]
		g/cm³	°C	°C	W/(m·K)	kJ/(kg·K)	kJ/kg	x10⁻⁶/K
Graphite, pure	C	2.24	≈3800	≈4200	168	0.71	–	2.7
Gray cast iron		7.25	1200	2500	58	0.50	125	10.5
Hard coal (anthracite)		1.35	–	–	0.24	1.02	–	–
Hard metal K 20		14.8	>2000	≈4000	81.4	0.80	–	5...7
Hard rubber		1.2...1.5	–	–	0.16	1.42	–	50...90[5]
Heat-conductor alloy NiCr 8020		8.3	1400	2350	14.6	0.50[6]	–	–
Ice (0 °C)		0.92	0	100	2.33[7]	2.09[7]	333	51[8]
Indium	In	7.29	156.6	2006	81.6	0.24	28.4	33
Iodine	I	4.95	113.5	184	0.45	0.22	120.3	–
Iridium	Ir	22.55	2447	4547	147	0.13	137	6.4
Iron, pure	Fe	7.87	1535	2887	80.2	0.45	267	12.3
Lead	Pb	11.3	327.5	1749	35.5	0.13	24.7	29.1
Lead monoxide	PbO	9.3	880	1480	–	0.22	–	–
Leather, dry		0.86...1	–	–	0.14...0.16	≈1.5	–	
Linoleum		1.2	–	–	0.19	–	–	–
Lithium	Li	0.534	180.5	1317	84.7	3.3	663	56
Magnesium	Mg	1.74	648.8	1100	156	1.02	372	26.1
Magnesium alloys		≈1.8	≈630	1500	46...139	–	–	24.5
Manganese	Mn	7.47	1244	2100	7.82	0.48	362	22
Marble	$CaCO_3$	2.6...2.8	Decomposes into CaO and CO_2		2.8	0.84	–	–
Mica		2.6...2.9	Decomposes at 700 °C		0.35	0.87	–	3
Molybdenum	Mo	10.22	2623	5560	138	0.28	288	5.4
Monel metal		8.8	1240...1330	–	19.7	0.43	–	–
Mortar, cement		1.6...1.8	–	–	1.40	–	–	–
Mortar, lime		1.6...1.8	–	–	0.87	–	–	–
Nickel	Ni	8.90	1455	2782	90.7	0.46	300	13.3
Nickel silver CuNi12Zn24		8.7	1020	–	48	0.40	–	18
Niobium	Nb	8.58	2477	4540	53.7	0.26	293	7.1
Osmium	Os	22.57	3045	5027	87.6	0.13	154	4.3...6.8
Palladium	Pd	12.0	1554	2927	71.8	0.24	162	11.2
Paper		0.7...1.2	–	–	0.14	1.34	–	–
Paraffin		0.9	52	300	0.26	3.27	–	–
Peat dust (mull), air-dried		0.19	–	–	0.081	–	–	–
Phosphorus (white)	P	1.82	44.1	280.4	–	0.79	20	–
Pitch		1.25	–	–	0.13	–	–	–
Plaster		2.3	1200	–	0.45	1.09	–	–
Platinum	Pt	21.45	1769	3827	71.6	0.13	101	9
Plutonium	Pu	19.8	640	3454	6.7	0.14	11	55
Polyamide		1.1	–	–	0.31	–	–	70...150
Polycarbonate		1.2	–	–	0.20	1.17	–	60...70
Polyethylene		0.94	–	–	0.41	2.1	–	200
Polystyrene		1.05	–	–	0.17	1.3	–	70
Polyvinyl chloride		1.4	–	–	0.16	–	–	70...150
Porcelain		2.3...2.5	≈1600	–	1.6[9]	1.2[9]	–	4...5
Potassium	K	0.86	63.65	754	102.4	0.74	61.4	83

[1]) At 1.013 bar. [2]) At 20 °C. ΔH of chemical elements at 27 °C (300 K). [3]) At 0...100 °C. [4]) At melting point and 1.013 bar. [5]) At 20...50 °C. [6]) At 0...1000 °C. [7]) At –20...0 °C. [8]) At –20...–1 °C. [9]) At 0...100 °C.

Properties of solids[12]) (continued)

Substance	Density	Melting point[1])	Boiling point[1])	Thermal conductivity[2])	Mean specific heat capacity[3])	Melting enthalpy ΔH[4])	Coefficient of linear expansion[3])
	g/cm³	°C	°C	W/(m·K)	kJ/(kg·K)	kJ/kg	x10⁻⁶/K
Quartz	2.1...2.5	1480	2230	9.9	0.80		8[5])/14.6[6])
Radium Ra	5	700	1630	18.6	0.12	32	20.2
Red bronze CuSn5ZnPb	8.8	950	2300	38	0.67	–	–
Red lead, minium Pb_3O_4	8.6...9.1	Forms PbO		0.70	0.092	–	–
Resin bonded fabric, paper	1.3...1.4	–	–	0.23	1.47	–	10...25[7])
Resistance alloy CuNi 44	8.9	1280	≈ 2400	22.6	0.41	–	15.2
Rhenium Re	21.02	3160	5762	150	0.14	178	8.4
Rigid foam plastic, air-filled[8])	0.015... ...0.06	–	–	0.036... ...0.06	–	–	–
Rigid foam plastic, freon-filled	0.015... ...0.06	–	–	0.02... ...0.03	–	–	–
Roofing felt	1.1	–	–	0.19	–	–	–
Rubber, raw (caoutchouc)	0.92	125	–	0.15	–	–	–
Rubidium Rb	1.53	38.9	688	58	0.33	26	90
Sand, quartz, dry	1.5...1.7	≈ 1500	2230	0.58	0.80	–	–
Sandstone	2...2.5	≈ 1500	–	2.3	0.71	–	–
Selenium Se	4.8	217	684.9	2.0	0.34	64.6	37
Silicon Si	2.33	1410	2480	148	0.68	1410	4.2
Silicon carbide	2.4	Decomposes above 3000 °C		9[9])	1.05[9])	–	4.0
Sillimanite	2.4	1820	–	1.51	1.0	–	–
Silver Ag	10.5	961.9	2195	429	0.24	104.7	19.2
Slag, blast furnace	2.5...3	1300... ...1400	–	0.14	0.84	–	–
Sodium Na	0.97	97.81	883	141	1.24	115	70.6
Soft rubber	1.08	–	–	0.14...0.24	–	–	–
Soot	1.7...1.8	–	–	0.07	0.84	–	–
Steatite	2.6...2.7	≈ 1520	–	1.6[10])	0.83	–	8...9[11])
Steel, chromium steel	–	–	–	–	–	–	11
Steel, electrical sheet steel	–	–	–	–	–	–	12
Steel, high-speed steel	–	–	–	–	–	–	11.5
Steel, magnet steel AlNiCo12/6	–	–	–	–	–	–	11.5
Steel, nickel steel 36% Ni (invar)	–	–	–	–	–	–	1.5
Steel, sintered	–	–	–	–	–	–	11.5
Steel, stainless (18Cr, 8Ni)	7.9	1450	–	14	0.51	–	16
Steel, tungsten steel (18 W)	8.7	1450	–	26	0.42	–	–
Steel, unalloyed and low-alloy	7.9	1460	2500	48...58	0.49	205	11.5
Sulfur (α) S	2.07	112.8	444.67	0.27	0.73	38	74
Sulfur (β) S	1.96	119.0	–	–	–	–	–
Thermosets							
Melamin resin with cellulose fibers	1.5	–	–	0.35	–	–	≈ 60
Phenolic resin with asbestos fibers	1.8	–	–	0.70	1.25	–	15...30
Phenolic resin with fabric chips	1.4	–	–	0.35	1.47	–	15...30
Phenolic resin with wood dust	1.4	–	–	0.35	1.47	–	30...50
Phenolic resin w/o filler	1.3	–	–	0.20	1.47	–	80

[1]) At 1.013 bar. [2]) At 20 °C. ΔH of chemical elements at 27 °C (300 K). [3]) At 0...100 °C. [4]) At melting point and 1.013 bar. [5]) Parallel to crystal axis. [6]) Perpendicular to crystal axis. [7]) At 20...50 °C. [8]) Rigid foam plastic from phenolic resin, polystyrene, polyethylene & similar. Values dependent on cell diameter and filler gas. [9]) At 1000 °C. [10]) At 100...200 °C. [11]) At 20...1000 °C. [12]) Materials, PP. 193...227.

Substance		Density	Melting point[1]	Boiling point[1]	Thermal conductivity[2]	Mean specific heat capacity[3]	Melting enthalpy ΔH[4]	Coefficient of linear expansion[3]
		g/cm³	°C	°C	W/(m·K)	kJ/(kg·K)	kJ/kg	x10⁻⁶/K
Tantalum	Ta	16.65	2996	5487	57.5	0.14	174	6.6
Tellurium	Te	6.24	449.5	989.8	2.3	0.20	106	16.7
Thorium	Th	11.72	1750	4227	54	0.14	<83	12.5
Tin (white)	Sn	7.28	231.97	2270	65.7	0.23	61	21.2
Titanium	Ti	4.51	1660	3313	21.9	0.52	437	8.3
Tombac CuZn 20		8.65	1000	≈1300	159	0.38	–	–
Tungsten	W	19.25	3422	5727	174	0.13	191	4.6
Uranium	U	18.95	1132.3	3677	27.6	0.12	65	12.6
Vanadium	V	6.11	1890	3000	30.7	0.50	345	8.3
Vulcanized fiber		1.28	–	–	0.21	1.26	–	–
Wax		0.96	60	–	0.084	3.4	–	–
Wood[5]) Ash		0.72	–	–	0.16	2.1...2.9	–	in fiber direction 3...4, transverse to fiber 22...43
Balsa		0.20	–	–	0.06		–	
Beech		0.72	–	–	0.17		–	
Birch		0.63	–	–	0.14		–	
Maple		0.62	–	–	0.16		–	
Oak		0.69	–	–	0.17		–	
Pine		0.52	–	–	0.14		–	
Poplar		0.50	–	–	0.12		–	
Spruce, fir		0.45	–	–	0.14		–	
Walnut		0.65	–	–	0.15		–	
Wood-wool building slabs		0.36...0.57	–	–	0.093	–	–	–
Zinc	Zn	7.14	419.58	907	116	0.38	102	25.0
Zirconium	Zr	6.51	1852	4377	22.7	0.28	252	5.8

[1]) At 1.013 bar. [2]) At 20°C. ΔH of chemical elements at 27°C (300 K). [3]) At 0...100°C.
[4]) At melting point and 1.013 bar. [5]) Mean values for air-dried wood (moisture content: approx. 12%). Thermal conductivity: radial. Axial conductivity is roughly twice as high.

Properties of liquids

Substance		Density[2]	Melting point[1]	Boiling point[1]	Thermal conductivity[2]	Specific heat capacity[2]	Melting enthalpy ΔH^3	Evaporation enthalpy[4]	Coefficient of volume expansion
		g/cm³	°C	°C	W/(m · K)	kJ/(kg · K)	kJ/kg	kJ/kg	x10⁻³/K
Acetone	$(CH_3)_2CO$	0.79	−95	56	0.16	2.21	98.0	523	–
Antifreeze-water mixture									
23 % by vol.		1.03	−12	101	0.53	3.94	–	–	–
38 % by vol.		1.04	−25	103	0.45	3.68	–	–	–
54 % by vol.		1.06	−46	105	0.40	3.43	–	–	–
Benzene	C_6H_6	0.88	+5.5[6]	80	0.15	1.70	127	394	1.25
Common-salt solution 20 %		1.15	−18	109	0.58	3.43	–	–	–
Diesel fuel		0.81...0.85	−30	150...360	0.15	2.05	–	–	–
Ethanol	C_2H_5OH	0.79	−117	78.5	0.17	2.43	109	904	1.1
Ethyl ether	$(C_2H_5)_2O$	0.71	−116	34.5	0.13	2.28	98.1	377	1.6
Ethyl dichloride	C_2H_5Cl	0.90	−136	12	0.11[5]	1.54[5]	69.0	437	–
Ethylene glycol	$C_2H_4(OH)_2$	1.11	−12	198	0.25	2.40	–	–	–
Fuel oil EL		≈0.83	−10	> 175	0.14	2.07	–	–	–
Gasoline/petrol		0.72...0.75	−50...−30	25...210	0.13	2.02	–	–	1.0
Glycerin	$C_3H_5(OH)_3$	1.26	+20	290	0.29	2.37	200	828	0.5
Hydrochloric acid 10 %	HCl	1.05	−14	102	0.50	3.14	–	–	–
Kerosene		0.76...0.86	−70	> 150	0.13	2.16	–	–	1.0
Linseed oil		0.93	−15	316	0.17	1.88	–	–	–
Lubricating oil		0.91	−20	> 300	0.13	2.09	–	–	–
Mercury[8]	Hg	13.55	−38.84	356.6	10	0.14	11.6	295	0.18
Methanol	CH_3OH	0.79	−98	65	0.20	2.51	99.2	1109	–
Methyl chloride	CH_3Cl	0.99[7]	−92	−24	0.16	1.38	–	406	–
m-xylene	$C_6H_4(CH_3)_2$	0.86	−48	139	–	–	–	339	–
Nitric acid, conc.	HNO_3	1.51	−41	84	0.26	1.72	–	–	–

[1]) At 1.013 bar. [2]) At 20 °C. [3]) At melting point and 1.013 bar [4]) At boiling point and 1.013 bar. [5]) At 0 °C. [6]) Setting point 0 °C. [7]) At −24 °C.
[8]) For conversion of torr to Pa, use 13.5951 g/cm³ (at 0 °C).

Substance		Density[1]	Melting point[1]	Boiling point[1]	Thermal conductivity[2]	Specific heat capacity[2]	Melting enthalpy ΔH^3	Evaporation enthalpy[4]	Coefficient of volume expansion
		g/cm³	°C	°C	W/(m · K)	kJ/(kg · K)	kJ/kg	kJ/kg	x10⁻³/K
Paraffin oil		–	–	–	–	–	–	–	0.764
Petroleum ether		0.66	−160	> 40	0.14	1.76	–	–	–
Rape oil		0.91	± 0	300	0.17	1.97	–	–	–
Silicone oil		0.76...0.98	–	–	0.13	1.09	–	–	–
Spirit 95 %[6]		0.81	−114	78	0.17	2.43	–	–	–
Sulfuric acid, conc.	H_2SO_4	1.83	+10.5[5]	338	0.47	1.42	–	–	0.55
Tar, coke oven		1.2	−15	300	0.19	1.56	–	–	–
Toluene	C_7H_8	0.87	−93	111	0.14	1.67	74.4	364	–
Transformer oil		0.88	−30	170	0.13	1.88	–	–	–
Trichlorcethylene	C_2HCl_3	1.46	−85	87	0.12	0.93	–	265	1.19
Turpentine oil		0.86	−10	160	0.11	1.80	–	293	1.0
Water		1.007[7]	±0	100	0.60	4.18	332	2256	0.18[8]

Water vapor

Absolute pressure bar	Boiling point °C	Evaporation enthalpy kJ/kg
0.1233	50	2382
0.3855	75	2321
1.0133	100	2256
2.3216	125	2187
4.760	150	2113
8.925	175	2031
15.55	200	1941

Absolute pressure bar	Boiling point °C	Evaporation enthalpy kJ/kg
25.5	225	1837
39.78	250	1716
59.49	275	1573
85.92	300	1403
120.5	325	1189
165.4	350	692
221.1	374.2	0

[1] At 1.013 bar.
[2] At 20 °C.
[3] At melting point and 1.013 bar.
[4] At boiling point and 1.013 bar.
[5] Setting point 0 °C.
[6] Denaturated ethanol.
[7] At 4 °C.
[8] Volume expansion on freezing: 9 %.

Properties of gases

Substance		Density[1]	Melting point[2]	Boiling point[2]	Thermal conductivity[3]	Specific heat capacity[3] kJ/(kg·K)			Evaporation enthalpy[2]
		kg/m³	°C	°C	W/(m·K)	c_p	c_v	c_p/c_v	kJ/kg
Acetylene	C_2H_2	1.17	−84	−81	0.021	1.64	1.33	1.23	751
Air		1.293	−220	−191	0.026	1.005	0.716	1.40	209
Ammonia	NH_3	0.77	−78	−33	0.024	2.06	1.56	1.32	1369
Argon	Ar	1.78	−189	−186	0.018	0.52	0.31	1.67	163
Blast-furnace gas		1.28	−210	−170	0.024	1.05	0.75	1.40	–
i-butane	C_4H_{10}	2.67	−145	−10.2	0.016	–	–	1.11	–
n-butane	C_4H_{10}	2.70	−138	−0.5	0.016	–	–	–	–
Carbon dioxide	CO_2	1.98	−57[4]	−78	0.016	0.82	0.63	1.30	368
Carbon disulfide	CS_2	3.41	−112	+46	0.0073	0.67	0.56	1.19	–
Carbon monoxide	CO	1.25	−199	−191	0.025	1.05	0.75	1.40	–
Chlorine	Cl_2	3.21	−101	−35	0.009	0.48	0.37	1.30	288
City/town gas		0.56...0.61	−230	−210	0.064	2.14	1.59	1.35	–
Cyanogen (dicyan)	$(CN)_2$	2.33	−34	−21	–	1.72	1.35	1.27	–
Dichlorodifluoromethane (= Freon F 12)	CCl_2F_2	5.51	−140	−30	0.010	–	–	1.14	–
Ethane	C_2H_6	1.36	−183	−89	0.021	1.66	1.36	1.22	522
Ethanol vapor		2.04	−114	+78	0.015	–	–	1.13	–
Ethylene	C_2H_4	1.26	−169	−104	0.020	1.47	1.18	1.24	516
Fluorine	F_2	1.70	−220	−188	0.025	0.83	–	–	172
Helium	He	0.18	−270	−269	0.15	5.20	3.15	1.65	20
Hydrogen	H_2	0.09	−258	−253	0.181	14.39	10.10	1.42	228
Hydrogen chloride	HCl	1.64	−114	−85	0.014	0.81	0.57	1.42	–
Hydrogen sulfide	H_2S	1.54	−86	−61	–	0.96	0.72	1.34	535
Krypton	Kr	3.73	−157	−153	0.0095	0.25	0.15	1.67	108
Methane	CH_4	0.72	−183	−164	0.033	2.19	1.68	1.30	557
Methyl chloride	CH_3Cl	2.31	−92	−24	–	0.74	0.57	1.29	446
Natural gas		≈0.83	–	−162	–	–	–	–	–
Neon	Ne	0.90	−249	−246	0.049	1.03	0.62	1.67	86
Nitrogen	N_2	1.24	−210	−196	0.026	1.04	0.74	1.40	199
Oxygen	O_2	1.43	−218	−183	0.267	0.92	0.65	1.41	213
Ozone	O_3	2.14	−251	−112	0.019	–	–	1.29	–
Propane	C_3H_8	2.00	−182	−42	0.018	–	–	1.14	
Propylene	C_3H_6	1.91	−185	−47	0.017	–	–	–	468
Sulfur dioxide	SO_2	2.93	−73	−10	0.010	0.64	0.46	1.40	402
Water vapor at 100 °C[5]		0.60	±0	+100	0.025	2.01	1.52	1.32	–
Xenon	Xe	5.89	−112	−108	0.0057	0.16	0.096	1.67	96

[1]) At 0 °C and 1.013 bar.
[2]) At 1.013 bar.
[3]) At 20 °C and 1.013 bar. C_p, C_v specific heat capacity at constant pressure and at constant volume.
[4]) At 5.3 bar.
[5]) At saturation and 1.013 bar, see also table "Properties of liquids".

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Properties of metallic materials

Material	Standard	Abbreviation of selected types	Primary alloying constituents, mean values in % by mass	R_m[1] N/mm²	R_e[2] N/mm²	A_5[3] %	σ_{bW}[4] Ref. value N/mm²	Test bar dia.[5] mm	Properties, typical applications
Cast iron and malleable cast iron[6] *E*[7] in 10^3 N/mm²: GG 78...143[8]; GGG 160...180; GTW and GTS 175...195									
Lamellar graphite iron (gray cast iron)	DIN EN 1561	EN-GJL-200	Not standardized	200...300	–	–	90	30	Brittle, very good machinability.
Nodular graphite iron	DIN EN 1563	EN-GJS-400-15	Not standardized	≥ 400	≥ 250	≥ 15	200	25	More ductile than gray cast iron, good machinability.
Malleable cast iron White-heart casting Black-heart casting	DIN EN 1569	GTW-40-05 GTS-35-10	Not standardized	≥ 400 ≥ 350	≥ 220 ≥ 200	≥ 5 (A_3) ≥ 10 (A_3)	– –	12 12	Ductility similar to nodular cast iron, good machinability.
Cast steel *E*[7] as steel	DIN 1681	GS-45	Not standardized	≥ 450	≥ 230	≥ 22	210	–	Heat-treatable.
Steel *E*[7] in 10^3 N/mm²: unalloyed and low-alloy steel 212, austenitic steels ≥ 190, high-alloy tool steels ≤ 230									
Untreated structural steel (dia. 16...40 mm)	DIN EN 10025	S 235 JR E 360	≤ 0.19 C	340...510 670...830	≤ 225 ≥ 355	≥ 26 ≥ 11	≥ 170 ≥ 330	– –	For low-stressed parts. For higher-stressed parts.
Cold-rolled strip of soft unalloyed steels	DIN EN 10139	DC 05 LC	Not standardized	270...330	≤ 180	≥ 40 (A_{80})	≥ 130	–	For difficult deep-drawn parts.
Hot-galvanized strip and sheet	DIN EN 10142	DX 53 D	Not standardized	≤ 380	≤ 260	≥ 30 (A_{80})	≥ 190	–	For corrosion-stressed, difficult deep-drawn parts.
Free-cutting steel (dia. 16 ... 40 mm)	DIN EN 10087	11 SMn30 35 S 20	≤ 0.14 C; 1.1 Mn; 0.30 S 0.35 C; 0.9 Mn; 0.20 S	380...570 520...680	– –	– –	≥ 190 ≥ 260	– –	Soft free-cutting steel. Free-cutting heat-treatable steel.

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Steel (continued)

Material Material state	Stan-dard	Abbreviation of selected types	Primary alloying constituents, mean values in % by mass	R_m[1] N/mm²	R_e[2] N/mm²	A[3] %	σ_{bW}[4] Ref. value N/mm²	Test bar dia.[5] mm	Properties, typical applications
Heat-treatable steel, heat-treated (dia. ≤ 16 mm)	DIN EN 10083	C 45 E 34 Cr 4 42 CrMo 4 30 CrNiMo 8	0.45 C 0.34 C; 1.1 Cr 0.42 C; 1 Cr; 0.2 Mo 0.3 C; 2 Cr; 0.4 Mo; 2 Ni	700...850 900...1100 1100...1300 1250...1450	≥ 490 ≥ 700 ≥ 900 ≥ 1050	≥ 14 ≥ 12 ≥ 10 ≥ 9	≥ 280 ≥ 360 ≥ 440 ≥ 500	– – – –	→ Increasing hardenability.
Case-hardened steel, case-hardened and tempered (dia. ≤ 11 mm)	DIN EN 10084	C 15 E 16 MnCr 5 17 CrNi 6-6 18 CrNiMo 7-6	0.15 C; 0.16 C; 1 Cr 0.17 C; 1.5 Cr; 1.5 Ni 0.18 C; 1.6 Cr; 1.5 Ni; 0.3 Mo	Hardness HV (ref. value) Surface / Core 700...850 / 200...450 700...850 / 300...450 700...850 / 400...550 700...850 / 400...550		In the case of hard steels – hardened and tempered, case-hardened, nitration-hardened etc. – the material characteristic values measured in the tensile test are unsuitable for dimensioning of the hard components.			High wear resistance, high vibro-stability. → Increasing hardenability.
Nitriding steel, heat-treated and nitration-hardened	DIN EN 10085	31 CrMoV 9 34 CrAlMo 5	0.31 C; 2.5 Cr; 0.2 Mo; 0.15 V 0.34 C; 1.0 Al; 1.15 Cr; 0.2 Mo	700...850 850...1100	250...400 250...400				High wear resistance, high vibrostability.
Rolling-bearing steel, hardened and tempered	DIN EN ISO 683-17	100 Cr 6	1 C; 1.5 Cr	Hardness 60...64 HRC					High wear resistance.
Tool steel Unalloyed cold work steel, hardened and tempered	DIN EN ISO 4957	C 80 U	0.8 C	Standard hardness 60...64 HRC					Water hardening steel.
Alloyed cold work steel, hardened and tempered	DIN EN ISO 4957	90 MnCrV 8 X 153 CrMoV 12 X 210 Cr 12 2.1 C; 12 Cr 12 Cr	0.9 C; 2 Mn; 0.3 Cr; 0.1 V 1.53 C; 12 Cr; 0.8 Mo; 0.8 V	60...64 HRC 60...64 HRC 60...64 HR					Water/oil hardening steel. Oil hardening steel. → Increasing wear resistance.

Hot work steel, hardened and tempered	DIN EN ISO 4957	X 40 CrMoV 5-1	0.4 C; 5 Cr; 1.3 Mo; 1 V	43...45 HRC		In the case of hard steels – hardened and tempered, case-hardened, nitration-hardened etc. – the material characteristic values measured in the tensile test are unsuitable for dimensioning of the hard components.			
High-speed steel, hardened and tempered	DIN EN ISO 4957	HS6-5-2	0.85 C; 6 W; 5 Mo; 2 V; 4 Cr	61...65 HRC					Wear-resistant at high temperature.
Stainless steels -Ferritic steel, annealed	17440	X 6 Cr 17	≤ 0.08 C; 17 Cr	450...600	≥ 270	≥ 20	200...315		Non-hardenable.
				Hardness < 185 HV					
-Martensitic steel, hardened and tempered	DIN EN 10088	X 20 Cr 13 X 46 Cr 13 X 90 CrMoV 18	0.20 C; 13 Cr 0.46 C; 13 Cr 0.9 C; 18 Cr; 1.1 Mo; 0.1 V	Hardness approx. 40 HRC Hardness approx. 45 HRC Hardness ≥ 57 HRC					Increasing wear resistance.
-Austenitic steel, quenched	17440	X 5 CrNi 18-10 X 8 CrNiS 18-10	≤ 0.07 C; 18 Cr; 9 Ni ≤ 0.07 C; 18 Cr; 9 Ni; 0.3 S	500...700 500...700	≥ 190 ≥ 190	≥ 45 ≥ 35	–	–	Non-magnetic, non-hardenable.
Hard metals E = 440 000...550 000	–	–	W (Ti, Ta) carbide + Co	800...1900 HV					Sintered materials, extremely resistant to pressure and wear, but brittle; for machining, cutting, forming tools.
Extremely heavy metals E = 320 000...380 000	–	–	> 90 W; Ni & others	≥ 650 240...450 HV	≥ 560	≥ 2			Density 17...18.5 g/cm³; for governor flyweights, flywheel masses, counterweights.

1) Tensile strength.
2) Yield point (or $R_{p0.2}$).
3) Elongation at fracture.
4) Fatigue strength under reversed bending stresses; more precise strength values are to be calculated according to FMK Guideline "Computational verification of strength for machine components".
5) The Fatigue limits given apply to the separately cast test bar.
6) The Fatigue limits of all types of cast iron are dependent on the weight and section thickness of the cast pieces.
7) Modulus of elasticity.
8) For gray cast iron, E decreases with increasing tensile stress and remains almost constant with increasing compression stress.

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Steel (continued)

Spring steel

Material	DIN	Primary alloying constituents, approx. in % by mass: E and G in N/mm²	Diameter mm	R_m[1] min. N/mm²	Z[2] %	σ_b[3] N/mm²	τ_{sh}[4] N/mm²	τ_{zul}[5] N/mm²	Properties Typical applications
Spring steel wire D, patented and springy drawn[6])	17223 Sheet 1	0.8 C; 0.6 Mn; < 0.35 Si E = 206 000 G = 81 500	1 3 10	2230 1840 1350	40 40 30	1590 1280 930	380[7]) 360[7]) 320	1115 920 675	For high maximum stresses (P. 294).
Nonrusting spring steel wire	17224	< 0.12 C; 17 Cr; 7.5 Ni E = 185 000 G = 73 500	1 3	2000 1600	40 40	1400 1130	– –	1000 800	For nonrusting springs.
Heat-treated valve-spring steel wire [6])	17223 Sheet 2	0.65 C; 0.7 Mn; ≤ 0.30 Si E = 206 000 G = 80 000	1 3 8	1720 1480 1390	45 45 38	1200 1040 930	380[8]) 380[8]) 360[8])	860 740 690	For high alternating cyclic stress.
Heat-treated, alloyed valve-spring steel wire VD Si Cr[6])	–	0.55 C; 0.7 Mn; 0.65 Cr; 1.4 Si E = 200 000 G = 79 000	1 3 8	2060 1920 1720	50 50 40	– – –	430[8]) 430[8]) 380[8])	1030 960 860	For maximum alternating cyclic stress and higher temperatures.
Heat-treated, alloyed valve-spring steel wire VD Cr V[6])	–	0.7 C; 0.7 Mn; 0.5 Cr; 0.15 V; ≤ 0.30 S E = 200 000 G = 79 000	1 3 8	1860 1670 1420	45 45 40	– – –	470[8]) 470[8]) 400[8])	930 835 710	For maximum alternating cyclic stress.
Spring steel strip Ck 85	17222	0.85 C; 0.55 Mn; 0.25 Si E = 206 000	h ≤ 2.5	1470	–	1270	σ_{bh} = 640	–	For highly stressed leaf springs.
Nonrusting spring steel strip	17224	< 0.12 C; 17 Cr; 7.5 Ni E = 185 000	h ≤ 1	1370	–	1230	σ_{bh} = 590	–	For nonrusting leaf springs.

[1]) Tensile strength.
[2]) Reduction of area at fracture.
[3]) Permissible bending stress.
[4]) Permissible lift stress for number of stress cycles $N \geq 10^7$.
[5]) Permissible maximum stress for temperatures to approx. 30 °C and 1...2 % relaxation in 10 hrs.; for higher temperatures, see P. 294.
[6]) See pp. 294 and 295 for fatigue-strength diagrams.
[7]) 480 N/mm² for peened springs.
[8]) Approx. 40 % higher for peened springs.

Vehicle-body sheet metal

Material Abbreviated name	Standard material thickness mm	$R_{p0.2}$ [1] N/mm²	R_m [2] N/mm²	A_{80} [3] %	Properties Typical applications
St 12	0.6...2.5	≈ 280	270...410	≈ 28	For simple drawn metal parts.
St 13		≈ 250	270...370	≈ 32	For complicated drawn metal parts.
St 14		≈ 240	270...350	≈ 38	For very complex deep-drawn parts, outer body parts (roof, doors, fenders etc.; 0.75...1.0 mm); see also DIN 1623.
ZE 260	0.75...2.0	260...340	≈ 370	≈ 28	For highly stressed supporting parts whose degree of forming is not too complicated.
ZE 340		340...420	≈ 420	≈ 24	
ZE 420		420...500	≈ 490	≈ 20	
AlMg 0.4 Si 1.2	0.8...2.5	≈ 140	≈ 250	≈ 28	For outer body parts such as front fenders, doors, engine hood, trunk lid etc.; mostly 1.25 mm; see DIN 1745.
AlMg 4.5 Mn 0.3	0.5...3.5	≈ 130	≈ 270	≈ 28	For inner reinforcements of hinged covers; for parts which are not visible; lines of stress tolerated.

[1] Yield strength.
[2] Tensile strength.
[3] Elongation at fracture.

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Nonferrous metals, heavy metals

Material Examples	Abbreviated name Examples	Composition, mean values, in % by mass	$E^{1)}$ N/mm²	R_m[2] min. N/mm²	$R_{p0.2}$[3] approx. N/mm²	σ_{bW}[4] approx. N/mm²	Properties Typical applications
Wrought copper alloys (DIN EN 1652 ... 1654, 1758, 12163 ... 12168)							
High-conductivity copper	EN CW-Cu-FRTP	99.90 Cu	$128 \cdot 10^3$	200	120[5]	70	Very good electrical conductivity.
Brass	EN CW-CuZn 28 R370	72 Cu; 28 Zn	$114 \cdot 10^3$	370	320	120	Deep-drawing capability. Good cold formability. Machine parts.
	EN CW-CuZn 37 R440	63 Cu; 37 Zn	$110 \cdot 10^3$	440	400	140	
	EN CW-CuZn 39 Pb3 R430	58 Cu; 39 Zn; 3 Pb	$96 \cdot 10^3$	430	250	150	
Nickel silver	EN CW-CuNi 18 Zn 20 R500	62 Cu; 20 Zn; 18 Ni	$135 \cdot 10^3$	500	300		Corrosion-resistant.
Tin bronze	EN CW-CuSn 6 R400	94 Cu; 6 Sn	$118 \cdot 10^3$	410	300	175	Good antifriction qualities; bearing bushings, connectors.
Cast copper alloys (DIN 1705)							
Cast tin bronze	G-CuSn 10 Zn	88 Cu; 10 Sn; 2 Zn	$100 \cdot 10^3$	260[6]	140[6]	90	Corrosion-resistant, wear-resistant; gears, bearings.
Red bronze	GC-CuSn 7 ZnPb	85 Cu; 7 Sn; 4 Zn; 6 Pb	$95 \cdot 10^3$	270	130	80	
Other alloys							
Tin alloy (DIN ISO 4381)	SnSb 12 Cu 6 Pb	80 Sn; 12 Sb; 6 Cu; 2 Pb	$30 \cdot 10^3$	–	60	28	Plain bearings.
Zinc diecastings (DIN 1743)	GD-ZnAl 4 Cu 1	96 Zn; 4 Al	$85 \cdot 10^3$	280[6]	230[6]	80	Dimensionally accurate castings.
Heating-conductor alloy (DIN 17 470)	NiCr 80 20	80 Ni; 20 Cr	–	650	–	–	High electrical resistance (P 215).
	NiCr 60 15	60 Ni; 22 Fe; 17 Cr	–	600	–	–	
Resistance alloy (DIN 17 471)	CuNi 44	55 Cu; 44 Ni; 1 Mn	–	420	–	–	
	CuNi 30 Mn	67 Cu; 30 Ni; 3 Mn	–	400	–	–	

[1] Modulus of elasticity, reference values. [2] Tensile strength. [3] 0.2 % yield strength. [4] Fatigue limit under reversed bending stress. [5] Maximum.
[6] For separately cast test rod.

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Nonferrous metals, light metals

Material Examples	Composition, mean values in % by mass	R_m[1] min. N/mm²	$R_{p0.2}$[2] min. N/mm²	σ_{bW}[3] approx. N/mm²	Properties Typical applications
Wrought aluminum alloys (DIN EN 458, 485, 515, 573, 754 ...), modulus of elasticity E = 65 000 ... 73 000 N/mm²					
ENAW-Al 99.5 O	99.5 Al	65	20	40	Soft, very good conductor, can be anodized/polished.
ENAW-AlMg 2 Mn 0.8 O	97 Al; 2 Mg; 0.8 Mn	190	80	90	Seawater-resistant, can be anodized.
ENAW-AlSiMgMn T 6	97 Al; 0.9 Mg; 1 Si; 0.7 Mn	310	260	90	Aged artificially, seawater-resistant.
ENAW-AlCu 4 MgSi (A) T 4	94 Al; 4 Cu; 0.7 Mg; 0.7 Mn; 0.5 Si	390	245	120	Precipitation-hardened, good creep rupture properties.
ENAW-AlZn 5.5 MgCu T 651	90 Al; 6 Zn; 2 Mg; 2 Cu; 0.2 Cr	525	460	140	Maximum strength.
Cast aluminum alloys[5] (DIN EN 1706), modulus of elasticity E = 68 000 ... 80 000 N/mm²					
ENAC-AlSi 7 Mg 0.3 KT 6	89 Al; 7 Si; 0.4 Mg; 0.1 Ti	290	210	80	Aged artificially; highly stressed parts with good vibration strength.
ENAC-AlSi 6 Cu 4 KF	89 Al; 6 Si; 4 Cu; 0.3 Mn; 0.3 Mg	170	100	60	Highly versatile, heat-resistant.
ENAC-AlCu 4 Ti KT 6	95 Al; 5 Cu; 0.2 Ti	330	220	90	Aged artificially; simple parts with maximum strength and toughness.
ENAC-AlSi 12 Cu 1 (Fe) DF	88 Al; 12 Si; 1 Cu; 1 Fe	240	140	70	Thin-walled, vibration-resistant parts.
ENAC-AlSi 9 Cu 3 (Fe) DF	87 Al; 9 Si; 3 Cu; 0.3 Mn; 0.3 Mg	240	140	70[6]	Heat-resistant; complicated diecastings.
ENAC-AlMg 9 DF	90 Al; 9 Mg; 1 Si; 0.4 Mn	200	130	60[6]	Seawater-resistant; medium-stressed parts.
Magnesium alloys (DIN 1729, 9715), modulus of elasticity E = 40 000 ... 45 000 N/mm²					
MgAl 6 Zn F 27	93 Mg; 6 Al; 1 Zn; 0.3 Mn	270	195	–	Parts subject to medium to high stress. Chips are combustible.
GK-MgAl 9 Zn 1 wa	90 Mg; 9 Al; 0.6 Zn; 0.2 Mn	240	150	80	Aged artificially.
GD-MgAl 9 Zn 1	90 Mg; 9 Al; 0.6 Zn; 0.2 Mn	200	150	50	Complicated diecastings.
Titanium alloys (DIN 17 850, 17 851, 17 860 ... 17 864), modulus of elasticity E ≈ 110 000 N/mm²					
Ti 1	99.7 Ti	290	180	–	Corrosion-resistant.
TiAl 6 V 4 F 89	90 Ti; 6 Al; 4 V	890	820	–	Corrosion-resistant, maximum strength.

[1]) Tensile strength. [2]) 0.2 % yield strength. [3]) Rotating bending fatigue strength. [4]) Maximum. [5]) Strength values apply to permanent mold castings and diecastings for separately cast test rods. Sand castings have slightly lower values than permanent mold castings. [6]) Flat bending fatigue strength.

Sintered metals[1]) for plain bearings

Material	Material code	Permissible ranges					Representative examples						
		Density ϱ	Porosity	Chemical composition % by mass	Radial breaking resistance K^2)	Hardness	Density ϱ	Chemical composition % by mass	Radial breaking resistance K^2)	Compressive yield point $\delta_{d\,0.2}$	Hardness	Thermal conductivity
	Sint	g/cm³	$(\Delta V/V) \cdot 100$ %	%	N/mm²	HB	g/cm³	%	N/mm²	N/mm²	HB²)	λ W/mK
Sintered iron	A 00	5.6...6.0	25 ± 2.5	< 0.3 C; < 1.0 Cu;	> 150	> 25	5.9	< 0.2 others; rest Fe	160	130	30	37
	B 00	6.0...6.4	20 ± 2.5	< 2 others; rest Fe	> 180	> 30	6.3		190	160	40	43
	C 00	6.4...6.8	15 ± 2.5		> 220	> 40	6.7		230	180	50	48
Sintered steel containing Cu	A 10	5.6...6.0	25 ± 2.5	< 0.3 C; 1 ... 5 Cu;	> 160	> 35	5.9	2.0 Cu;	170	150	40	36
	B 10	6.0...6.4	20 ± 2.5	< 2 others; rest Fe	> 190	> 40	6.3	< 0.2 others; rest Fe	200	170	50	37
	C 10	6.4...6.8	15 ± 2.5		> 230	> 55	6.7		240	200	65	42
Sintered steel containing Cu and C	B 11	6.0...6.4	20 ± 2.5	0.4 ... 1.0 C; 1 ... 5 Cu; < 2 others; rest Fe	> 270	> 70	6.3	0.6 C; 2.0 Cu; < 0.2 others; rest Fe	280	160	80	28
Sintered steel containing high percentage of Cu	A 20	5.8...6.2	25 ± 2.5	< 0.3 C; 15 ... 25 Cu;	> 180	> 30	6.0	20 Cu;	200	140	40	41
	B 20	6.2...6.6	20 ± 2.5	< 2 others; rest Fe	> 200	> 45	6.4	< 0.2 others; rest Fe	220	160	50	47
Sintered steel containing high percentage of Cu and C	A 22	5.5...6.0	25 ± 2.5	0.5...2.0 C;	> 120	> 20	5.7	2.0 C³); 20 Cu;	125	100	25	30
	B 22	6.0...6.5	20 ± 2.5	15 ... 25 Cu; < 2 others; rest Fe	> 140	> 25	6.1	< 0.2 others; rest Fe	145	120	30	37
Sintered bronze	A 50	6.4...6.8	25 ± 2.5	< 0.2 C; 9 ... 11 Sn;	> 120	> 25	6.6	10 Sn;	140	100	30	27
	B 50	6.8...7.2	20 ± 2.5	< 2 others; rest Cu	> 170	> 30	7.0	< 0.2 others; rest Cu	180	130	35	32
	C 50	7.2...7.7	15 ± 2.5		> 200	> 35	7.4		210	160	45	37
Sintered bronze containing graphite⁴)	A 51	6.0...6.5	25 ± 2.5	0.5 ... 2.0 C;	> 100	> 20	6.3	1.5 C⁴); 10 Sn;	120	80	20	20
	B 51	6.5...7.0	20 ± 2.5	9 ... 11 Sn;	> 150	> 25	6.7	< 0.2 others; rest Cu	155	100	30	26
	C 51	7.0...7.5	15 ± 2.5	< 2 others; rest Cu	> 170	> 30	7.1		175	120	35	32

[1]) According to "Material Specification Sheets for Sintered Metals": DIN 30 910, 1990 Edition.
[2]) Measured on calibrated bearings 10/16 dia. · 10.
[3]) C is mainly present as free graphite.
[4]) C is present as free graphite.

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Sinter (PM) metals[1]) for structural parts

Material	Material code	Permissible ranges				Representative examples						
		Density ϱ	Porosity	Chemical composition % by mass	Hardness	Density ϱ	Chemical composition % by mass	Tensile strength	Yield point	Elongation at break	Hardness	Elastic modulus
	Sint	g/cm³	$(\Delta V/V)\cdot 100$ %	%	HB	g/cm³	%	R_m N/mm²	$R_{p\,0.1}$ N/mm²	A %	HB	$E\cdot 10^3$ N/mm²
Sintered iron	C 00	6.4...6.8	15 ± 2.5	< 0.3 C; < 1.0 Cu;	> 35	6.6	< 0.5 others; rest Fe	130	60	4	40	100
	D 00	6.8...7.2	10 ± 2.5	< 2 others; rest Fe	> 45	6.9		190	90	10	50	130
	E 00	> 7.2	< 7.5		> 60	7.3		260	130	18	65	160
Sintered steel containing C	C 01	6.4...6.8	15 ± 2.5	0.3...0.6 C; < 1.0 Cu;	> 70	6.6	0.5 C;	260	180	3	80	100
	D 01	6.8...7.2	10 ± 2.5	< 2 others; rest Fe	> 90	6.9	< 0.5 others; rest Fe	320	210	3	100	130
Sintered steel containing Cu	C 10	6.4...6.8	15 ± 2.5	< 0.3 C; 1...5 Cu;	> 40	6.6	1.5 Cu;	230	160	3	55	100
	D 10	6.8...7.2	10 ± 2.5	< 2 others; rest Fe	> 50	6.9	< 0.5 others; rest Fe	300	210	6	85	130
	E 10	> 7.2	< 7.5		> 80	7.3		400	290	12	120	160
Sintered steel containing Cu and C	C 11	6.4...6.8	15 ± 2.5	0.4...1.5 C; 1...5 Cu;	> 80	6.6	0.6 C; 1.5 Cu;	460	320	2	125	100
	D 11	6.8...7.2	10 ± 2.5	< 2 others; rest Fe	> 95	6.9	< 0.5 others; rest Fe	570	400	2	150	130
	C 21	6.4...6.8	15 ± 2.5	0.4...1.5 C; 5...10 Cu;	> 105	6.6	0.8 C; 6 Cu;	530	410	< 1	150	100
				< 2 others; rest Fe			< 0.5 others; rest Fe					
Sintered steel containing Cu, Ni and Mo	C 30	6.4...6.8	15 ± 2.5	< 0.3 C; 1...5 Cu;	> 55	6.6	0.3 C; 1.5 Cu; 4.0 Ni;	390	310	2	105	100
	D 30	6.8...7.2	10 ± 2.5	1...5 Ni; < 0.8 Mo;	> 60	6.9	0.5 Mo;	510	370	3	130	130
	E 30	> 7.2	< 7.5	< 2 others; rest Fe	> 90	7.3	< 0.5 others; rest Fe	680	440	5	170	160
Sintered steel containing P	C 35	6.4...6.8	15 ± 2.5	< 0.3 C; < 1.0 Cu;	> 70	6.6	0.45 P;	310	200	11	85	100
	D 35	6.8...7.2	10 ± 2.5	0.3...0.6 P;	> 80	6.9	< 0.5 others; rest Fe	330	230	12	90	130
				< 2 others; rest Fe								
Sintered steel containing Cu and P	C 36	6.4...6.8	15 ± 2.5	< 0.3 C; 1...5 Cu;	> 80	6.6	2.0 Cu; 0.45 P;	360	290	5	100	100
	D 36	6.8...7.2	10 ± 2.5	0.3...0.6 P;	> 90	6.9	< 0.5 others; rest Fe	380	320	6	105	130
				< 2 others; rest Fe								
Sintered steel containing Cu, Ni, Mo and C	C 39	6.4...6.8	15 ± 2.5	0.3...0.6 C; 1...3 Cu;	> 90	6.6	0.5 C; 1.5 Cu; 4.0 Ni;	520	370	1	150	100
	D 39	6.8...7.2	10 ± 2.5	1...5 Ni; < 0.8 Mo;	> 120	6.9	0.5 Mo;	600	420	2	180	130
				< 2 others; rest Fe			< 0.5 others; rest Fe					

1) According to "Material Specification Sheets for Sintered Metals": DIN 30 910, 1990 Edition.

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Sintered metals[1]) for structural parts (continued)

Material	Material code Sint	Permissible ranges: Density ϱ g/cm³	Permissible ranges: Porosity $(\Delta V/V)\cdot 100$ %	Permissible ranges: Chemical composition % by mass %	Permissible ranges: Hardness HB	Representative examples: Density ϱ g/cm³	Representative examples: Chemical composition % by mass %	Representative examples: Tensile strength R_m N/mm²	Representative examples: Yield point $R_{p\,0.1}$ N/mm²	Representative examples: Elongation at break A %	Representative examples: Hardness HB	Representative examples: Elastic modulus $E\cdot 10^3$ N/mm²
Stainless sintered steel AISI 316	C 40	6.4...6.8	15 ± 2.5	< 0.08 C; 10 ... 14 Ni; 2...4 Mo; 16 ... 19 Cr; < 2 others; rest Fe	> 95	6.6	0.06 C; 13 Ni; 2.5 Mo; 18 Cr; < 0.5 others; rest Fe	330	250	1	110	100
	D 40	6.8...7.2	10 ± 2.5		> 125	6.9		400	320	2	135	130
AISI 430	C 42	6.4...6.8	15 ± 2.5	< 0.08 C; 16 ... 19 Cr; < 2 others; rest Fe	> 140	6.6	0.06 C; 18 Cr; < 0.5 others; rest Fe	420	330	1	170	100
AISI 410	C 43	6.4...6.8	15 ± 2.5	0.1 ...0.3 C; 11 ... 13 Cr; < 2 others; rest Fe	> 165	6.6	0.2 C; 13 Cr; < 0.5 others; rest Fe	510	370	1	180	100
Sintered bronze	C 50	7.2...7.7	15 ± 2.5	9...11 Sn; < 2 others; rest Cu	> 35	7.4	10 Sn; < 0.5 others; rest Cu	150	90	4	40	50
	D 50	7.7...8.1	10 ± 2.5		> 45	7.9		220	120	6	55	70
Sintered aluminum containing Cu	D 73	2.45...2.55	10 ± 2.5	4...6 Cu; < 1 Mg; < 1 Si; < 2 others; rest Al	> 45	2.5	4.5 Cu; 0.6 Mg; 0.7 Si; < 0.5 others; rest Al	160	130	1	50	50
	E 73	2.55...2.65	6 ± 1.5		> 55	2.6		200	150	2	60	60

[1]) According to "Material Specification Sheets for Sintered Metals": DIN 30910, 1990 Edition.

Soft-magnetic metallic materials

Magnet type	Alloying constituents by mass %	Static magnetic properties: Coercive field strength $H_{c(max)}$ in A/m, Thickness in mm 0.4...1.5	> 1.5	Minimum magnetic polarization in tesla (T) at field strength H in A/m: 20	50	100	300	500	800	1600	4000	8000	AC test data, 50 Hz[1]): Measuring point $\hat{H}$ in A/m	Minimum amplitude permeability μ_r, Sheet thickness in mm 0.30...0.38	0.15...0.20
A – 240	100 Fe	240	240				1.15	1.30			1.60		Not suitable for AC applications.		
A – 120	100 Fe	120	120				1.15	1.30			1.60				
A – 60	100 Fe	60	60				1.25	1.35			1.60				
A – 12	100 Fe	12	12			1.15	1.30	1.40			1.60				
C1 – 48	0...5 Si (typical 2...4.5)	48	48			0.60	1.10	1.20			1.50				
C1 – 12	0...5 Si (typical 2...4.5)	12	12			1.20	1.30	1.35			1.50				
C21 – 09	0.4...5 Si (typical 2...4.5)												1.60	900	750
C22 – 13	0.4...5 Si (typical 2...4.5)												1.60	1300	–
E11 – 60	72...83 Ni	2	4	0.50	0.65	0.70		0.73			0.75		0.40	40000	40000
E21	54...68 Ni	Not suitable for this thickness												After agreement	
E31 – 06	45...50 Ni	10	10	0.50	0.90	1.10		1.35			1.45		0.40	6000	6000
E32	45...50 Ni	Not suitable for this thickness												After agreement	
E41 – 03	35...40 Ni	24	24	0.20	0.45	0.70		1.00			1.18		1.60	2900	2900
F11 – 240	47...50 Co		240				1.40		1.70	1.90	2.06	2.15	As agreed between manufacturer and buyer.		
F11 – 60	47...50 Co	60					1.80		2.10	2.20	2.25	2.25			
F21	35 Co	300							1.50	1.60	2.00	2.20			
F31	23...27 Co	300									1.85	2.00			

[1]) Data apply to laminated rings.

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Soft-magnetic metallic materials

Magnetic steel sheet and strip

Sheet type		Nominal thickness	Density ϱ	Max. cyclic magnetization loss (50 Hz) in W/kg under modulation			Magnetic polarization in tesla (T) min. at field strength H in A/m			Static coercive field strength H_c in A/m	Permeability μ max	Properties, typical applications
Abbreviated name	Material number	mm	g/cm³	P 1,0	P 1.5	P 1.7	(B25) 2500	(B50) 5000	(B100) 10000			
M 270–35A	1.0801	0.35	7.60	1.10	2.70	–	1.49	1.60	1.70			
M 330–35A	1.0804	0.35	7.65	1.30	3.30	–	1.49	1.60	1.70			
M 330–50A	1.0809	0.50	7.60	1.35	3.30	–	1.49	1.60	1.70			
M 530–50A	1.0813	0.50	7.70	2.30	5.30	–	1.56	1.65	1.75			
M 800–50A	1.0816	0.50	7.80	3.60	8.00	–	1.60	1.70	1.78			Cyclic magnetization losses.
M 400–65A	1.0821	0.65	7.65	1.70	4.00	–	1.52	1.62	1.72			
M1000–65A	1.0829	0.65	7.80	4.40	10.00	–	1.61	1.71	1.80			
M 800–100A	1.0895	1.00	7.70	3.60	8.00	–	1.56	1.66	1.75			
M1300–100A	1.0897	1.00	7.80	5.80	13.00	–	1.60	1.70	1.78	≈ 100	≈ 5000	
M 660–50D	1.0361	0.50	7.85	2.80	6.60	–	1.62	1.70	1.79			
M1050–50D	1.0363	0.50	7.85	4.30	10.50	–	1.57	1.65	1.77	...300		Manufacture of magnetic circuits with alternating magnetization (e.g. motors).
M 800–65D	1.0364	0.65	7.85	3.30	8.00	–	1.62	1.70	1.79			
M1200–65D	1.0366	0.65	7.85	5.00	12.00	–	1.57	1.65	1.77			
							at field strength H 800 A/m (B8)					
M 097–30N	1.0861	0.30	–	–	0.97	1.50		1.75				
M 140–30S	1.0862	0.30	–	–	0.92	1.40		1.78		≈ 1	≈ 30000	
M 111–30P	1.0881	0.30	–	–	–	1.11		1.85				
M 340–50E	1.0841	0.50	7.65	1.42	3.40	–	1.54	1.62	1.72			
M 560–50E	1.0844	0.50	7.80	2.42	5.60	–	1.58	1.66	1.76	≈ 100	≈ 5000	
M 390–65E	1.0846	0.65	7.65	1.62	3.90	–	1.54	1.62	1.72	...300		
M 630–65E	1.0849	0.65	7.80	2.72	6.30	–	1.58	1.66	1.76			

Materials for transformers and reactors
Core-lamination permeability for alloy classes C21, C22, E11, E31 and E41 for core-lamination section YEI1.

Minimum core-lamination permeability μ_{lam} (min)													
IEC designation		C21-09 Thickness in mm			C22-13 Thickness in mm			E11-60 Thickness in mm					
		0.3...0.38	0.15...0.2		0.3...0.38			0.3...0.38	0.15...0.2	0.1	0.05		
YEI1	−10	630	630		1000			14000	18000	20000	20000		
	13	800	630		1000			18000	20000	22400	20400		
	14	800	630		1000			18000	22400	22400	22400		
	16	800	630		1000			20000	22400	25000	22400		
	18	800	630		1000			22400	25000	25000	22400		
	20	800	630		1120			22400	25000	25000	25000		
	22	800	630		1120								
	25	800	630		1120								
IEC designation		E11-100 Thickness in mm			E31-04 Thickness in mm			E31-06 Thickness in mm					
		0.3...0.38	0.15...0.2	0.1	0.05	0.3...0.38	0.15...0.2	0.1	0.05	0.3...0.38	0.15...0.2	0.1	0.05
YEI1	−10	18000	25000	31500	31500	2800	2800	3150	3150	3550	4000	4500	5000
	13	20000	28000	35500	35500	2800	3150	3150	3550	4000	4500	5000	5000
	14	22400	28000	35500	35500	2800	3150	3150	3550	4000	4500	5000	5000
	16	25000	31500	35500	35500	2800	3150	3150	3550	4500	4500	5000	5000
	18	25000	31500	40000	35500	3150	3150	3550	3550	4500	4500	5000	5000
	20	28000	35500	40000	40000	3150	3150	3550	3550	4500	5000	5000	5000
IEC designation		E31-10 Thickness in mm				E41-02 Thickness in mm				E41-03 Thickness in mm			
		0.3...0.38	0.15...0.2	0.1	0.05	0.3...0.38	0.15...0.2	0.1	0.05	0.3...0.38	0.15...0.2	0.1	0.05
YEI1	−10	5600	6300	5600	6300	1600	1800	1800	2000	2000	2240	2500	2240
	13	6300	7100	6300	6300	1800	1800	2000	2000	2240	2240	2500	2240
	14	6300	7100	6300	7100	1800	1800	2000	2000	2240	2240	2500	2240
	16	6300	7100	6300	7100	1800	1800	2000	2000	2240	2500	2500	2240
	18	7100	7100	6300	7100	1800	1800	2000	2000	2240	2500	2500	2240
	20	7100	7100	6300	7100	1800	2000	2000	2000	2240	2500	2500	2240

Materials for direct-current relays

Material type	Alloying constituents	Density[1] ϱ	Hardness[1]	Remanence[1]	Permeability[1]	Specific el. resistance[1]	Coercive field strength	Magnetic polarization in T (Tesla) min. at field strength H in A/m							Characteristic properties, applications
Abbreviated name / Material number	by mass %	g/cm³	HV	T (Tesla)	μ_{max}	$\frac{\Omega \cdot mm^2}{m}$	A/m max.	20	50	100	200	300	500	1000	4000	
Unalloyed steels																
RFe 160 1.1011		7.85	max. 150	1.10	–	0.15	160	–	–	–	–	1.15	1.30	–	1.60	Low coercive field strength.
RFe 80 1.1014				1.20	–	0.15	80	–	–	–	1.10	1.20	1.30	1.45	1.60	
RFe 60 1.1015	–			1.20	–	0.12	60	–	–	–	1.15	1.25	1.35	1.45	1.60	
RFe 20 1.1017				1.20	≈ 20 000	0.10	20	–	–	1.15	1.25	1.30	1.40	1.45	1.60	
RFe 12 1.1018				1.20		0.10	12	–	–	1.15	1.25	1.30	1.40	1.45	1.60	
Silicon steels																For DC relays and similar purposes.
RSi 48 1.3840	2.5	7.55	130	0.50	–	0.42	48	–	–	0.60	–	1.10	1.20	–	1.50	
RSi 24 1.3843	–	–	–	1.00	≈ 20 000	–	24	–	–	1.20	–	1.30	1.35	–	1.50	
RSi 12 1.3845	4 Si	7.75	200	1.00	≈ 10 000	0.60	12	–	–	1.20	–	1.30	1.35	–	1.50	
Nickel steels and nickel alloys																
RNi 24 1.3911	≈ 36 Ni	8.2	130...180	0.45	≈ 5000	0.75	24	0.20	0.45	0.70	–	0.90	1.0	–	1.18	
RNi 12 1.3926	≈ 50 Ni	8.3	130...180	0.60	≈ 30 000	0.45	12	0.50	0.90	1.10	–	1.25	1.35	–	1.45	
RNi 8 1.3927	≈ 50 Ni	8.3	130...180	0.60	30000...100000	0.45	8	0.50	0.90	1.10	–	1.25	1.35	–	1.45	
RNi 5 2.4596	70 ... 80 Ni	8.7	120...170	0.30	≈ 40 000	0.55	5	0.50	0.65	0.70	–	–	–	–	0.75	
RNi 2 2.4595	small quantities Cu, Cr, Mo	8.7	120...170	0.30	≈ 100 000	0.55	2	0.50	0.65	0.70	–	–	–	–	0.75	

[1]) Standard values.

Sinter metals for soft-magnetic components

Material	Characteristic alloying substances (except Fe)	Sinter density	Porosity	Maximum coercive field strength	Magnetic polarization in Tesla (T) at field strength H in A/m				Maximum permeability	Vickers hardness	Specific electrical resistance
Abbreviated name	Mass proportions %	ϱ_s g/cm³	p_s %	$H_{c(max)}$ A/m	500	5000	15000	80000	$\mu_{(max)}$	HV5	ϱ $\mu\Omega$m
S-Fe-175	–	6.6	16	175	0.70	1.10	1.40	1.55	2 000	50	0.15
S-Fe-170	–	7.0	11	170	0.90	1.25	1.45	1.65	2 600	60	0.13
S-Fe-165	–	7.2	9	165	1.10	1.40	1.55	1.75	3 000	70	0.12
S-FeP-150	≈0.45 P	7.0	10	150	1.05	1.30	1.50	1.65	3 400	95	0.20
S-FeP-130	≈0.45 P	7.2	8	130	1.20	1.45	1.60	1.75	4 000	105	0.19
S-FeSi-80	≈3 Si	7.3	4	80	1.35	1.55	1.70	1.85	8 000	170	0.45
S-FeSi-50	≈3 Si	7.5	2	50	1.40	1.65	1.70	1.95	9 500	180	0.45
S-FeNi-20	≈50 Ni	7.7	7	20	1.10	1.25	1.30	1.30	20 000	70	0.50
S-FeNi-15	≈50 Ni	8.0	4	15	1.30	1.50	1.55	1.55	30 000	85	0.45
S-FeCo-100	≈50 Co	7.8	3	100	1.50	2.00	2.10	2.15	2 000	190	0.10
S-FeCo-200	≈50 Co	7.8	3	200	1.55	2.05	2.15	2.20	3 900	240	0.35

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