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

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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	=	10^5	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 66034 Conversion tables, kilopond – newton, newton – kilopond, DIN 66037 Conversion tables, kilopond/cm² – bar, bar – kilopond/cm², DIN 66038 Conversion tables, torr – millibar, millibar – torr

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

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

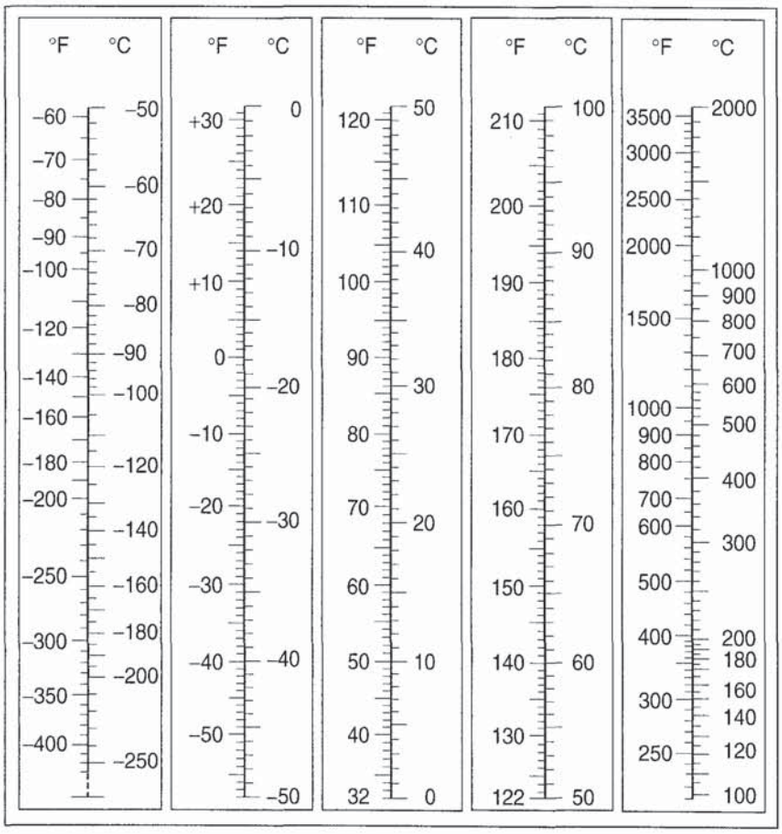
Temperature difference

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.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

Units of viscosity

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

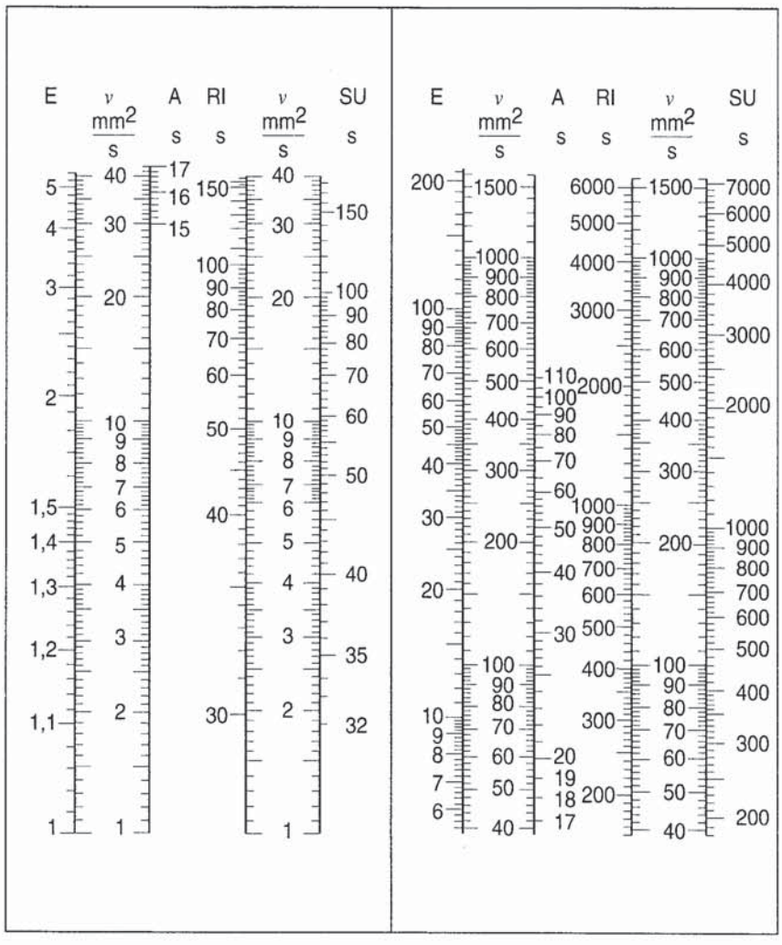
British and American units:
1 ft^2/s = 0.092903 m^2/s,
RI seconds = efflux time from Redwood-I viscometer (UK),
SU seconds = efflux time from Saybolt-Universal viscometer (US).

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 ν > 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.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

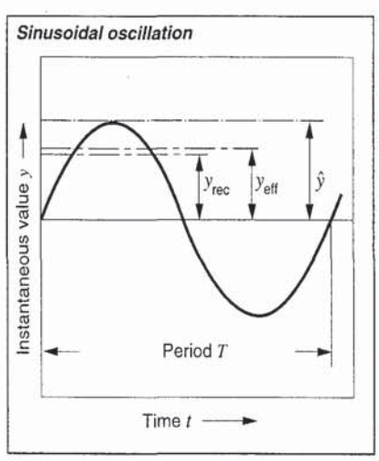
$$y_{rec} = (1/T) \int_0^T | y | \, dt$$

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



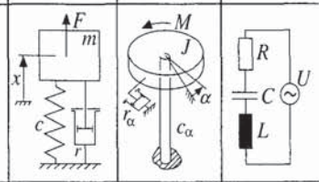
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

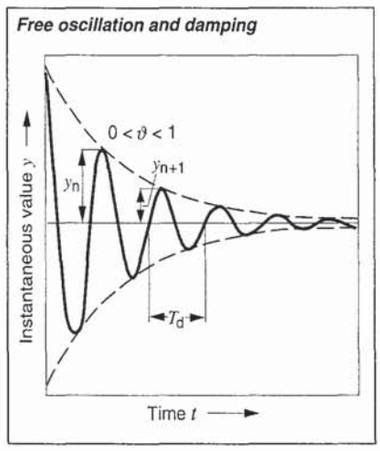
Form factor = y_{eff}/y_{rec}
For a sine curve:
$y_{eff}/y_{rec} \approx 1.111$.

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	$1/C$



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

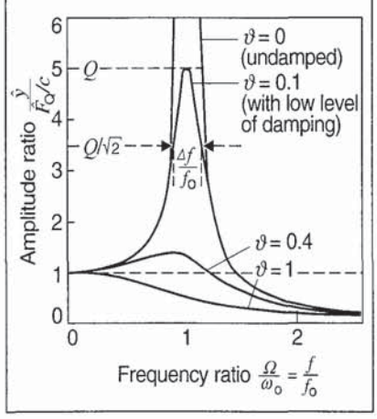
Vibration damping
If damping can only be carried out between the machine and a quiescent point, the damping must be at a high level (cf. "Standardized transmission function" diagram).

Vibration isolation

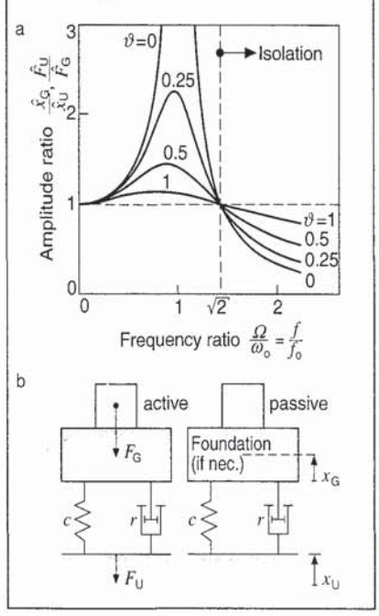
Active vibration isolation
Machines are to be mounted so that the

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US PATENT NO. 6,557,540

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.

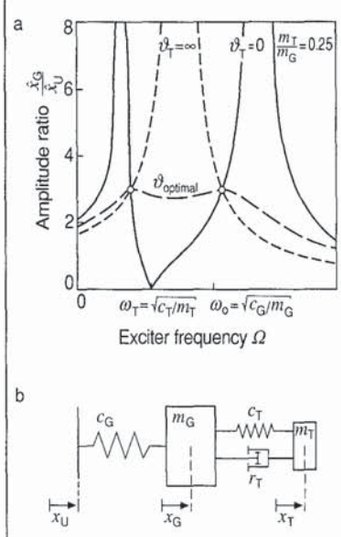
Absorber with changeable natural frequency

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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US PATENT NO. 6,557,540

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).

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US PATENT NO. 6,557,540

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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US PATENT NO. 6,557,540

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

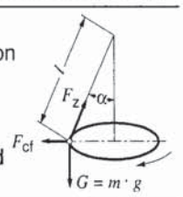
(Mathematical pendulum, i.e. a point-size mass suspended from a thread of zero mass)

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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US PATENT NO. 6,557,540

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	$v_2 = 0;\quad h_2 = \frac{v_1^2}{2g};\quad t_2 = \frac{v_1}{g}$

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	$t = \frac{s}{v_1 \cdot \cos \alpha} = \frac{2v_1 \cdot \sin \alpha}{g}$
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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US PATENT NO. 6,557,540

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		
		Long plate $l : d = 30$	
Sphere		$Re \approx 500\,000$	0.78
$Re < 200\,000$	0.45	$Re \approx 200\,000$	0.66
$Re > 250\,000$	0.20		
		Long airfoil	
Slender rotating body $l : d = 6$	0.05	$l : d = 18$	0.2
		$l : d = 8$ $Re \approx 10^6$	0.1
		$l : d = 5$	0.08
		$l : d = 2$ $Re \approx 2 \cdot 10^5$	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

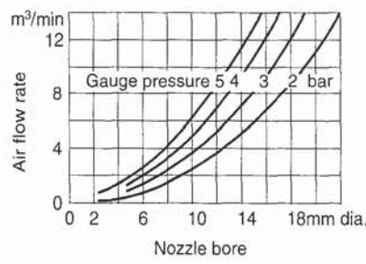
The results of flow measurements on two geometrically similar bodies of different sizes are comparable only if the Reynolds number is of equal magnitude in both cases (this is important in tests on models).

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

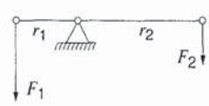
Discharge of air from nozzles

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

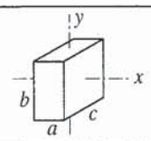
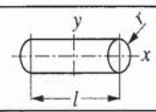
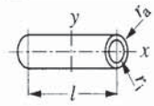
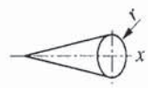
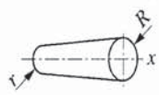
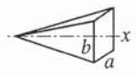
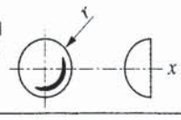
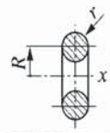
$F_1 \cdot r_1 = F_2 \cdot r_2$



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US PATENT NO. 6,557,540

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 parallele-piped, 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 	$J_x = m \left(R^2 + \frac{3}{4}r^2\right)$

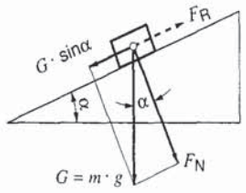
[1]) The moment of inertia for an axis parallel to the x-axis or y-axis at a distance a is $J_A = J_x + m \cdot a^2$ or $J_A = J_y + m \cdot a^2$.

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US PATENT NO. 6,557,540

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])
$a = g \, (\sin \alpha - \mu \cdot \cos \alpha)$

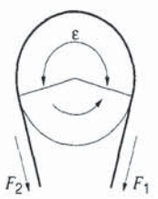
Velocity after distance s
(or height $h = s \cdot \sin \alpha$)
$v = \sqrt{2g \cdot h \, (1 - \mu \cdot \cot \alpha)}$

[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:
$F_1 = F_2 \cdot e^{\mu\varepsilon}$

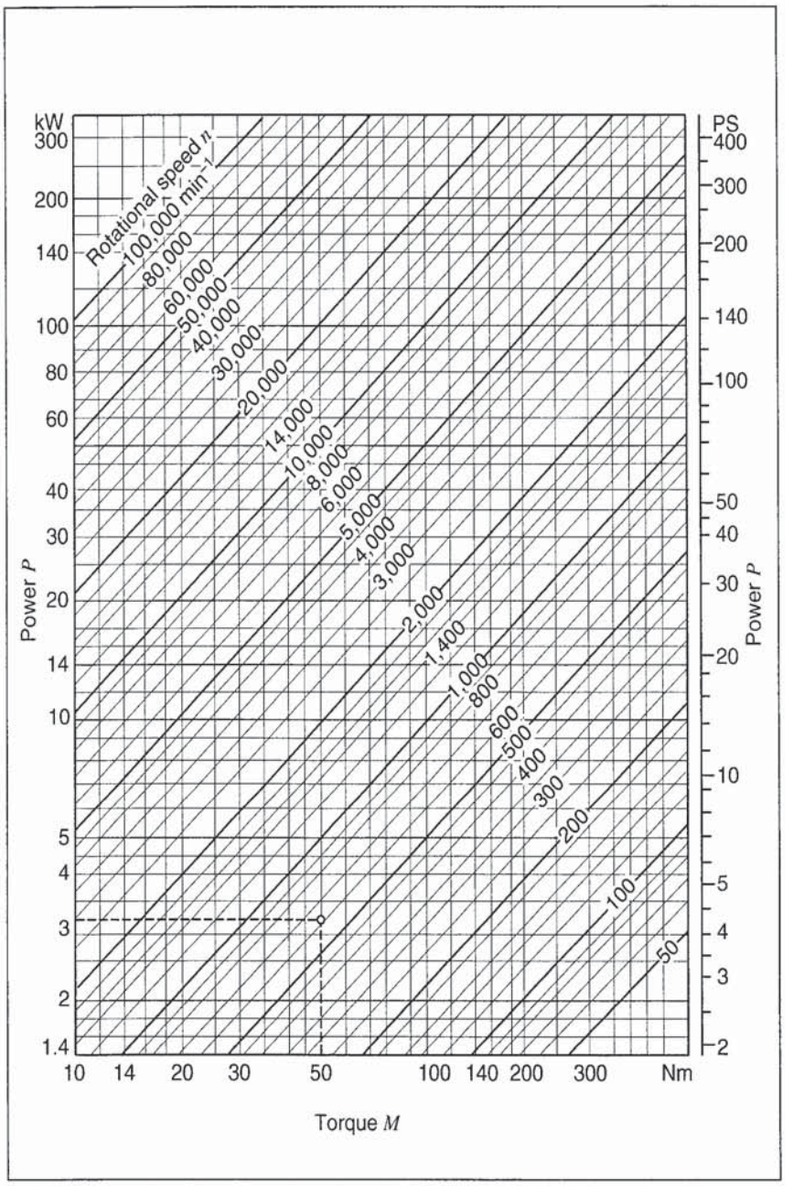
Transmittable peripheral force:
$F_u = F_1 - F_2 = F_1 \, (1 - e^{-\mu\varepsilon}) = F_2 \, (e^{\mu\varepsilon} - 1)$
$e = 2.718$ (base of natural logarithms)



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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

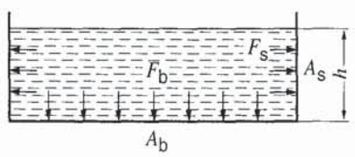
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US PATENT NO. 6,557,540

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

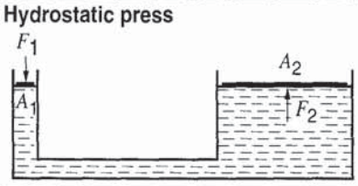
Symbol	Quantity	SI unit
p	Fluid pressure	Pa[2])
	$p_1 - p_2$ differential pressure	Pa
p_e	Gauge pressure compared with atmospheric pressure	Pa
Q	Flow rate	m^3/s
V	Volume	m^3
v	Flow velocity	m/s
ϱ	Density	kg/m^3
	Density of water[3]) $\varrho_w = 1\ kg/dm^3 = 1000\ kg/m^3$	

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

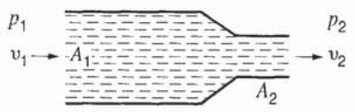


Fluid pressure $p = \frac{F_1}{A_1} = \frac{F_2}{A_2}$

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

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

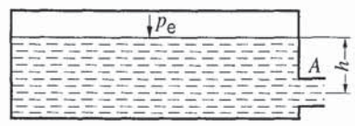
Flow with change in cross section



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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

Strength of materials

Symbols and units

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

Quantity		Unit
A	Cross-sectional area	mm^2
E	Modulus of elasticity	N/mm^2
F	Force, load	N
G	Modulus of elasticity in shear	N/mm^2
I_a	Axial planar moment of inertia (P. 49)	mm^4
I_p	Polar planar moment of inertia (P. 49)	mm^4
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/mm^2
R_e	Yield point	N/mm^2
R_m	Tensile strength	N/mm^2
$R_{p0.2}$	0.2% yield strength[1])	N/mm^2
S	Safety factor	–
s	Maximum deflection	mm
W_b	Section modulus under bending (P. 49)	mm^3
W_t	Section modulus under torsion (P. 49)	mm^3
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/mm^2
σ_{zdw}	Reversed-bending fatigue strength	N/mm^2
σ_{gr}	Limit stress	N/mm^2
σ_D	Endurance limit = fatigue limit	N/mm^2
σ_W	Endurance limit at complete stress reversal	N/mm^2
σ_a	Stress amplitude	N/mm^2
σ_{bB}	Bending strength	N/mm^2
σ_{bF}	Elastic limit under bending	N/mm^2
σ_{bW}	Fatigue limit under reversed bending stresses	N/mm^2
τ	Shear stress	N/mm^2
τ_t	Torsional stress	N/mm^2
τ_{gr}	Torsional stress limit	N/mm^2
τ_{tB}	Torsional strength	N/mm^2
τ_{tF}	Elastic limit under torsion	N/mm^2
τ_{tW}	Fatigue limit under reversed torsional stress	N/mm^2
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.

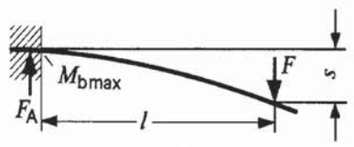
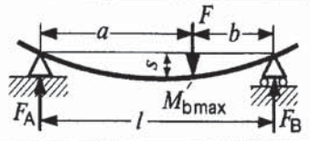
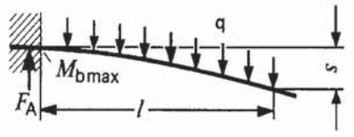
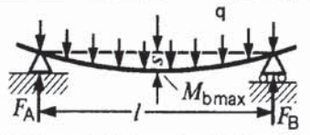
W Section modulus of a cross section: indicates, for the edge stress 1, the inner moment with which the cross section can resist an external bending load.

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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US PATENT NO. 6,557,540

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,

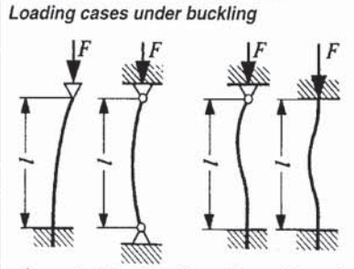
$\lambda \geq 80$ for GG 25 gray cast iron,

$\lambda \geq 100$ 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,

Loading cases under buckling



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

- 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.

---

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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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)].

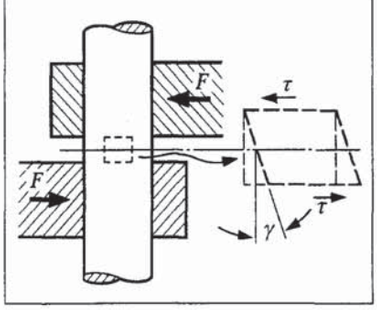
Torsion (twisting)

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.

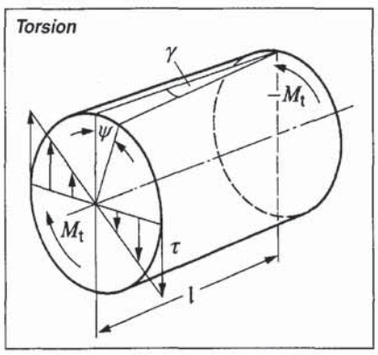
Angle of rotation $\psi = \dfrac{l \cdot M_t}{G \cdot I_p} = \dfrac{l \cdot W_t \cdot \tau}{I_p \cdot G}$

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.

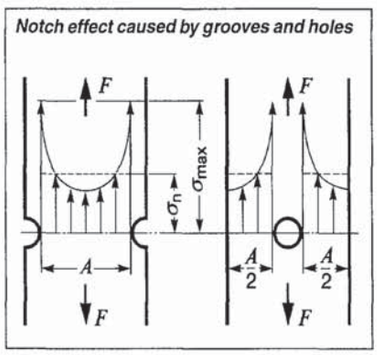
Notches (such as grooves and holes) and changes in cross section (shoulders and offsets) as well as various clamping methods give rise to local stress concentrations σ_{max}, which are usually far in excess of the nominal stresses:

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

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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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 σ_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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

Limit stresses under pulsating loads

If the load alternates between two stress values, different (lower) stress limits σ_{gr} 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

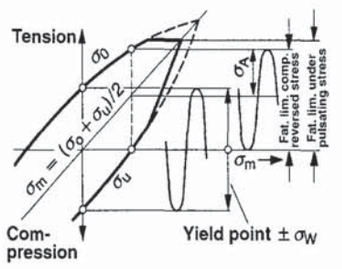
The greatest "infinitely" often endurable stress amplitude can be determined from the fatigue limit diagram (at right) for any minimum stress σ_u or mean stress σ_m. The diagram is produced using several Wöhler curves with various mean stress factors.

Special cases of fatigue limit

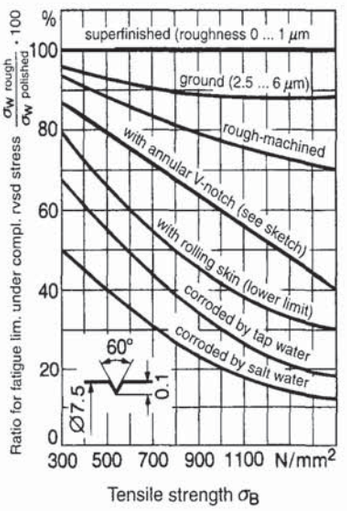
Fatigue limit under completely reversed stress σ_W

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).

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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).

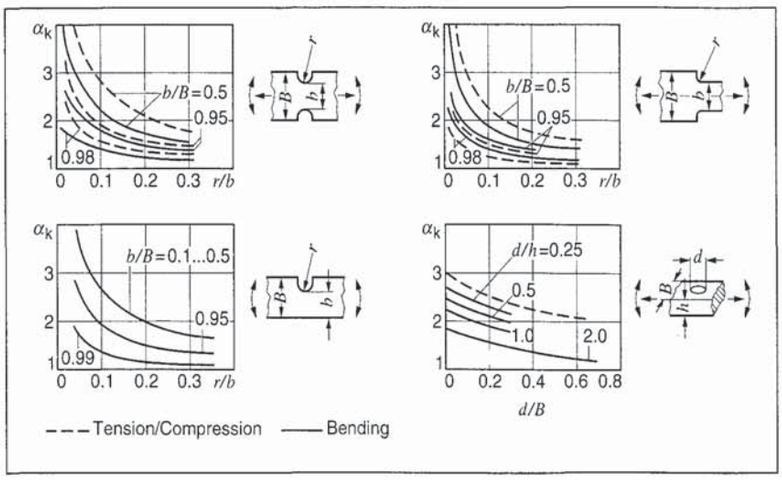
In the case of alternating loads (where $\sigma_a \geq 0.1\ \sigma_B$) and maximum stresses and temperatures such as are encountered in static relaxation tests, the same deformations and losses of force only occur after a period of load which is approximately 10 times (or more) as long as that of the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

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

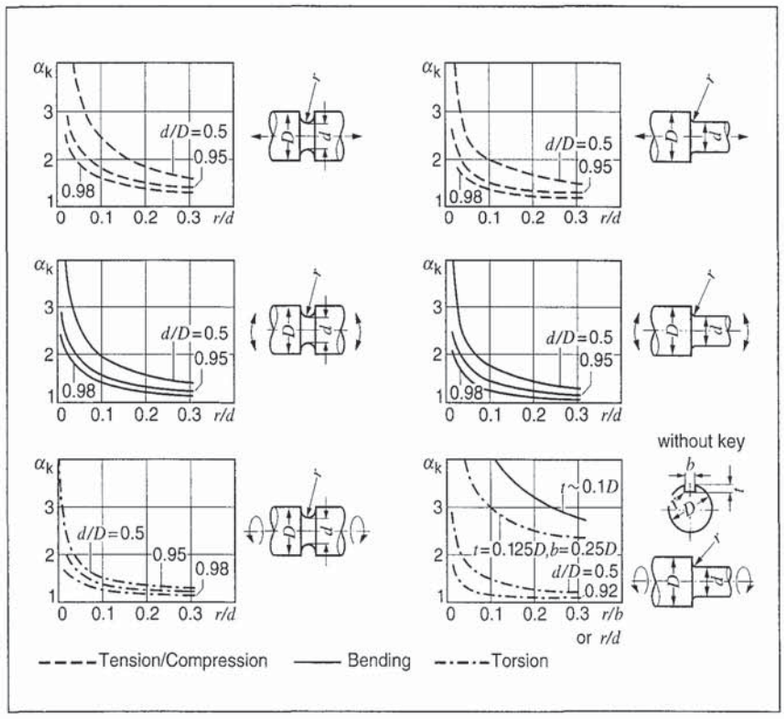
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US PATENT NO. 6,557,540

Stress concentration factor α_k for various notch configurations

Stress concentration factors for flat bars



Stress concentration factors for rods

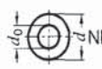
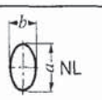
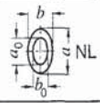
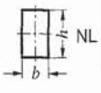
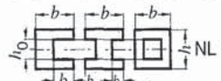
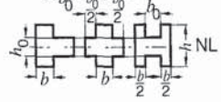


PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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 $\frac{a_0}{b_0} = n$
	$W_b = 0.118\ a^3$ $W_t = 0.208\ a^3$	$I_a = 0.083\ a^4$ $I_p = 0.140\ a^4$
$h:b$ | 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 	$W_b = 0.167\ b \cdot h^2$ $W_t = x \cdot b^2 \cdot h$ (In the case of torsion, the initially plane cross sections of a rod do not remain plane.)	$I_a = 0.083 \cdot b \cdot h^3$ $I_p = \eta \cdot b^3 \cdot h$
	$W_b = 0.104\ d^3$ $W_t = 0.188\ d^3$	$I_a = 0.060\ d^4$ $I_p = 0.115\ d^4$
	$W_b = 0.120\ d^3$ $W_t = 0.188\ d^3$	$I_a = 0.060\ d^4$ $I_p = 0.115\ d^4$
	$W_b = \frac{h^2 (a^2 + 4a \cdot b + b^2)}{12\ (2a + b)}$	$I_a = \frac{h^3 (a^2 + 4a \cdot b + b^2)}{36\ (a + b)}$
	$W_b = \frac{b \cdot h^3 - b_0 \cdot h_0^3}{6\ h}$	$I_a = \frac{b \cdot h^3 - b_0 \cdot h_0^3}{12}$
	$W_b = \frac{b \cdot h^3 + b_0 \cdot h_0^3}{6\ h}$	$I_a = \frac{b \cdot h^3 + b_0 \cdot h_0^3}{12}$

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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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US PATENT NO. 6,557,540

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

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

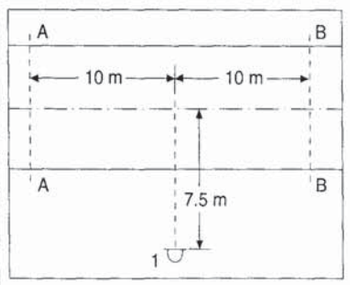
Noise emissions from moving vehicles
The vehicle approaches line AA, which is located 10 m from the microphone plane, at a constant velocity. Upon reaching line AA, the vehicle continues under full acceleration as far as line BB (also placed 10 m from the microphone plane), which serves as the end of 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



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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)

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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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US PATENT NO. 6,557,540

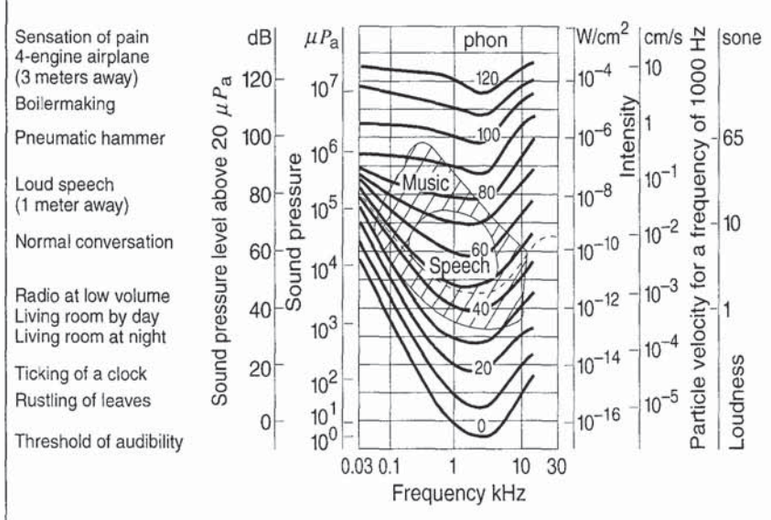
- Measuring rooms for standard sound measurements are generally equipped with highly sound-absorbent walls.
- Vibrations, structure-borne sound: acceleration sensor (mass partly under 1 g), e.g. according to piezoelectric principle; laser vibrometer for rapid non-contact measurement according to Doppler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



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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

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

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

$$Q = \varepsilon \cdot \sigma \cdot A \cdot T^4$$

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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US PATENT NO. 6,557,540

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
Porcelain, 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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US PATENT NO. 6,557,540

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.

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US PATENT NO. 6,557,540

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: $p \cdot \upsilon = R_i \cdot T$)

Change of state	Characteristics	Specific heat capacity[1])	Equations (k, K are constants)[1])	Examples
Isobaric	Constant pressure	c_p	$p = k$ $\upsilon = K \cdot T$	"Constant pressure" combustion in diesel engines; heating or cooling in once-through boilers.
Isochoric	Constant volume	c_v	$\upsilon = k$ $p = K \cdot T$	"Constant volume" combustion in spark-ignition engines; heating or cooling in closed boilers.
Isothermal	Constant temperature	–	$T = k$ $p \cdot \upsilon = K$	Slow change of state (heat flows through partitions).
Adiabatic	Heat neither supplied nor dissipated	–	$P \cdot \upsilon^{\varkappa} = k$ $T \cdot \upsilon^{\varkappa - 1} = k$	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	$c = \frac{c_v (n - \varkappa)}{n - 1}$	$P \cdot \upsilon^n = K$ $T \cdot \upsilon^{n-1} = K$ $T^n \cdot p^{1-n} = K$	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, $n = \frac{\lg p_2 - \lg p_1}{\lg \upsilon_1 - \lg \upsilon_2}$

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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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US PATENT NO. 6,557,540

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

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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

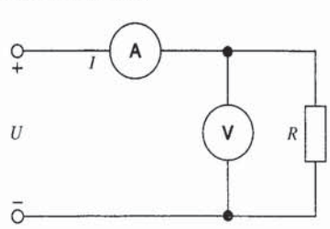
ϱ Resistivity in Ωmm²/m

$\sigma = 1/\varrho$ Conductivity

l Wire length in m

q Wire cross section in mm²

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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

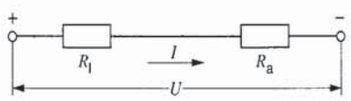
Direct-current circuits

Circuit with load

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

R_a = Load

R_i = Line resistance

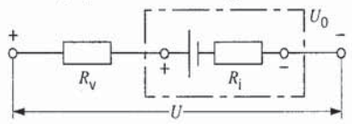


Battery-charging circuit

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

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.



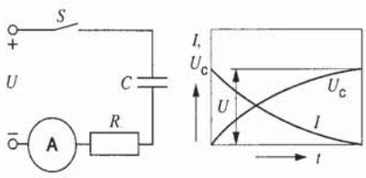
Charging and discharging a capacitor

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.

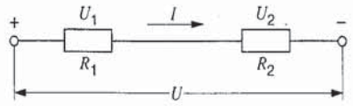
[1]) Formerly called emf (electromotive force).

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.



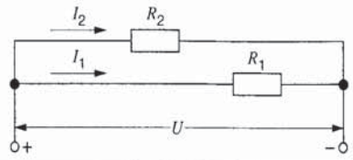
Parallel connection of resistors

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

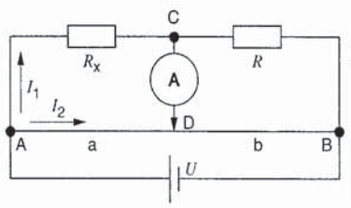
$I_1 \cdot R_x = I_2 \cdot \varrho \cdot a/q$

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

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.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

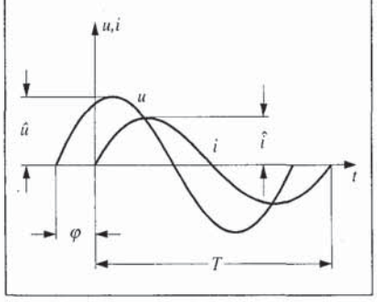
There are three kinds of power specified in an alternating-current circuit:

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).

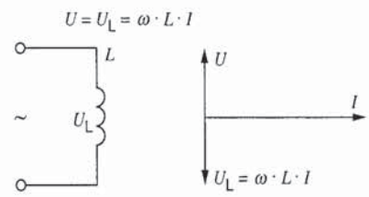
Alternating-current diagram
T Duration of one complete oscillation (period) in s, f Frequency in Hz ($f = 1/T$), $\hat{i}$ Peak value (amplitude) of current, $\hat{u}$ Peak value (amplitude) of voltage, ω Angular frequency in 1/s ($\omega = 2\pi \cdot f$), φ Phase displacement angle between current and 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°.

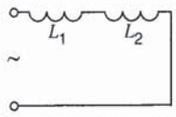


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US PATENT NO. 6,557,540

Inductance of coils connected in series and parallel:

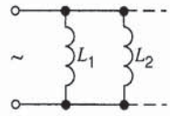
Coils connected in series

$L_{total} = L_1 + L_2$



Coils connected in parallel

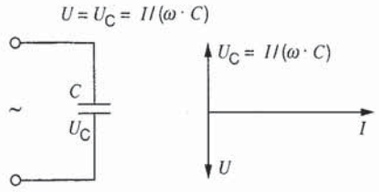
$\frac{1}{L_{total}} = \frac{1}{L_1} + \frac{1}{L_2} + \ldots$



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°.

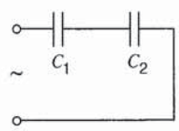
$U = U_C = I/(\omega \cdot C)$



Capacitance of capacitors connected in series and parallel:

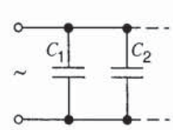
Capacitor connected in series

$1/C_{total} = 1/C_1 + 1/C_2$



Capacitor connected in parallel

$C_{total} = C_1 + C_2 + \ldots$

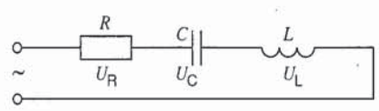


Ohm's Law for alternating current (AC)

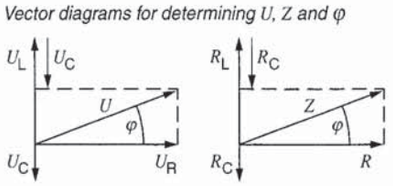
In an alternating-current circuit with ohmic resistance (R), coil (inductance L) and capacitor (capacitance C), the same laws apply to the electrical parameters of resistance, voltage and current as in a direct-current circuit.

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.

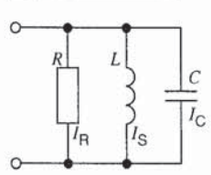
The following equation defines the phase displacement φ between current and voltage:

$\tan\varphi = [\omega \cdot L - 1/(\omega \cdot C)]/R$

The maximum possible current ($I = U/R$) flows when the circuit resonates; the circuit will resonate if:

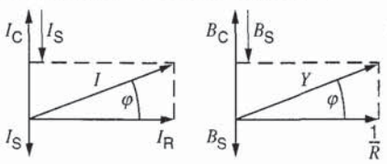
$\omega^2 \cdot L \cdot C = 1$ (i.e. $X = 0$)

Parallel connection



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US PATENT NO. 6,557,540

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:

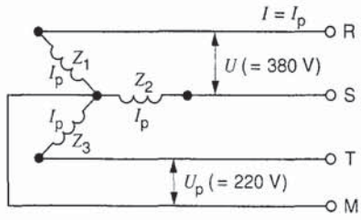
Apparent power:

$P_s = \sqrt{3} \cdot U \cdot I = 3\, U_p \cdot I_p$

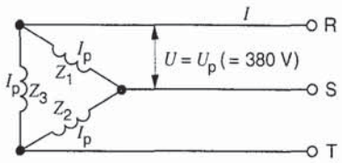
True power:

$P = P_s \cdot \cos\varphi = \sqrt{3} \cdot U \cdot I \cdot \cos\varphi$

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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US PATENT NO. 6,557,540

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:

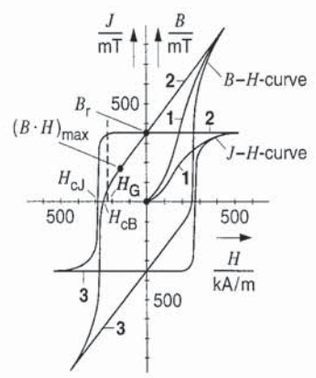
Diamagnetic materials ($\mu_r < 1$)
(e.g. Ag, Au, Cd, Cu, Hg, Pb, Zn, water, organic materials, gases)
μ_r is independent of magnetic field strength and smaller than 1; the values are in the range

$(1 - 10^{-11}) > \mu_r > (1 - 10^{-5})$

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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US PATENT NO. 6,557,540

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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US PATENT NO. 6,557,540

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

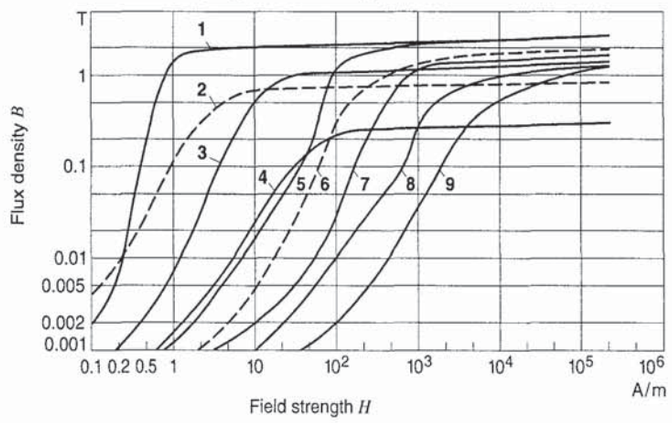
In addition to material equations, the following equations also determine the design of magnetic circuits:
1. Ampère's law (equation of magnetic voltage).
The following equation holds true for a closed magnetic circuit:

$$\sum_i H_i \cdot l_i = V_1 + V_2 + \ldots + V_i = I \cdot w \text{ or } 0,$$

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-

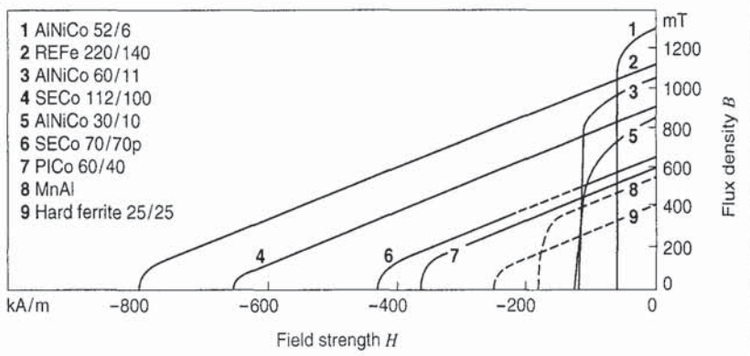
Type of steel sheet	Nominal thickness mm	Specific total loss W/kg P1	P1.5	B (for H = 10 kA/m) T
M 270 – 35 A	0.35	1.1	2.7	1.70
M 330 – 35 A	0.35	1.3	3.3	1.70
M 400 – 50 A	0.5	1.7	4.0	1.71
M 530 – 50 A	0.5	2.3	5.3	1.74
M 800 – 50 A	0.5	3.6	8.1	1.77

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



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US PATENT NO. 6,557,540

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:

$$F \approx 0.2 \cdot 10^{-6} \cdot I_1 \cdot I_2 \cdot l/a$$ [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).

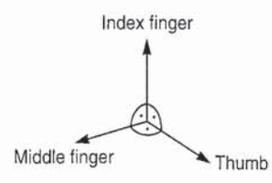
[1]) F Force in N; I_1, I_2 and I Current in A; l and a Length in m; B Inductance in T.

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US PATENT NO. 6,557,540

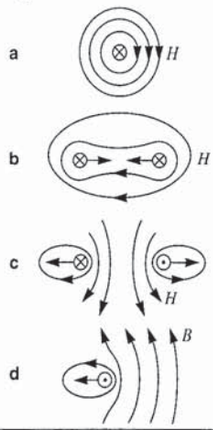
Law of induction

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.

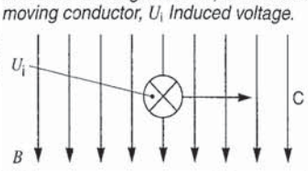
Three-finger rule



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:

$$U_i = B \cdot l \cdot \upsilon$$

U_i in V, B in T, l Conductor length in m, υ 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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US PATENT NO. 6,557,540

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-

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US PATENT NO. 6,557,540

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)

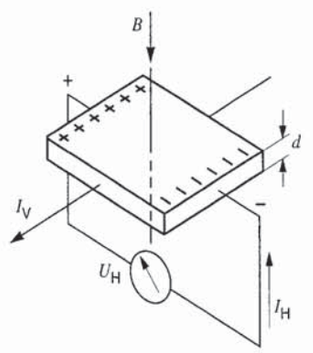
Material	Thermoelectric voltage 10^{-6} V/°C
Selenium	1003
Tellurium	500
Silicon	448
Germanium	303
Antimony	47 ... 48.6
Nickel chromium	22
Iron	18.7 ... 18.9
Molybdenum	11.6 ... 13.1
Cerium	10.3
Cadmium	8.5 ... 9.2
Steel (V2A)	7.7
Copper	7.2 ... 7.7
Silver	6.7 ... 7.9
Tungsten	6.5 ... 9.0
Iridium	6.5 ... 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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US PATENT NO. 6,557,540

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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US PATENT NO. 6,557,540

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	Germanium	Teflon
Copper	Silicon	Quarz glass
Aluminum	Gallium-arsenide	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

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US PATENT NO. 6,557,540

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.

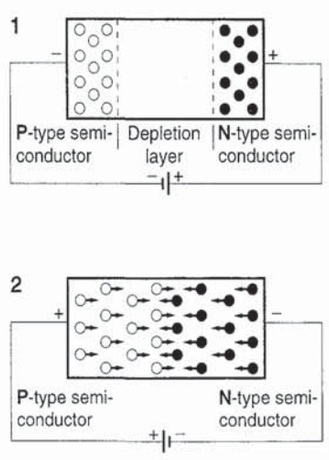
The pn-junction in the semiconductor
The area of transition between a p-type and an n-type zone within the same semiconductor crystal is referred to as the pn-junction. The properties of this area exercise a major influence on the operating properties of most semiconductor components.

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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US PATENT NO. 6,557,540

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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US PATENT NO. 6,557,540

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.

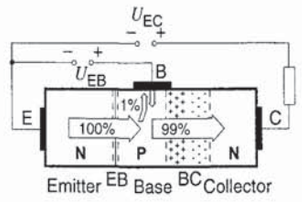
Bipolar transistors
Bipolar transistors consist of three zones of varying conductivity, the configuration being either pnp or npn. The zones (and their terminals) are called: emitter E, base B and collector C.

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.

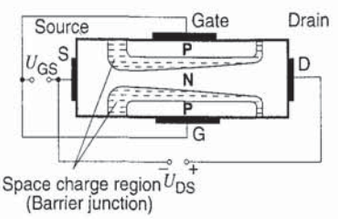
Operation of a bipolar transistor
(explanation based on the npn transistor)
The emitter-base junction (EB) is forward biased. This causes electrons to be injected into the base region.

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)*



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

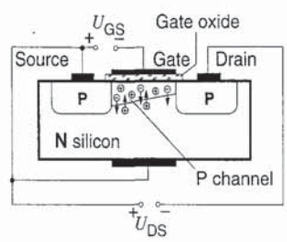
Field-effect transistors (FET)
In these devices, control of the current flow in a conductive path is exercised essentially by an electric field. The field, in turn, is generated with voltage applied at the control electrode, or gate. Field-effect transistors differ from their bipolar counterparts in 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).

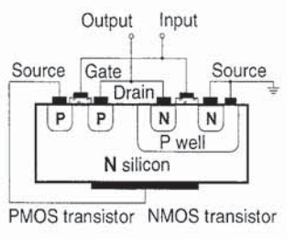
Operation of a junction FET
(applies to the n-channel FET)
DC voltage is present at the ends of an n-type crystal. Electrons flow from the source to the drain. The width of the channel is defined by two laterally diffused p-type zones and by the negative voltage present within them. Raising the negative 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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US PATENT NO. 6,557,540

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).

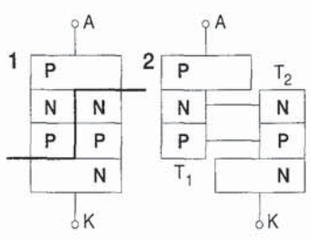
Thyristors
Three consecutive pn-junctions provide the thyristor effect, which is applied for components which act as snap switches when triggered by an electrical signal. The term "thyristor" is the generic designation for all devices which can be switched from the forward (conducting) state to the reverse (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.

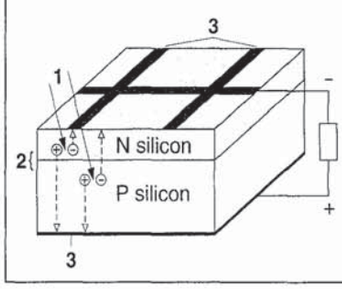
Thyristor with control terminal
DIN definition: Triode thyristor (also SCR, silicon-controlled rectifier), a controllable device with switching characteristics. It consists of four zones of alternating conductivity type. Like the four-layer diode, it has two stable states (high resistance and low resistance). 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.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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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US PATENT NO. 6,557,540

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.

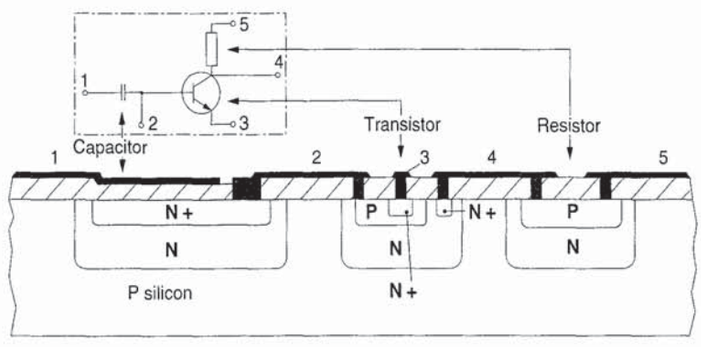
Classifications for integrated circuitry

- 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.*



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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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US PATENT NO. 6,557,540

Overview of semiconductor memory devices

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US PATENT NO. 6,557,540

- 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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US PATENT NO. 6,557,540

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

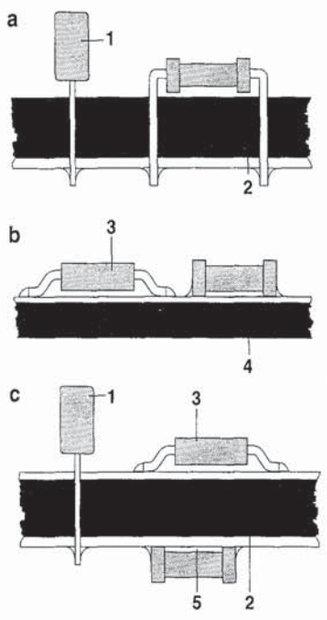
Integrated film circuits in which the layers are usually applied to ceramic carriers in a silk-screening process before being fused on. Advantages: Multi-layer construction provides high circuit-element density and good HF characteristics. A high degree of manufacturing automation is possible for large-scale 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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US PATENT NO. 6,557,540

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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US PATENT NO. 6,557,540

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

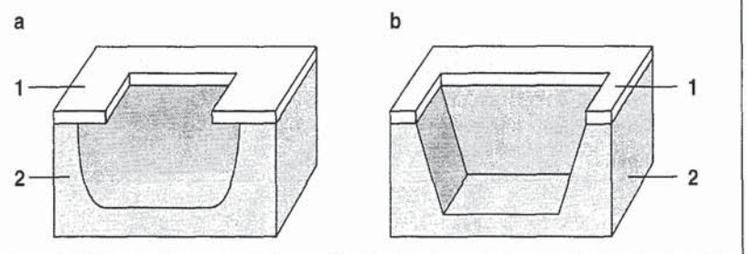
The term "micromechanics" is employed to designate the production of mechanical components using semiconductors (generally silicon) and semiconductor technology. This type of application exploits both the semiconductive and the mechanical properties of silicon. The first micromechanical silicon pressure 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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US PATENT NO. 6,557,540

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.

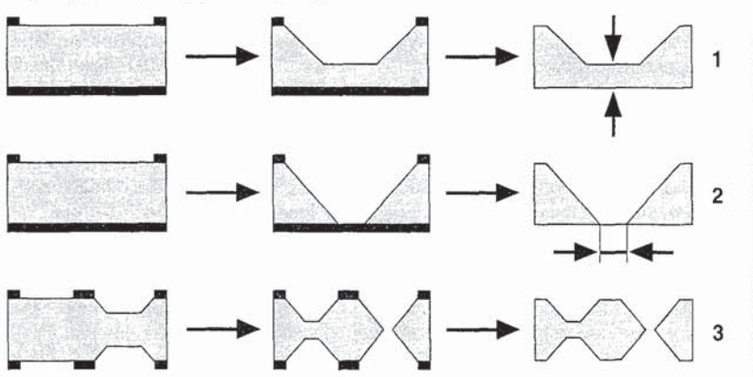


Both methods use the standard procedures of microelectronics (e.g. epitaxial growth, oxidation, diffusion and photolithography) together with some additional special procedures: For the removal of material, bulk micromechanics requires anisotropic etching with or without electrochemical etch stop, while 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.



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US PATENT NO. 6,557,540

applications such as pressure sensors and air-mass meters.

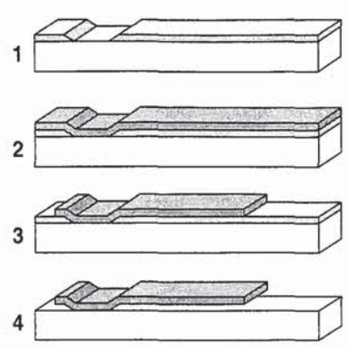
Surface micromechanics (SMM)
In contrast to bulk micromechanics, SMM merely uses the silicon wafer as the base material. Moving structures are formed from polycrystalline silicon layers which, similar to a manufacturing process for integrated circuits, are deposited on the surface of the silicon by epitaxial 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.

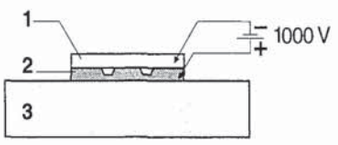
Among other things, SMM is used in the manufacture of capacitive acceleration sensors with movable and fixed electrodes for capacitive evaluation, and rotation-rate sensors with quasirotatory oscillators.

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.

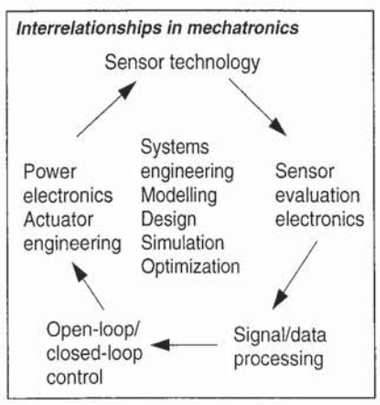
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US PATENT NO. 6,557,540

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.



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.

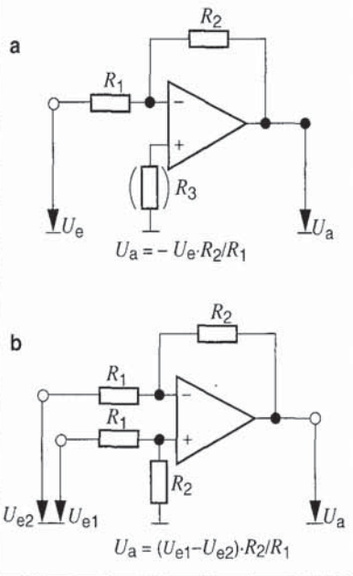
Example: 101 (dual) =
$1 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0 = 5$ (decimal).

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.

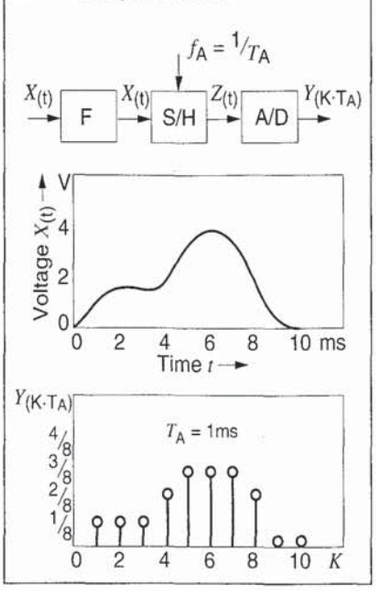
Example: 101 =
$-1 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0 = -3$.

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US PATENT NO. 6,557,540

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.



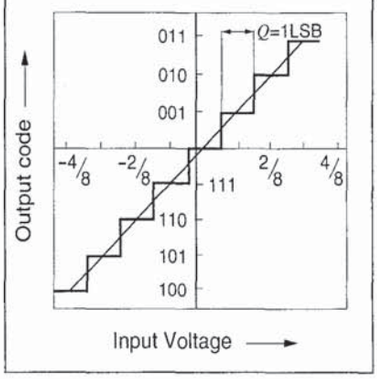
A word of n bits in length is able to represent 2^n different values. This is 256 for 8 bits, for 16 bits it is 65 536. An analog input voltage of ± 5 V (FSR – Full Scale Range) results in a resolution (LSB value) of 39 mV for 8 bits and 0.15 mV for 16 bits.

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



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US PATENT NO. 6,557,540

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

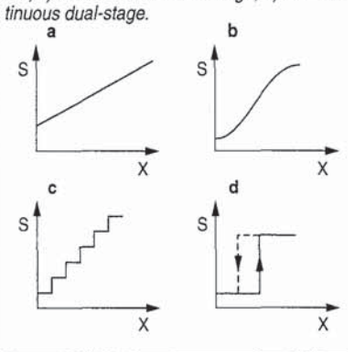
Output signal proportional to:
- current/voltage, amplitude,
- frequency/periodicity,
- pulse duration/pulse duty factor.

Discrete output signal:
- dual stage (binary),
- multi-stage (irregular graduation),
- multi-stage (equidistant) or digital.

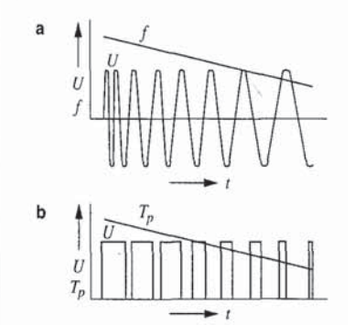
Automotive applications

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

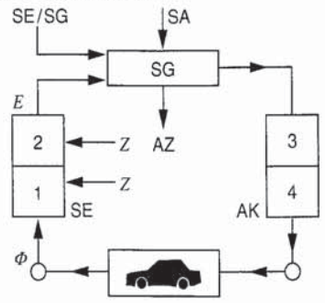
The degree of stress to which the sensor is subjected is determined by the operating conditions (mechanical, climatic, chemical, electromagnetic influences) present at the installation location (for standard Degrees of Protection, see DIN 40 050, Sheet 9).

According to application and technical

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US PATENT NO. 6,557,540

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).

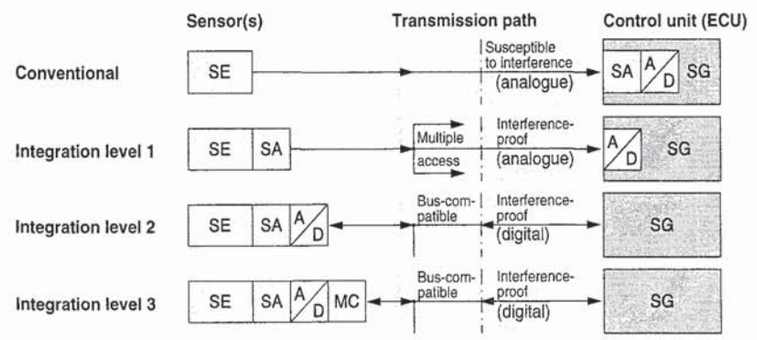
Automotive sensors
Φ Physical quantity, E Electrical quantity, Z Influencing quantities, AK *Actuator,* AZ *Display,* SA *Switch,* SE *Sensor(s),* SG *Control unit (ECU).*
1 Measuring sensor, 2 Adapter circuit, 3 Driver, 4 Actuators.



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.*



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US PATENT NO. 6,557,540

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.

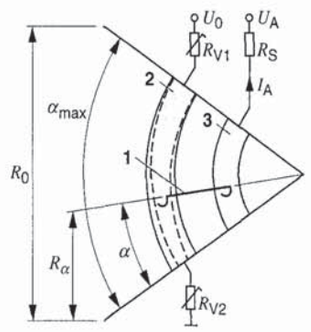
Indirectly monitored variable quantities:
- Sensor-flap deflection angle (flow rate/FLR),
- Deflection angle of a spring-mass system (acceleration),
- Diaphragm deflection angle (pressure),
- Suspension compression travel (headlamp vertical-aim adjustment),
- Torsion angle (torque).

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.

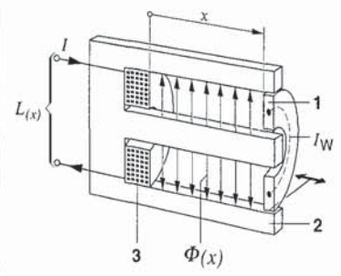
The voltage on the measurement track is usually routed through smaller series resistors R_V for overload protection (as well as for zero and progression-rate adjustments). The shape of the contour across the width of the measurement track (including that of individual sections) influences the shape of 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.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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).

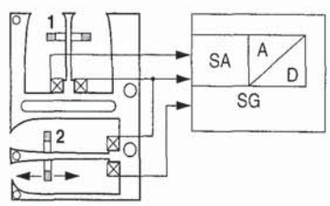
The measuring effect is fairly substantial, typically $L_{max}/L_{min} = 4$.

Other sensor types

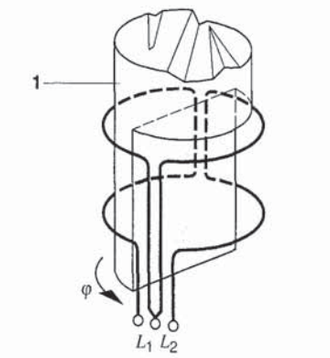
Solenoid plunger, differential-throttle and differential-transformer sensors operate based on the variation in the inductance of an individual coil and the proportional relationship of voltage dividers (supplied either directly or via inductive coupling) with moving cores. The overall length is often 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.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

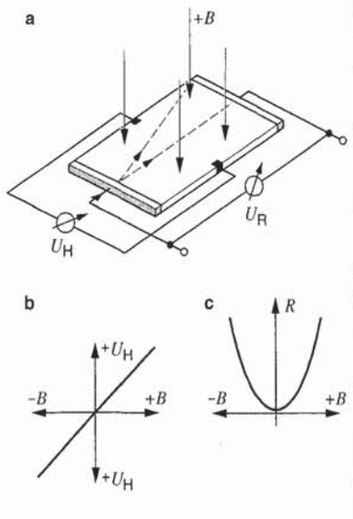
Integrated Hall ICs

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.

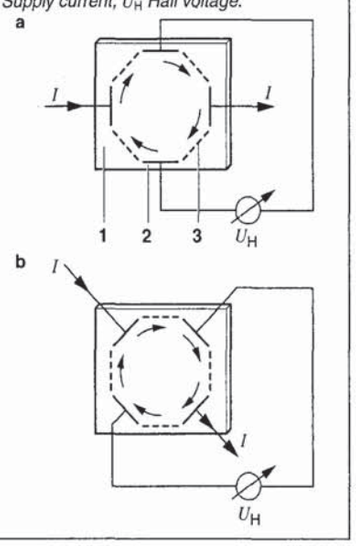
A disadvantage in the past proved to be their sensitivity to the mechanical stress which was inevitable due to packaging and resulted in an unfavorable offset temperature coefficient. This disadvantage has been overcome by the application of the "spinning-current" principle. This now made Hall ICs well 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.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

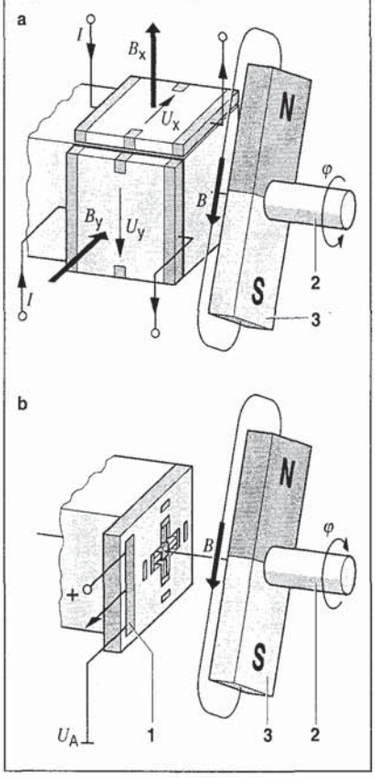
measured e.g. with the configuration shown in the illustration: The two Hall-effect sensors arranged at right angles supply sinusoidal/cosinusoidal signals which can be converted by means of the arctan function into the angle of rotation φ. In principle, the configuration can also be integrated in planar 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.

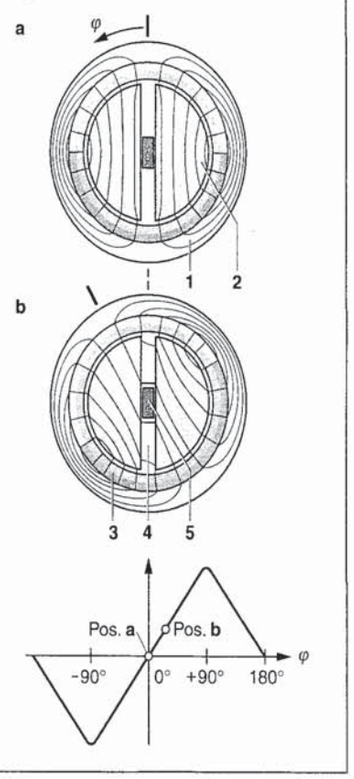
The disadvantage here is the persisting dependency on geometrical tolerances of the magnetic circuit and intensity fluctuations of the permanent magnet.

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.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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

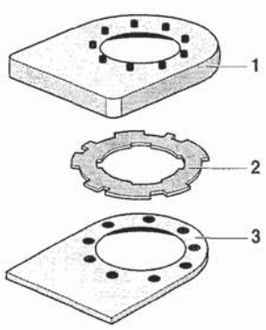
Magnetoresistive NiFe thin-film sensors (AMR – anisotropic magnetoresistive thin-film NiFe, permalloy) provide extremely compact designs for contactless, proximity-based angular-position sensors.

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.

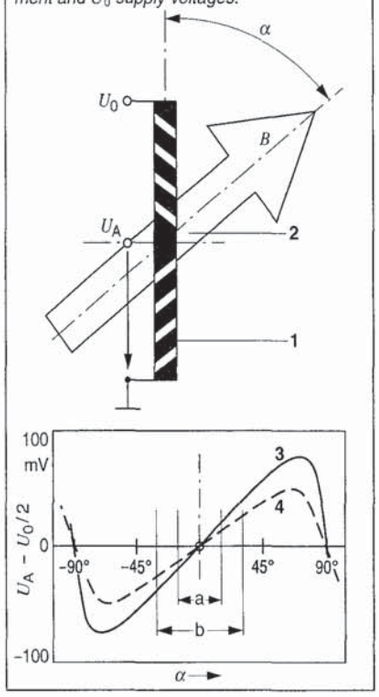
Magnetoresistive angle sensors in "barber's pole" configuration display serious limitations in both precision and measurement ranges (max. ±15°). Operation is based on the detuning of a magnetoresistant voltage divider consisting of longitudinal permalloy resistors with high-conductance lateral strips 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.



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US PATENT NO. 6,557,540

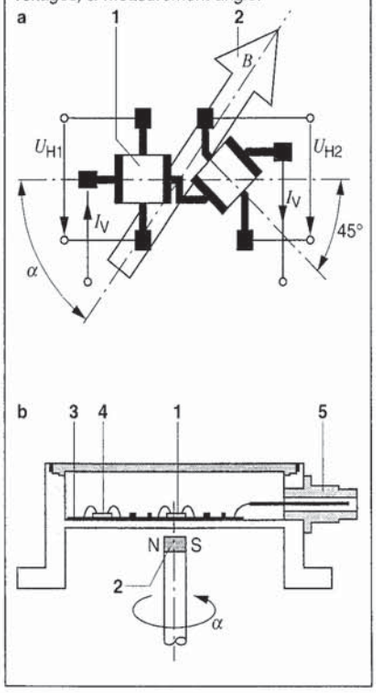
ASIC) with great accuracy over a range of 180°, largely irrespective of fluctuations in temperature and magnetic-field intensity (distance, aging).

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.

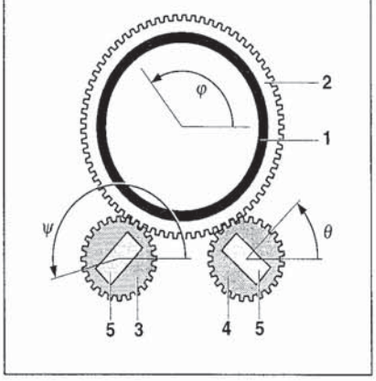
Systems for monitoring vehicle to vehicle distances can use ultrasonic transit-time processes (close-range, 0.5...5 m), as well as processes based on transit-time and triangulation principles using short-range infrared light (lidar: mid-range measurements extending up to 50 m). Another option is electromagnetic 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 $n > m$ teeth, 3 Gear with m teeth, 4 Gear with m+1 teeth, 5 Magnets.
φ, ψ, θ Angle of rotation.



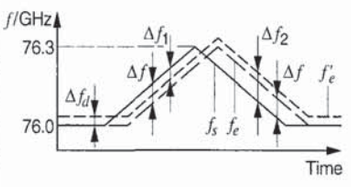
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US PATENT NO. 6,557,540

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.

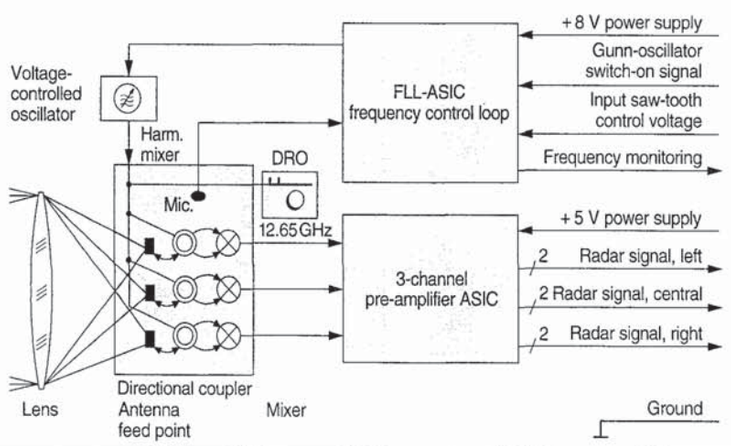
The frequency of the Gunn oscillator is compared continually with that of a stable reference oscillator DRO (Dielectric Resonance Oscillator) and regulated to a prespecified setpoint value. Here the supply voltage to the Gunn diode is modulated until it corresponds again to the setpoint value. This control 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), $\Delta f_s/\Delta f_{1,2}$ Differential frequency without/with relative velocity.



ACC-sensor control unit *(block diagram)*



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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

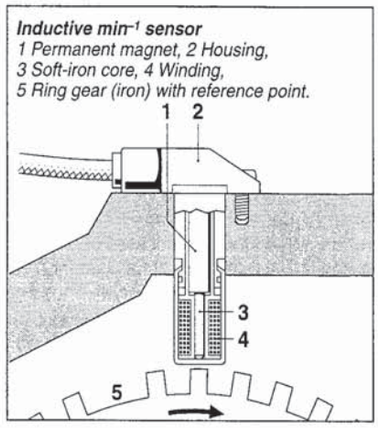
The inductive sensor consists of a bar magnet with a soft-magnetic pole pin supporting an induction coil with two connections. When a ferromagnetic ring gear (or a rotor of similar design) turns past this sensor, it generates a voltage in the coil which is directly proportional to the periodic variation 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).

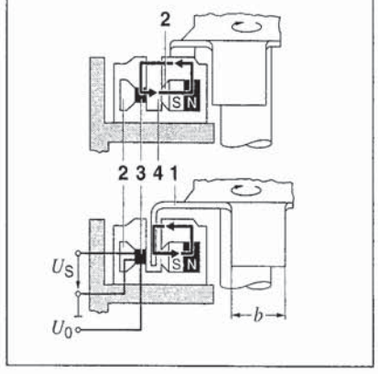
Hall-effect sensors/vane switches

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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

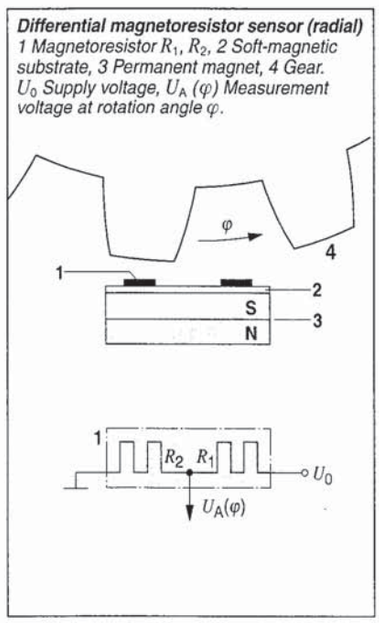
The differential Hall-effect sensor of a system with electronic ignition distribution picks off the camshaft position at a special, soft-magnetic segment disk.

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 semi-punctiform 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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US PATENT NO. 6,557,540

Oscillation gyrometers

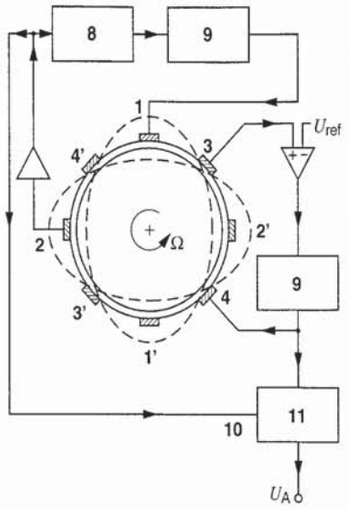
Oscillation gyrometers measure the absolute yaw rate Ω around the vehicle's vertical axis (yaw axis), e.g. in systems for controlling a vehicle's dynamic behavior (ESP, Electronic Stability Program) and for navigation. They are similar in principle to mechanical gyroscopes and for measurement purposes utilize the Coriolis acceleration that occurs during rotational motions in conjunction with an oscillating motion.

Piezoelectric yaw-rate sensors

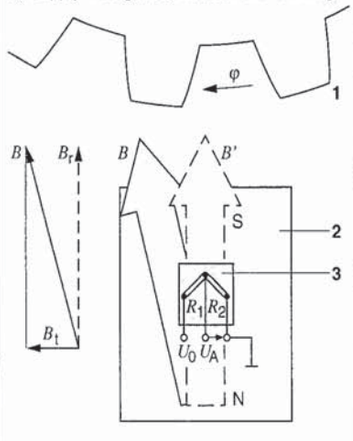
Two diametrically opposed piezo-ceramic elements (1-1′) induce radial resonant oscillation in an oscillatory metallic hollow cylinder. A second piezoelectric pair (2-2′) governs the cylinder to a constant oscillation amplitude with four axial nodes (45° offset to direction of excitation).

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-

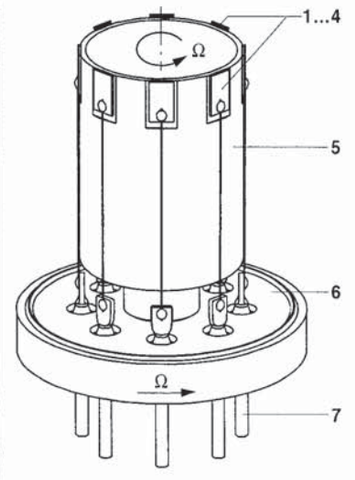
Piezoelectric yaw-rate sensor
Operating concept.
1...4 Piezoelectric elements, 8 Control circuit (fixed phase), 9 Bandpass filter, 10 Phase reference, 11 Rectifier (selective-phase).
U_A Measurement voltage, Ω Yaw rate, U_{ref} = 0 (normal operation), $U_{ref} \neq 0$ ("built-in" test).



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.



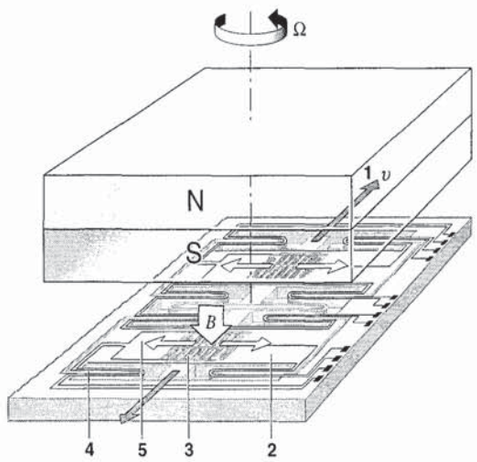
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.



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US PATENT NO. 6,557,540

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.

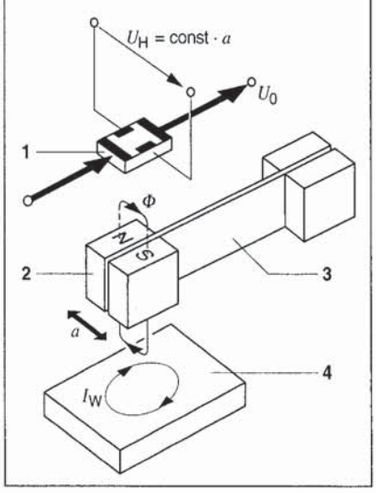
Piezoelectric sensors

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.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

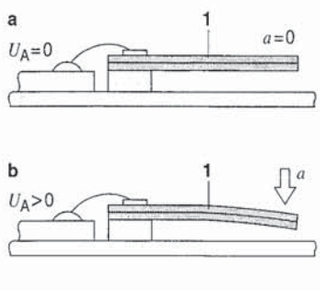
The sensor's actuating principle can also be inverted: An additional actuator electrode makes it easy to check the sensor (on-board diagnosis).

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 counterelectrodes 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.

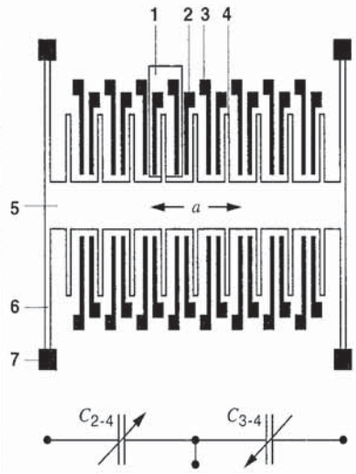
In contrast to the bulk silicon sensors with capacitance levels of 10...20 pF, these sensors only have a typical capacitance of 1 pF. The electronic evaluating circuitry is therefore installed on a single chip along with the sensor (usually position-controlled systems).

Pressure sensors
Pressure measurement is direct, by means of diaphragm deflection or force sensor. Typical applications:

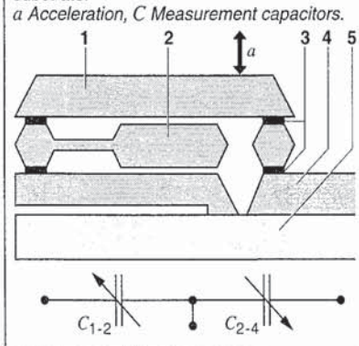
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US PATENT NO. 6,557,540

- 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.

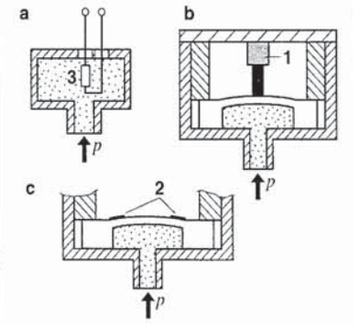


Thick-film pressure sensors

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.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

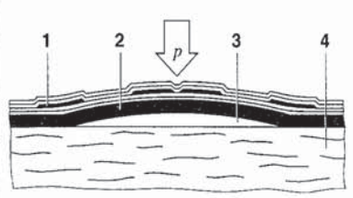
Semiconductor pressure sensors

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.

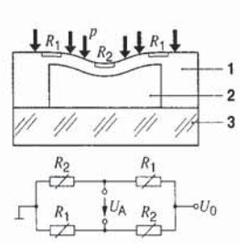
Integrated single-chip sensors with fully electronic calibration are suitable for use as load sensors for electronic ignition and fuel-injection systems. Due to their extremely compact dimensions, they are suitable for the functionally more favorable installation directly on the intake manifold (earlier 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.

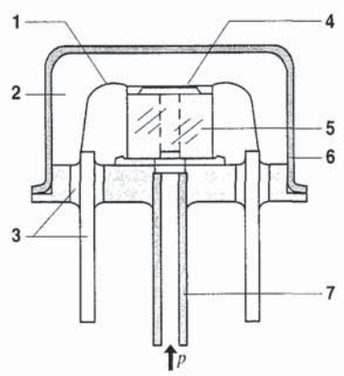


Semiconductor pressure sensor
1 Silicon, 2 Vacuum, 3 Glass (Pyrex). p Pressure, U_0 Supply voltage, U_A Measurement voltage, strain-gauge resistors R_1 (expanded) and R_2 (deflected) in bridge circuit.

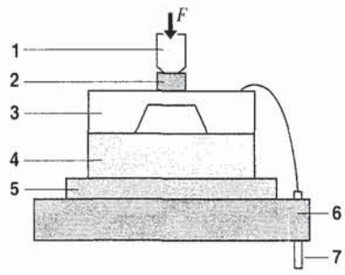


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US PATENT NO. 6,557,540

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

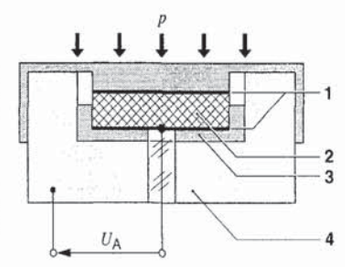
Piezoelectric sensors provide dynamic pressure measurement. On electronically controlled diesel fuel-injection pumps, for determining port opening and port closing (end of pump delivery and start of pump delivery respectively) only changes of pumping-element pressure are registered by the sensor. A thin 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.



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US PATENT NO. 6,557,540

- 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.

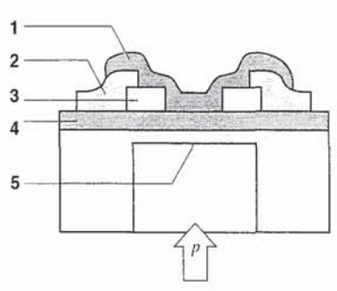
New sensor concepts

- 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.

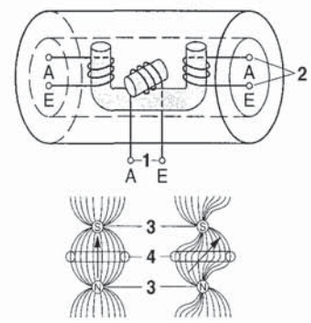
New applications:

- 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.



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US PATENT NO. 6,557,540

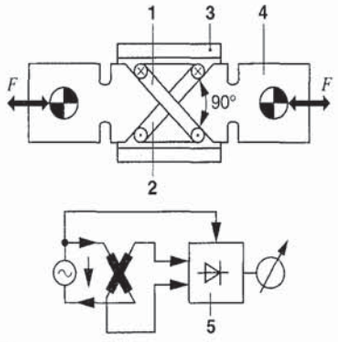
- Measurement of braking force in electrically actuated and electronically controlled braking systems.
- Non-contact measurement of drive and braking torque.
- Non-contact measurement of steering/power-steering torque.
- Finger-protection for electric power windows and sunroofs.

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).

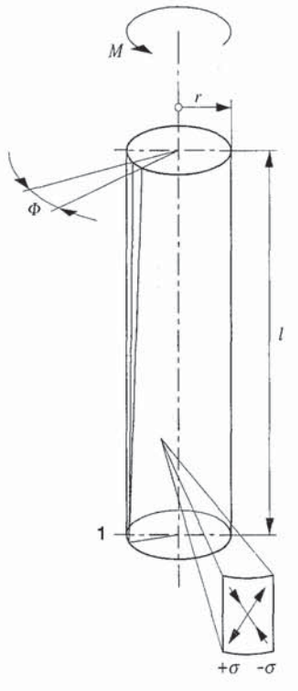
Torque measurement:
There are essentially two different ways of measuring torque: angle- and stress-measuring methods. In contrast to stress-measuring methods (DMS, magnetoelastic), angle-measuring methods (e.g. eddy current) require a particular length of torsion shaft over which the torsion angle (approx. 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.



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US PATENT NO. 6,557,540

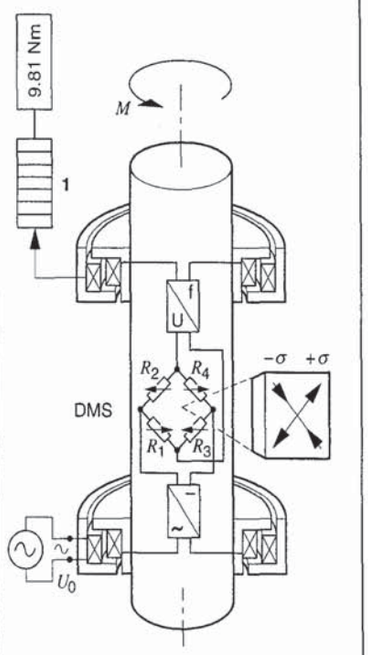
plate (e.g. in thin-film form, P. 87) and then welded with the round plate onto the shaft. High precision levels can be achieved with such a configuration in spite of reasonable manufacturing costs.

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.

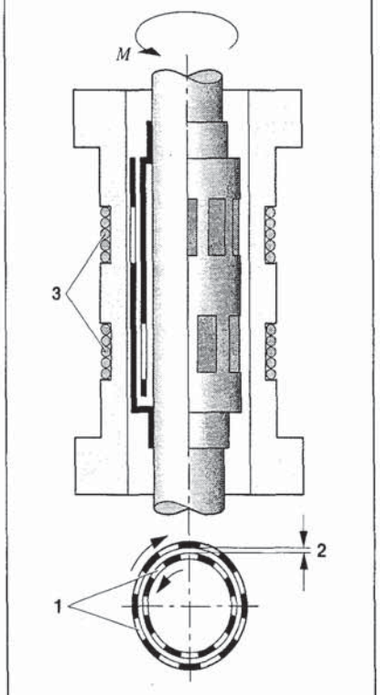
Flow meters
Flow quantities in automotive applications:
- Fuel flow rate, i.e., amount of fuel actually consumed by the engine, is based on the difference between forward and return flow rates.

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.



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US PATENT NO. 6,557,540

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:

$f = 1/T = \text{const} \cdot Q_V$.

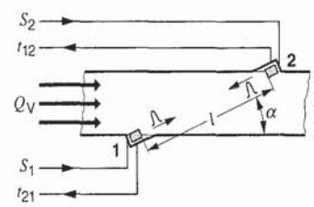
Disadvantage: Pulsation in the flow can result in measuring errors.

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, a 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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US PATENT NO. 6,557,540

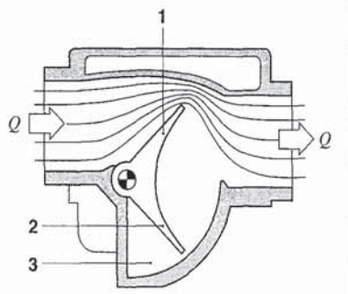
closed-loop control circuit in the meter's housing maintains a constant temperature differential between a fine platinum wire or thin-film resistor and the passing air stream. The current required for heating provides an extremely precise – albeit non-linear – index of mass air flow. The system's ECU 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).

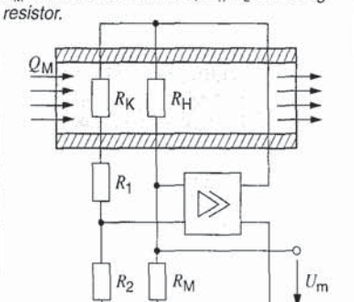
The hot-film air-mass meter combines all measuring elements and the control electronics on a single substrate. In current versions, the heating resistor is located on the back of the base wafer, with the corresponding temperature sensor on the front. This results in somewhat greater response lag than 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.

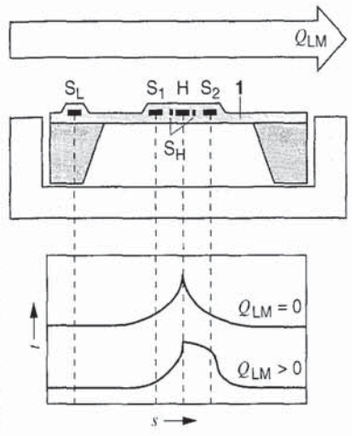


Hot-wire air-mass meter
Q_M Mass flow, U_m Measurement voltage, R_H Hot-wire resistor, R_K Compensation resistor, R_M Measurement resistor, R_1, R_2 Trimming resistor.

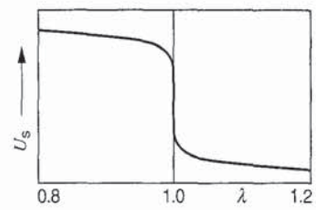


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US PATENT NO. 6,557,540

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)

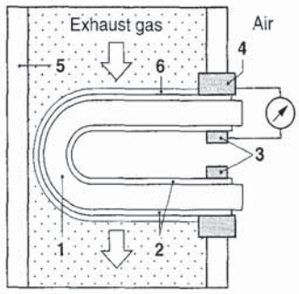
The fuel-metering system employs the exhaust-gas residual-oxygen content as measured by the lambda sensor to very precisely regulate the air-fuel mixture for combustion to the value λ (lambda) = 1 (stoichiometric combustion, P. 458).

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).



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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).

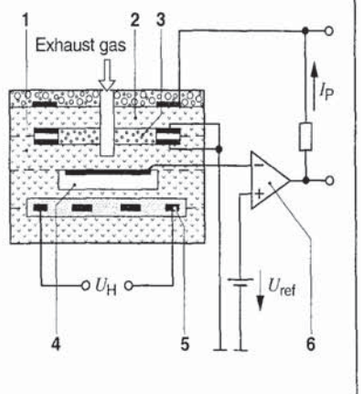
Capacitive sensors are mostly used to determine relative humidity. A sensor of this type is composed of a thin-film polymer with a metal coating on both sides. The capacitance of this capacitor is considerably but reversibly modified by the adsorption of water. The time constant is typically approx. 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.

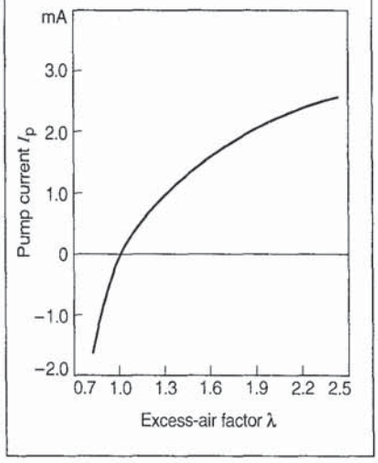
Temperature sensors

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)



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US PATENT NO. 6,557,540

prevention of window misting); this has been made economically viable by the introduction of microsystems technology. The following temperatures occur in motor vehicles:

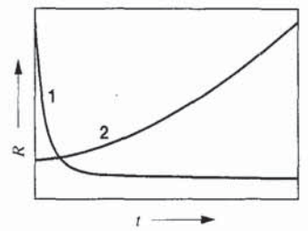
Location	Range	°C
Intake air/charge air	−40 ...	170
Outside atmosphere	−40 ...	60
Passenger compartment	−20 ...	80
Ventilation & heating air	−20 ...	60
Evaporator (AC)	−10 ...	50
Engine coolant	−40 ...	130
Engine oil	−40 ...	170
Battery	−40 ...	100
Fuel	−40 ...	120
Tire air	−40 ...	120
Exhaust gas	100 ...	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.

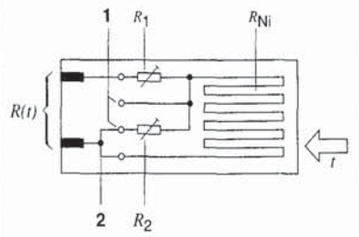
Sintered-ceramic resistors (NTC)
Sintered-ceramic resistors (heat conductors, thermistors) made of heavy-metal oxides and oxidized mixed crystals (sintered in pearl or plate-form) are included among those semiconductive materials which display an inverted exponential response curve. High thermal sensitivity 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-

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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).

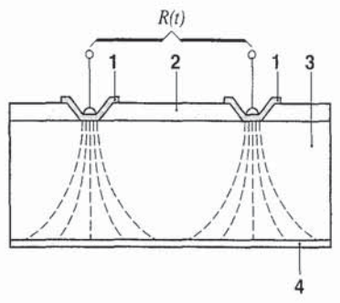
Due to the closer tolerancing which is possible, these are manufactured according to the spreading-resistance principle. The current flows through the measuring resistor and through a surface-point contact before arriving at the Si bulk material. It then proceeds, widely distributed, to a counterelectrode 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.

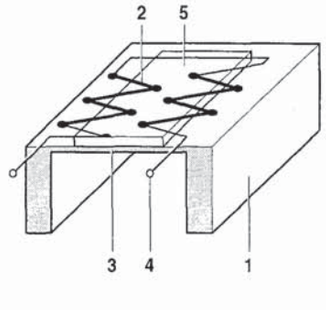
Thermopile sensors

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.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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

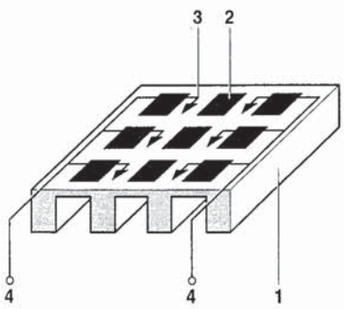
The sensor measures the level of contamination on the headlamp lens to furnish the data required for automatic lens cleaning systems.

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.

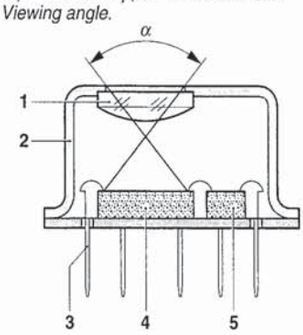
Rain sensors

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.

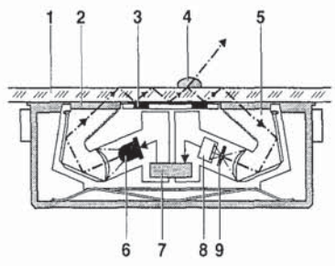


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US PATENT NO. 6,557,540

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.).

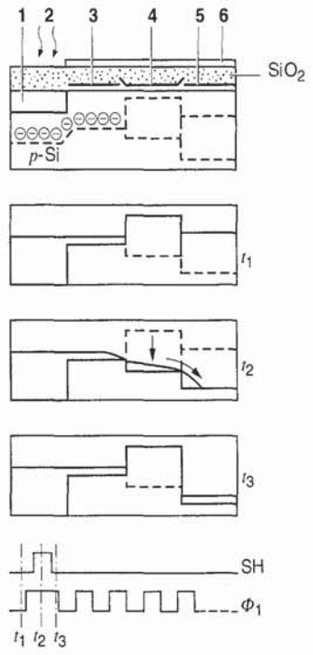
Imaging sensors are a special instance of "multisensor structures" composed of light-sensitive elements (pixels) which are arranged in line or matrix form and receive their light from a conventional optical imaging system. With the Si imaging sensors available today (CCD Charge-Coupled Devices), the 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.

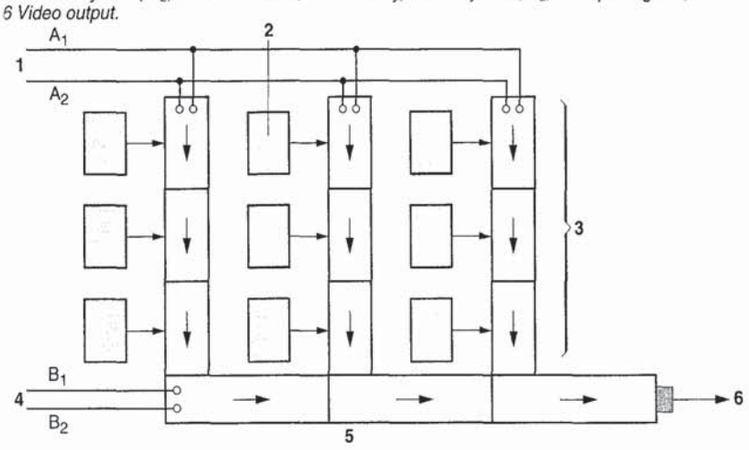
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US PATENT NO. 6,557,540

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.



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US PATENT NO. 6,557,540

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	$N \cdot m$
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.

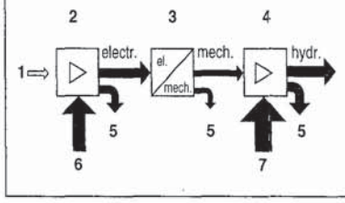
Actuator: Control chain comprising servo component and converter.
The term actuator is also employed as a general-purpose designation for servo components without converters on their own.

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.

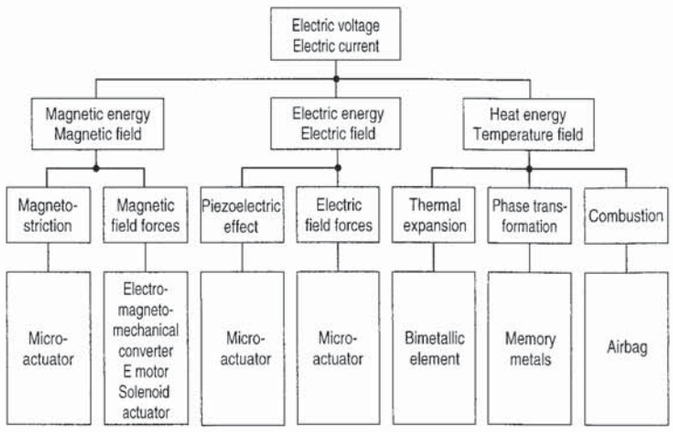
Actuators in a motor vehicle are mostly electro-magneto-mechanical transformers and by extension electrical servomotors (P. 132) and translational and rotational solenoid actuators. An exception is the pyrotechnical airbag system (P. 803). The solenoid actuators can themselves be the servo element, or 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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US PATENT NO. 6,557,540

Electromechanical actuators (system)



Force generation in the magnetic field

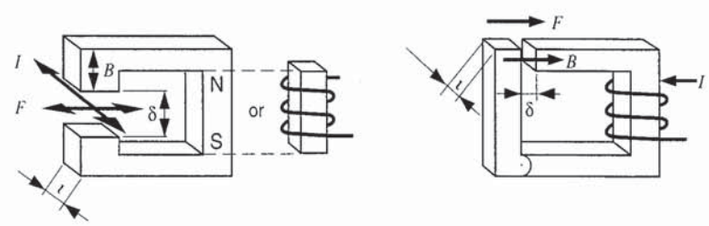
The distinction between the electrodynamic and the electromagnetic actuator principles stems from the manner in which forces are generated in the magnetic field. Common to both principles is the magnetic circuit with soft-magnetic material and the coil for excitation of the magnetic field. A major difference 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 $F = B^2 \cdot A / 2\mu_0$

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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).

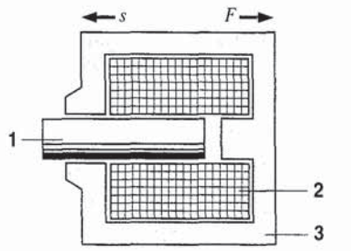
Dynamic response

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.

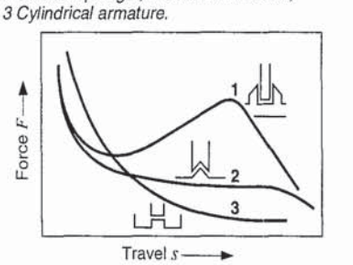
The most basic electrical circuit consists of an inductor with an ohmic resistor. One means of enhancing the dynamic response is through over-excitation at the instant of activation, while deactivation can be accelerated with a Zener diode. In each case, increasing the dynamic response of the electrical 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

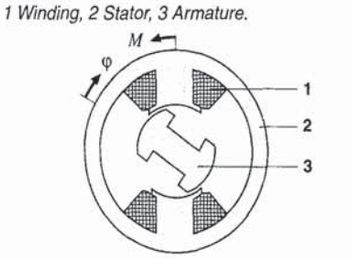
Switching solenoid
1 Armature, 2 Coil, 3 Magnetic yoke.



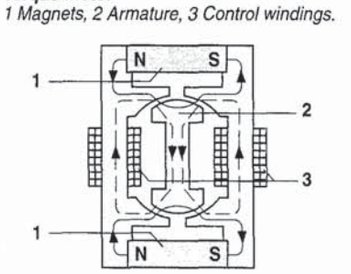
Switching solenoid (characteristic curves)
1 Solenoid plunger, 2 Conical armature, 3 Cylindrical armature.



Electromagnetic single-winding rotary actuator
1 Winding, 2 Stator, 3 Armature.



Torque motor
1 Magnets, 2 Armature, 3 Control windings.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

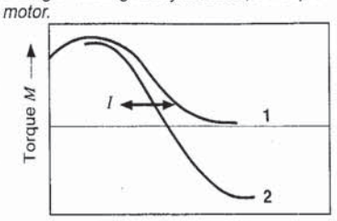
The single-winding rotary actuator incorporates a pair of poles in each of the two main sections, as well as a coil in the stator. Its maximum positioning range is approx. 45°.

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.

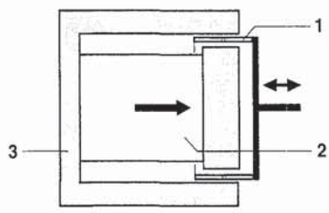
Electrodynamic actuators

In a pot magnet (immersion-coil actuator), a cylindrical immersion coil (armature winding) is set in motion in a working gap.

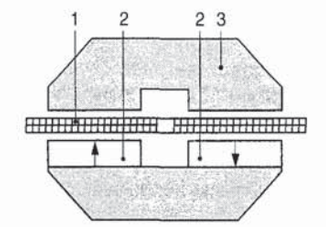
Electromagnetic rotary actuator (characteristic curves)
1 Single-winding rotary actuator, 2 Torque motor.



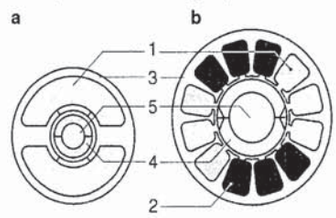
Electrodynamic immersion-coil actuator
1 Immersion coil, 2 Permanent magnet, 3 Magnetic yoke.



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.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

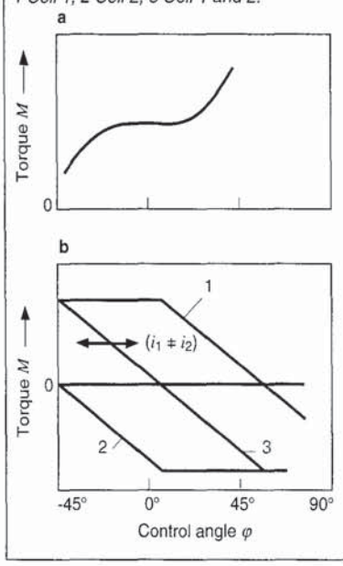
The positioning range is limited by the axial length of the armature winding and by the gap.

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.

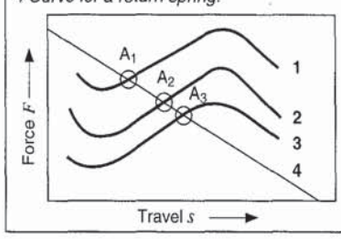
Both types include a permanent magnet within the rotor and one or two stator windings. The rotor magnet is magnetized at both ends to produce magnetic flux in the rotary magnet's working gap, which combines with the armature current to produce a torque. Originating from the position illustrated, the 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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

	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

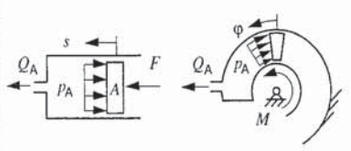
$Q_{Heat} = Q_1 \cdot (p_1 - p_2)$

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-

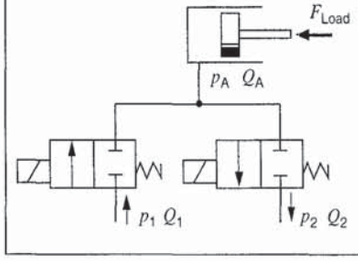
Fluid-mechanical actuators



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



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

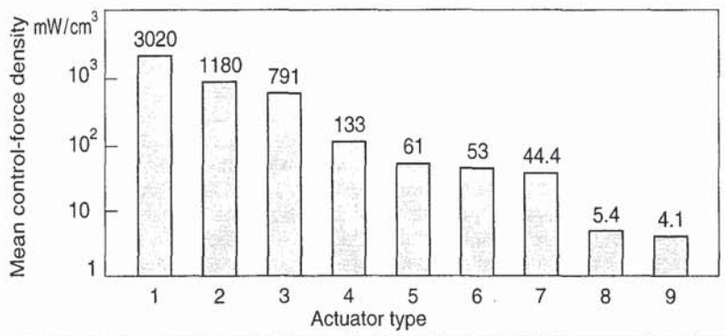
In electric motors, high peripheral velocities compensate for low magnetic-field forces, allowing these motors to provide high levels of force density in continuous operation.

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.

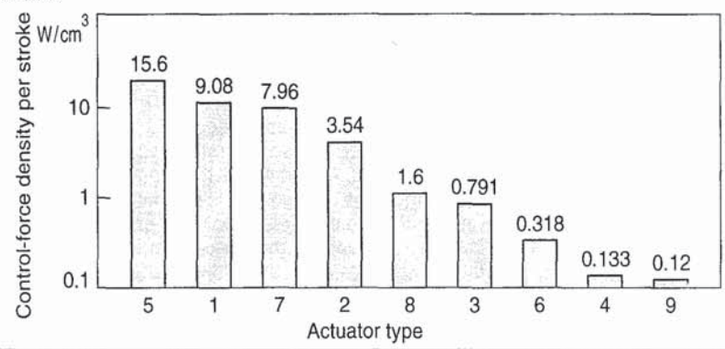
Mean control-force density of selected actuators

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.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

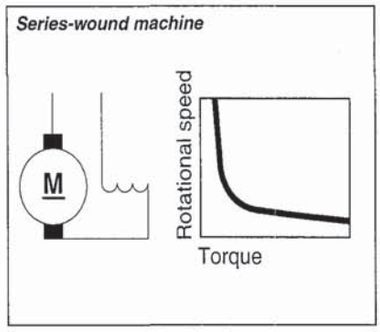
Electrical machines

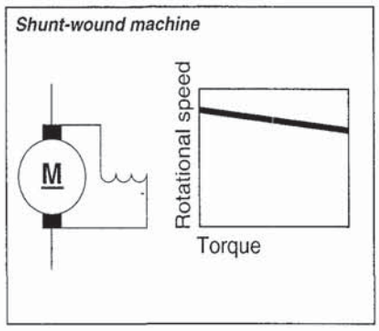
Operating concept

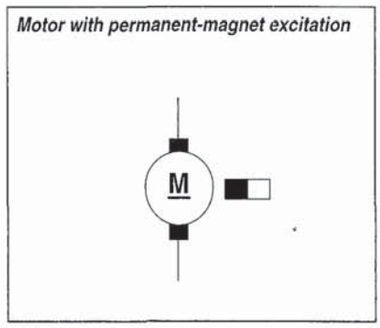
Electrical machines are used to convert electrical and mechanical energy. An electric motor converts electrical energy into mechanical energy, a generator converts energy in the opposite direction. Electrical machines consist of a stationary component (the stator) and a rotating component (the rotor). 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 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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

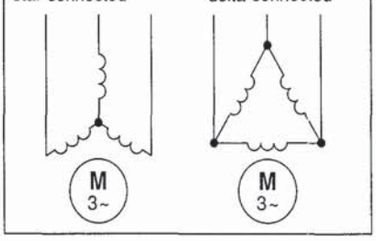
Asynchronous machines
The laminated rotor contains either a three-phase winding, as in the stator, or a bar winding. The three-phase winding is connected to slip rings which are short-circuited either directly or via series resistors. In the case of the bar winding, the bars are connected to one another 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

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

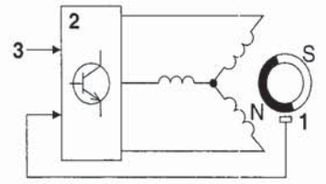
For this reason, a synchronous machine is not self-starting. The synchronous machine also differs from the asynchronous machine in that the reactive power absorption and generation are adjustable. The synchronous machine is most frequently used as a generator in electric power plants. Synchronous motors 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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

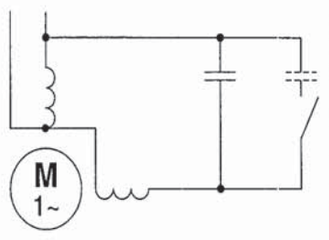
Single-phase asynchronous motors with squirrel-cage rotor

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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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		

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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:

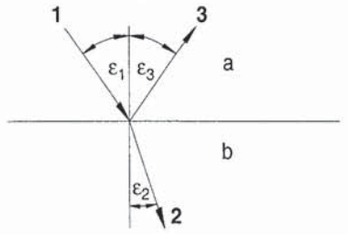
$$\varepsilon_3 = \varepsilon_1$$

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

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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

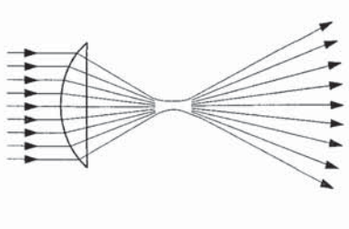
Motor-vehicle lamps must meet precise specifications with regard to chromaticity coordinates depending upon their intended functions (turn-signal lamps, stop lamps). These specifications can be met through the use of color filters which weaken the light emitted in certain parts of the visible spectrum.

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

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.).

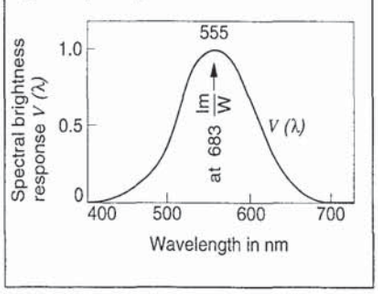
Definition of photometric quantities and units:

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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

Laser technology

Compared to other light sources, the laser has the following characteristic properties:

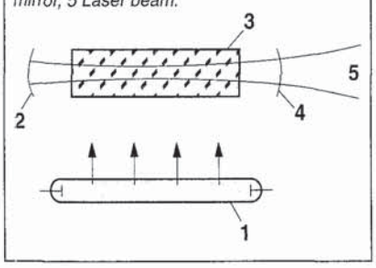
- High luminance, concentration of radiation on a diameter of a few light wavelengths,
- Low beam expansion,
- Monochromatic radiation,
- Can be used for coherent measuring technology (high radiation coherence length),
- High power (in laser tools).

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):

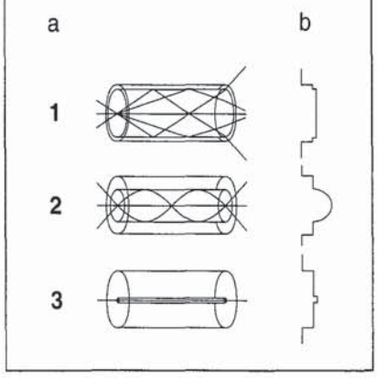
- The step-index optical fiber, with a sharply-defined border between the core and the cladding,
- The graded-index optical fiber, with parabolic refractive index curve form in the core zone,
- The monomode fiber with a very small core diameter.

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.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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)

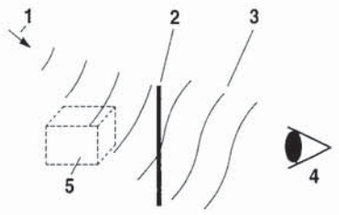
Fiber type	Diameter Core µm	Diameter Cladding µm	Wavelength nm	Numerical aperture NA	Attenuation dB/km	Bandwidth MHz · km
Step-index fiber						
Quartz/glass	50...1000	70...1000	250...1550	0.2...0.87	5...10	10
Polymer	200...>1000	250...2000	450...850	0.2...0.6	100...500	<10
Graded-index fiber	50...150	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

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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.

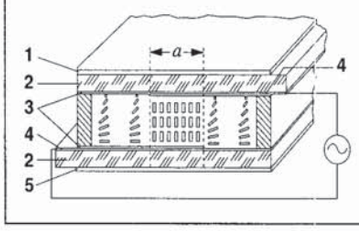
Liquid crystal display

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).

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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).

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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)

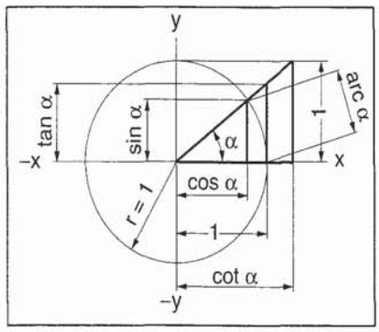
Principal series				Exact values	
R 5	**R 10**	**R 20**	**R 40**		lg
100	1.00	1.00	1.00	1.0000	0.0
			1.06	1.0593	0.025
		1.12	1.12	1.1220	0.05
			1.18	1.1885	0.075
	1.25	1.25	1.25	1.2589	0.1
			1.32	1.3335	0.125
		1.40	1.40	1.4125	0.15
			1.50	1.4962	0.175
1.60	1.60	1.60	1.60	1.5849	0.2
			1.70	1.6788	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

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

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):

$$e^{\pm ix} = \cos x \pm i \sin x$$

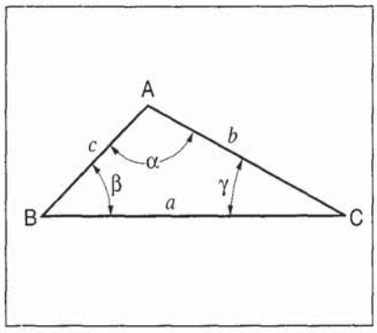
$$\sin x = \frac{e^{ix} - e^{-ix}}{2i}\,;\ \cos x = \frac{e^{ix} + e^{-ix}}{2}$$

where $i = \sqrt{-1}$

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

Equations for plane and spherical triangles

Plane triangle

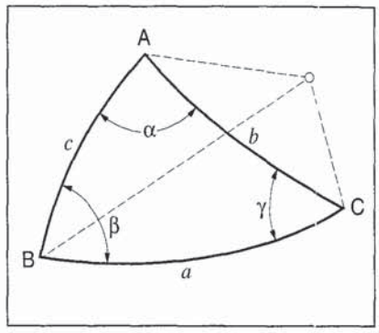


$\alpha + \beta + \gamma = 180°$

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
$\cos\alpha = -\cos\beta\cos\gamma + \sin\beta\sin\gamma\cos a$

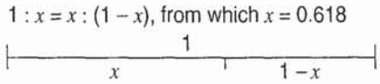
Equations often used

Solution of quadratic equation
$ax^2 + bx + c = 0$

$$x = \frac{-b \pm \sqrt{b^2 - 4\,ac}}{2a}$$

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 $q^n = 0$

$$\sum_{n \to \infty} = a/(1 - q)$$

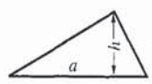
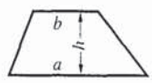
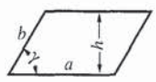
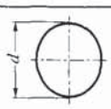
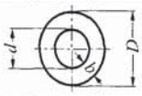
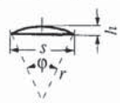
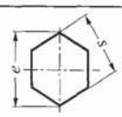
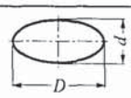
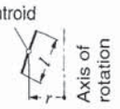
Arithmetic series

$a + (a + d) + (a + 2d) + (a + 3d) + \ldots$
n^{th} member $= a + (n - 1)\,d$

$$\sum_n = \frac{n}{2}\,[2a + (n - 1)\,d]$$

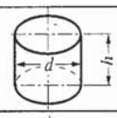
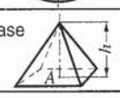
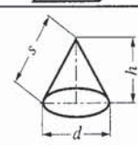
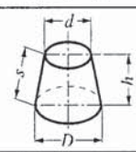
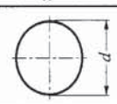
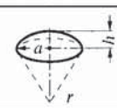
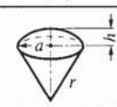
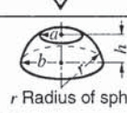
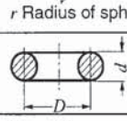
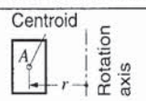
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

Areas of plane surfaces

Type of surface	Area A $\pi \approx 3.1416$
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	$A = \frac{r^2}{2}\left(\frac{\pi \cdot \varphi}{180°} - \sin\varphi\right) \approx h \cdot s\left[0.667 + 0.5\left(\frac{h}{s}\right)^2\right]$ Chord length $s = 2\,r \cdot \sin\frac{\varphi}{2}$ 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 $U \approx 0.75\ \pi\ (D+d) - 0.5\ \pi \sqrt{D \cdot d}$
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 $A = 2\pi \cdot r \cdot l$

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US PATENT NO. 6,557,540

Volume and surface area of solids

Type of solid	Volume V, surface S, lateral area M $\pi \approx 3.1416$
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	$V \approx \frac{\pi \cdot h}{12} (2D^2 + d^2) \approx 0.26\, h\, (2D^2 + d^2)$
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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