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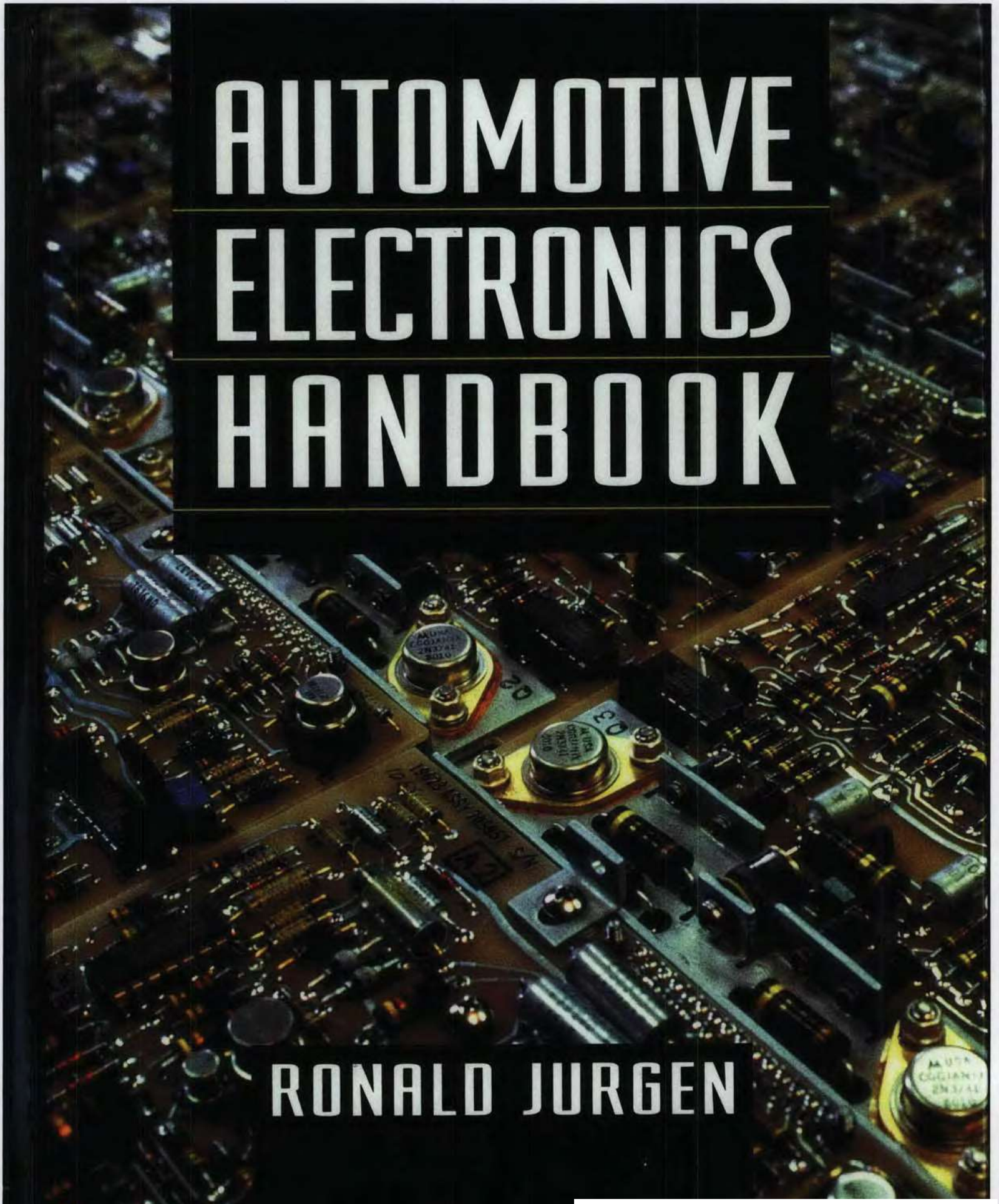

RONALD JURGEN

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This book is dedicated to Robert H. Lewis and to the memories of Douglas R. Jurgen and Marion Schappel.

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PREFACE

Automotive electronics as we know it today encompasses a wide variety of devices and systems. Key to them all, and those yet to come, is the ability to sense and measure accurately automotive parameters. Equally important at the output is the ability to initiate control actions accurately in response to commands. In other words, sensors and actuators are the heart of any automotive electronics application. That is why they have been placed first in this handbook where they are described in technical depth. In other chapters, application-specific discussions of sensors and actuators can be found.

The importance of sensors and actuators cannot be overemphasized. The future growth of automotive electronics is arguably more dependent on sufficiently accurate and low-cost sensors and actuators than on computers, controls, displays, and other technologies. Yet it is those nonsensor, nonactuator technologies that are to many engineers the more "glamorous" and exciting areas of automotive electronics.

In the section on control systems, a key in-depth chapter deals with automotive microcontrollers. Without them, all of the controls described in the chapters that follow in that section—engine, transmission, cruise, braking, traction, suspension, steering, lighting, windshield wipers, air conditioner/heater—would not be possible. Those controls, of course, are key to car operation and they have made cars over the years more drivable, safe, and reliable.

Displays, trip computers, and on- and off-board diagnostics are described in another section, as are systems for passenger safety and convenience, antitheft, entertainment, and multiplex wiring. Displays and trip computers enable the driver to readily obtain valuable information about the car's operation and anticipated trip time. On- and off-board diagnostics have of necessity become highly sophisticated to keep up with highly sophisticated electronic controls. Passenger safety and convenience items and antitheft devices add much to the feeling of security and pleasure in owning an automobile. Entertainment products are what got automotive electronics started and they continue to be in high demand by car buyers. And multiplex wiring, off to a modest start in production cars, holds great promise for the future in reducing the cumbersome wiring harnesses presently used.

The section on electromagnetic interference and compatibility emphasizes that interference from a variety of sources, if not carefully taken into account early on, can raise havoc with what otherwise would be elegant automotive electronic designs. And automotive systems themselves, if not properly designed, can cause interference both inside and outside the automobile.

In the final section on emerging technologies, some key newer areas are presented:

- Navigation aids and intelligent vehicle-highway systems are of high interest worldwide since they hold promise to alleviate many of vehicle-caused problems and frustrations in our society.
- While it may be argued that electric vehicles are not an emerging technology, since they have been around for many years, it certainly is true that they have yet to come into their own in any really meaningful way.
- Electronic noise cancellation is getting increasing attention from automobile designers seeking an edge over their competitors.

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The final chapter on future vehicle electronics is an umbrella discussion that runs the gamut of trends in future automotive electronics hardware and software. It identifies potential technology developments and trends for future systems.

Nearly every chapter contains its own glossary of terms. This approach, rather than one overall unified glossary, has the advantage of allowing terms to be defined in a more application-specific manner—in the context of the subject of each chapter. It should also be noted that there has been no attempt in this handbook to cover, except peripherally, purely mechanical and electrical devices and systems. To do so would have restricted the number of pages available for automotive electronics discussions.

Finally, the editor would like to thank all contributors to the handbook and particularly two individuals: Otto Holzinger of Robert Bosch GmbH in Stuttgart, Germany and Randy Frank of Motorola Semiconductor Products in Phoenix, Arizona. Holzinger organized the many contributions to this handbook from his company. Frank, in addition to contributing two chapters himself and cocontributing a third, organized the other contributions from Motorola. Without their help, this handbook would not have been possible.

Ronald K. Jurgen

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P · A · R · T · 1

INTRODUCTION

CHAPTER 1
INTRODUCTION

Ronald K. Jurgen
Editor

1.1 THE DAWN OF A NEW ERA

In today's world of sophisticated automotive electronics, it is easy to forget how far the technology has come in a relatively short time. In the early 1970s, other than radios and tape players, the only standard electronic components and systems on most automobiles were alternator diodes and voltage regulators.[1] By the fall of 1974, "there were twelve electronic systems available, none of which were across the board standard production items. . . . The twelve electronic systems or subsystems were: alternator diodes, voltage regulators, electronic fuel injection, electronic controlled ignition, intermittent windshield wipers, cruise control, wheel lock control, traction control, headlamp control, climate control, digital clocks, and air bag crash sensors."[1]

1.1.1 Car Makers and the Electronics Industry: Friendly Adversaries

In the early days of automotive electronics, the automotive industry and the electronics industry were often at odds. Carmakers needed inexpensive components and systems that would operate reliably in the extremely harsh automotive environment. The electronics industry, on the other hand, used to producing high-quality but expensive parts and systems for the military, was skeptical about its ability to produce the components the automobile industry wanted at the prices they demanded. But both industries realized that electronics could provide the capability to solve automotive problems that defied conventional mechanical or electromechanical approaches.

Some of the leading electronics engineers who worked in the automotive industry—as well as their counterparts in the electronics industry—realized that this existing friendly adversarial relationship had to be converted to a mutual effort to find cost-effective and reliable solutions to urgent automotive problems.

Thus it was in 1973 that Trevor Jones (then with General Motors), Joseph Ziomek (then with Ford), Ted Schaller (Allen Bradley), Jerry Rivard (then with Bendix), Oliver McCarter (General Motors), and William Saunders (Society of Automotive Engineers), proposed that a new conference be held in 1974.[1] Dubbed Convergence to signify the coming together of the two industries, the first conference was successful and, sponsored alternately by the Society of Automotive Engineers and the Institute of Electrical and Electronics Engineers, it has been held successfully every other year ever since.

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1.1.2 The United States Government Forces the Issue

One of the major problems facing the automotive industry at the time of the first Convergence conference was upcoming stricter government-mandated exhaust emissions controls. When the United States government first mandated emissions standards for all United States cars, car makers met the challenge through the use of catalytic converters for hydrocarbon and carbon monoxide emissions and exhaust gas recirculation techniques for nitrogen oxides emissions. But they knew that in 1981, when the standards would be tightened from the previous limit of 2.0 grams per mile to 1.0 gram per mile, those approaches would no longer in themselves be sufficient. A new approach was necessary and it involved use of a three-way catalyst for all three emissions together with a closed-loop, engine control system.[2]

Tighter emissions control solved one problem but created another—fuel economy. The two seemed to be mutually exclusive. Charles M. Heinen and Eldred W. Beckman, writing in *IEEE Spectrum* in 1977,[3] said, "The simple truth is that there is very direct interaction between emissions and fuel economy. Probably the clearest example of that interaction is the fact that automobiles equipped to meet California's tight emissions control regulations have consistently demonstrated about 10 percent poorer fuel economy than have comparable cars equipped to meet the less stringent Federal U.S. standards." As a result of this interdependence, emissions and fuel economy measures tended to be compromises. Greater fuel economies could be achieved if emissions levels were not a problem.

1.2 THE MICROCOMPUTER TAKES CENTER STAGE

The microcomputer, introduced in 1971, had yet to make major inroads in automobiles. But it became increasingly obvious that it was the key to meeting government exhaust emission and fuel economy demands while also providing car buyers with cars that performed well. Meeting these needs necessitated precise engine control in such areas as the air/fuel ratio and idle speed.

1.2.1 Early Applications of Microcomputers

One of the first microcomputer applications in cars was an advanced ignition system built by Delco-Remy for the 1977 Oldsmobile Toronado. Called the MISAR (microprocessed sensing and automatic regulation) system, it controlled spark timing precisely no matter what load and speed conditions prevailed while meeting emissions control requirements and providing good driveability. Input signals from sensors provided data on crankshaft position, manifold vacuum, coolant temperature, and reference timing.[4] The microprocessor used had a capacity of 10,240 bits.

Early applications such as the MISAR paved the ground for what would later become the prolific use of microcomputers in cars. Once reliable microcomputers met the cost restraints of carmakers, there was no end in sight to microcomputer applications in cars. In the late 1970s, total engine control with microcomputers became widespread and, as time went on, use of microcomputers spread to other controls for transmission, braking, traction, suspension, steering, lighting, air conditioning, and so forth.

1.2.2 The Bells and Whistles Period

There was also a time in the early 1980s when carmakers, heady with success with microcomputers in other areas, went through a period of electronic overkill. Notable in this regard were voice commands and warnings that tended to wear out their welcome quickly with car drivers

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and elaborate and flashy information displays that also turned off many car buyers. It was a period of doing things with microcomputers because they could be done rather than doing them because they were needed.

That overindulgent microcomputer period quickly waned as car buyers made their feelings known. Voice commands were all but totally abandoned and displays were made less garish. There was even a return to analog displays for speedometers, for example, albeit electronically based rather than the old mechanical or electromechanical system. Carmakers returned to using microcomputers in truly functional ways to answer real needs.

1.3 LOOKING TO THE FUTURE

The future for automotive electronics is bright. Electronic solutions have proven to be reliable over time and have enabled carmakers to solve problems otherwise unsolvable. But what does the future hold? Some predictions for the future have been discussed in the following pages by contributors.

1.3.1 Contributors' Predictions

Although there have been many significant automotive electronics advances over the years, the end is certainly not in sight. The final chapter in this handbook describes many upcoming advances in detail. Authors Frank and Momin, for example, state that a likely future scenario "will be a combination of centralization and distributed intelligence where the centralization would be based along the lines of body, chassis and safety, powertrain, and audio/entertainment and communications. Within these centralized systems would be distributed intelligence based on multiplex wiring with smart sensors, switch decoders, and smart actuators all controlled by a central intelligence."

Here are additional selected future developments cited by contributors in other chapters:

- Expansion of the air bag system to include side impact protection (Dunn, Chap. 7)
- Magnetic transistors and diodes that can be directly integrated with signal conditioning circuits (Dunn, Chap. 7)
- Electronic switched stop lamps involving a rate-of-closure detector system to determine if the vehicle's speed is safe for objects ahead of it. If the closure rate is unsafe, the stop lights could be activated to alert trailing drivers to a pending accident (Valentine, Chap. 14)
- The integration of watchdog and failsafe functions onto a microcontroller (Boehmer, Chap. 11)
- Microcontrollers that operate at frequencies of 24 MHz or 32 MHz to allow more code to be executed in the same amount of time (Boehmer, Chap. 11)
- In the mid-90s, cars will have twice the electronic content of today's cars but will be easier to manufacture because there will be half the number of modules due to feature content integration. The data network interconnecting the modules will reduce the size and number of cables and cut the number of circuits by 50 percent (Miesterfeld, Chap. 26)
- A move from switching units to stepped operation actuators and the substitution of continuous for discrete time control (Müller, Chap. 10)
- Electrorheological and magnetorheological fluid actuators (Müller, Chap. 10)
- Micromechanical valves as actuators for converting low control power as in regulating the flow of fluids in hydraulic or pneumatic systems (Müller, Chap. 10)

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P · A · R · T · 2

SENSORS AND ACTUATORS

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CHAPTER 2
PRESSURE SENSORS

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2.1 AUTOMOTIVE PRESSURE MEASUREMENTS

Various pressure measurements are required in both the development and usage of vehicles to optimize performance, determine safe operation, assure conformance to government regulations, and advise the driver. These sensors monitor vehicle functions, provide information to control systems, and measure parameters for indication to the driver. The sensors can also provide data log information for diagnostic purposes.

Depending on the parameter being measured, different units for indicating pressure will be used. Since pressure is force per unit area, basic units are pounds per square inch (psi) or kilograms per square centimeter. For example, tire pressure is usually indicated in psi. Manifold pressure is typically specified in kiloPascals (kPa). A Pascal, which is the international unit (SI or Systems Internationale) for pressure, is equal to 1 Newton per meter^2 or 1 kg · m^{-1} · s^{-2}. Other common units of pressure measurement include: inches, feet, or centimeters of water; millibars or bars, inches, or millimeters of mercury (Hg), and torr. The conversion constants as defined per international convention are indicated in Table 2.1.

Pressure can be measured by a number of devices that provide a predictable variation when pressure is applied. Sensors used on vehicles range from mechanical devices—with position movement when pressure is applied—to a rubber or elastomer diaphragm, to semiconductor-based silicon pressure sensors. Various pressure-sensing techniques are explained in Sec. 2.3.

The type of pressure measurement that is made can be divided into five basic areas which are independent of the technology used for the measurement: gage, absolute, differential, liquid level, and pressure switch.

2.1.1 Gage Pressure Measurements

The silicon pressure sensor technology explained in Sec. 2.3.5 is used to visualize the difference between gage, absolute, and differential pressure (refer to Fig. 2.1). For gage pressure measurements, the pressure is applied to the top of a (silicon) diaphragm (Fig. 2.1), creating a positive output. The opposite (back) side of the diaphragm is exposed to atmospheric pressure. Gage vacuum is a special case of gage pressure. For gage vacuum measurements, vacuum is applied to the back side of the diaphragm resulting in a positive output signal. Gage and gage vacuum are single-sided pressure measurements. Gage pressure is frequently indicated by psig.

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TABLE 2.1 Pressure Unit Conversion Constants

(Most commonly used per international conventions)

	psi*	In $H_2O^{\dagger}$	In $Hg^{\ddagger}$	K Pascal	Millibar	cm $H_2O^{\S}$	mm $Hg^{\P}$
psi*	1.000	27.680	2.036	6.8947	68.947	70.308	51.715
In $H_2O^{\dagger}$	3.6127×10^{-2}	1.000	7.3554×10^{-2}	0.2491	2.491	2.5400	1.8683
In $Hg^{\ddagger}$	0.4912	13.596	1.000	3.3864	33.864	34.532	25.400
K Pascal	0.14504	4.0147	0.2953	1.000	10.000	10.1973	7.5006
Millibar	0/01450	0.40147	0.02953	0.100	1.000	1.01973	0.75006
cm $H_2O^{\S}$	1.4223×10^{-2}	0.3937	2.8958×10^{-2}	0.09806	0.9806	1.000	0.7355
mm $Hg^{\P}$	1.9337×10^{-2}	0.53525	3.9370×10^{-2}	0.13332	1.3332	1.3595	1.000

* PSI = pounds per square inch
† At 39 °F
‡ At 32 °F
§ At 4 °C
¶ At 0 °C

2.1.2 Absolute Pressure Measurements

An absolute pressure measurement is made with respect to a fixed (usually a vacuum) reference sealed within the sensor (Fig. 2.1). For a 100-kPa-rated absolute unit, the diaphragm is fully deflected with standard atmospheric pressure. Application of a vacuum restores the diaphragm to its undeflected (flat) position. The result is a high-level output with no vacuum applied and a low-level signal at full vacuum unless the zero is established at the full-scale deflection of the diaphragm. Pressure can also be applied to absolute units with appropriately designed diaphragms to withstand the additional applied stress. Absolute pressure is frequently indicated by psia.

2.1.3 Differential Pressure Measurements

Differential or Delta-P measurements are also shown in Fig. 2.1. The higher pressure is applied to the top of the diaphragm and the lower pressure, possibly a reference pressure, is applied to the opposite side. The diaphragm's deflection is a result of the pressure difference.

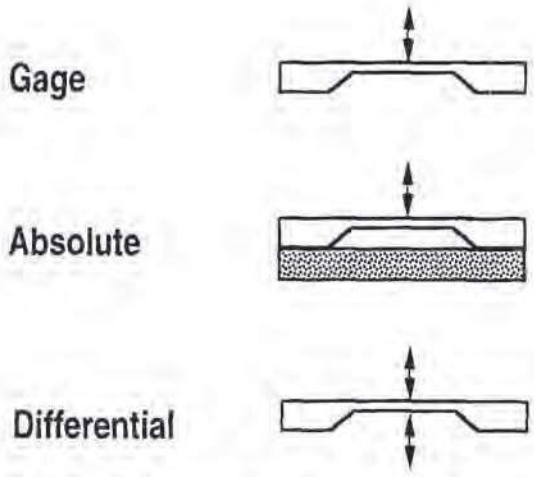

FIGURE 2.1 Types of pressure measurements: (*a*) gage, (*b*) absolute, and (*c*) differential.

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Typically, the pressure differential is only a small percentage of the total line pressure and a system fault can expose one side of the sensor to the full line pressure. This must be taken into account when choosing the sensor and determining the rated pressure range that will be required. Differential pressure is frequently indicated by psid.

2.1.4 Liquid Level Measurements

The height of a column of liquid can be measured by a pressure sensor. The term *head* is frequently used in hydraulics to denote pressure. Measurements of inches or feet of water and centimeters of mercury are direct indications of the effect of pressure on liquid level. Other liquid levels are dependent on their specific weight and can be calculated by $h = (P_L - P_H)/w$, where $(P_L - P_L)$ is the pressure differential caused by the height of the fluid column and w is the specific weight of the liquid. The vapor pressure in a sealed enclosure will have an effect on the measurement of liquid height. Returning the reference side of a differential pressure sensor to the top of the enclosure will compensate for vapor pressure.

2.1.5 Pressure Switch

A pressure switch is typically achieved by mounting an electric contact on a diaphragm (rubber or any elastic material). The application of sufficient pressure (or vacuum) on one side of the diaphragm causes the movable contact to meet a stationary contact and close the circuit.

A pressure switch can also be achieved by any of the previously described techniques merely by establishing a reference threshold voltage that is calibrated to indicate the point that the pressure changes from an acceptable to unacceptable (or low to high) level. Once the threshold voltage is achieved, additional electronic circuits can be used to produce an electronic switch that can control loads such as an indicator lamp.

2.2 AUTOMOTIVE APPLICATIONS FOR PRESSURE SENSORS

Automotive requirements for pressure measurements range from the basic—oil pressure—to the sophisticated—air pressure differential from one side of the vehicle to the other. This section elaborates on the various possibilities for pressure measurements that exist either in the development, laboratory, or pilot phases of the vehicle, to actual volume production. Table 2.2 lists a number of potential pressure measurements versus vehicle systems and provides an indication of the pressure range and type of measurement.

Automotive specification and testing guidelines have been developed and published by the Society of Automotive Engineers (SAE) specifically for manifold absolute pressure (MAP) sensors. These documents are intended to assist in establishing test methods and specifications for other sensors. Other SAE documents that may apply to sensors are summarized in Table 2.3.

The packaging and testing requirements for automotive sensors can represent 50 to 80 percent of the sensor cost and over 90 percent of the warranty and in-service problems. The pressure-sensing applications that are presented in the following sections will include packaging requirements that are of particular concern.

2.2.1 Existing Applications for Pressure Sensors

A late twentieth century production vehicle is likely to have a number of pressure sensors for measurements such as manifold pressure and engine oil pressure, and has the potential for

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TABLE 2.2 Pressure Sensing Requirements for Various Vehicle Systems

System	Parameter	Pressure range	Type
Engine control	Manifold absolute pressure	100 kPa	Absolute
	Turbo boost pressure	200 kPa	Absolute
	Barometric pressure (altitude)	100 kPa	Absolute
	EGR pressure	7.5 psi	Gage
	Fuel pressure	15 psi—450 kPa	Gage
	Fuel vapor pressure	15 in H_2O	Gage
	Mass air flow		Differential
	Combustion pressure	100 Bar, 16.7 Mpa	Differential
	Exhaust gas pressure	100 kPa	Gage
	Secondary air pressure	100 kPa	Gage
Elect transmission (continuously variable transmission)	Transmission oil pressure	80 psi	Gage
	Vacuum modulation	100 kPa	Absolute
Idle speed control	AC clutch sensor/switch	300–500 psi	Absolute*
	Power steering pressure	500 psi	Absolute*
Elect power steering (also elect assisted)	Hydraulic pressure	500 psi	Absolute*
Antiskid brakes/ traction control	Brake pressure	500 psi	Absolute*
	Fluid level	12 in H_2O	Gage
Air bags	Bag pressure	7.5 psi	Gage
Suspension	Pneumatic spring pressure	1 MPa	Absolute*
Security/keyless entry	Passenger compartment pressure	100 kPa	Absolute
HVAC (climate control)	Air flow (PC) Compressor pressure	300–500 psi	Absolute*
Driver information	Oil pressure	80 psi	Gage
	Fuel level	15 in H_2O	Gage
	Oil level	15 in H_2O	Gage
	Coolant pressure	200 kPa	Gage
	Coolant level	24 in H_2O	Gage
	Windshield washer level	12 in H_2O	Gage
	Transmission oil level	12 in H_2O	Gage
	Tire pressure	50 psi	Gage/absolute
	Battery fluid level	1–2 in below	Optical
Memory seat	Lumbar pressure	7.5 psi	Gage
Multiplex/diagnostics	Multiple usage of sensors		

* *Gage measurement but absolute sensors used for failsafe*

TABLE 2.3 SAE Specifications That Effect Pressure Sensors

Recommended environmental practices for electronic equipment design	SAE J1211
Performance levels and methods of measurement of electromagnetic radiation from vehicles and devices	SAEJ551
Performance levels and methods of measurement of EMR from vehicles and devices (narrowband RF)	SAEJ1816
Electromagnetic susceptibility procedures for vehicle components (except aircraft)	SAE J1113
Vehicle electromagnetic radiated susceptibility testing using a large TEM cell	SAE J1407
Open-field whole-vehicle radiated susceptibility 10 kHz–18 GHz, electric field	SAE J1338
Class B data communication network interface	SAE J1850
Diagnostic acronyms, terms, and definitions for electrical/electronic components	SAE J1930
Failure mode severity classification	SAE J1812
Guide to manifold absolute pressure transducer representative test method	SAE J1346
Guide to manifold absolute pressure transducer representative specification	SAE J1347

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several other pressure measurements. Tighter emissions control and improved efficiency may necessitate further sensor use in future systems.

Manifold, Barometric and Turbo Boost Pressure. Manifold absolute pressure (MAP) is used as an input to fuel and ignition control in internal combustion engine control systems. The speed-density system that uses the MAP sensor has been preferred over mass air flow (MAF) control because it's less expensive, but stricter emission standards are causing more manufacturers to use mass air flow for future models.

Higher resolution from 32-bit engine controllers, with greater analog-to-digital (A/D) conversion capability and higher operating frequencies, will provide greater accuracy for a given MAP sensor during the critical transitions of the engine cycle. As shown in Fig. 2.2, previous changes from 8-bit to 16-bit controllers have resulted in a two-time improvement in resolution in the digital conversion for the intake manifold pressure. The 8-bit control unit performed the A/D conversion on a 4-ms timer interrupt in order to maintain a balance with other controls, with the resulting 1.1-ms lag time (worst case) during periods of overlapping interrupts. The 16-bit microcontroller performs the A/D conversion every 2 ms, which reduces the lag time to 0.3 ms. The actual system improvements that can result from using the higher performing microcontrol units is a result of other factors such as more precise and faster control of fuel injectors and sparkplugs, and additional and/or more accurate sensors and control algorithms.

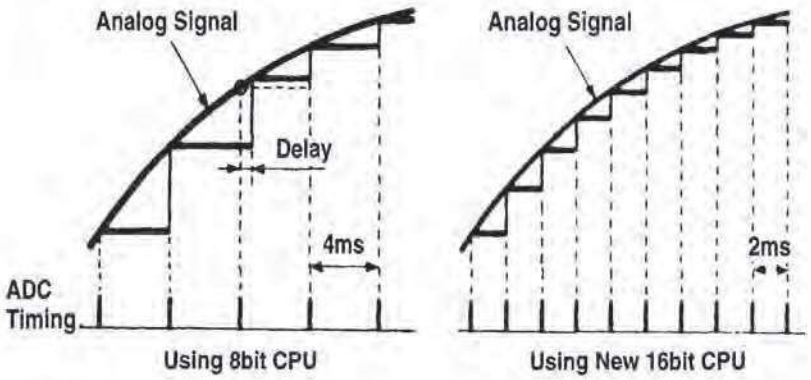

FIGURE 2.2 Effect of A-D on pressure measurements.

The MAP error band is also being tightened with a goal of 1 percent accuracy over the entire automotive temperature range. Existing specifications allow tolerances to increase as shown by the bowtie specification in Fig. 2.3 with associated multiplier(s).

The need for barometric pressure is often desirable in MAF systems to provide altitude information to the engine control computer. The barometric pressure range is typically from 60 to 115 kpA with accuracy on the order of 1.5 percent over the operating pressure range. The error band tolerance increases by a temperature multiplier of up to 2× outside the 0 to 85 °C range. MAP and barometric pressure sensors are frequently mounted inside control modules making the mounting technique a key consideration for manufacturability. The increased usage of surface mount technology, and the need to reduce space so that additional features can be included in control modules are factors that will affect next-generation sensor designs.

A typical turbocharger can provide boost pressure in the range of 80 kPa over the naturally aspirated internal combustion engine. This increases the maximum rating for the sensor to 200 kPa absolute, but other requirements are scaled appropriately.

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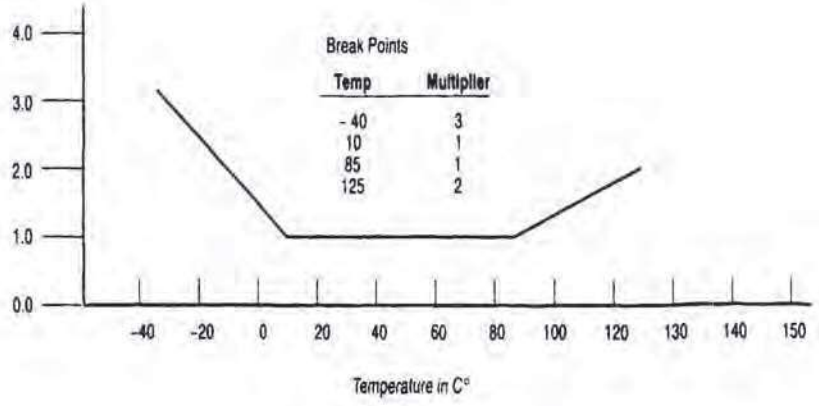
MPX4100 • MPX4101 SERIES

Transfer Function

Nominal Transfer Value: $V_{out} = V_S (0.01059 \times P - 0.1518)$
+/– (Pressure Error x Temp. Mult. x 0.01059 x V_S)
$V_S = 5.1\ V \pm 5\%$ P_{in} kPa

Temperature Error Multiplier

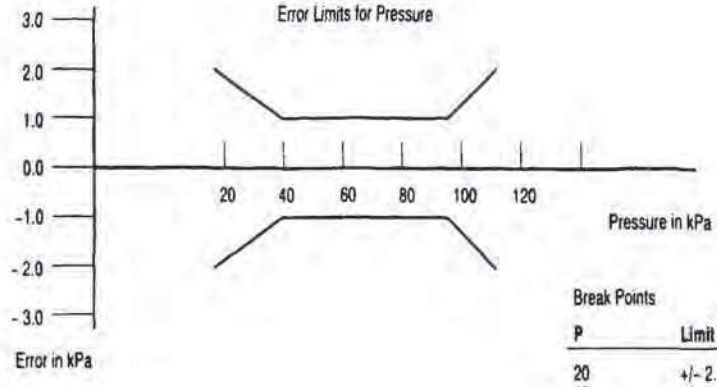
MPX4100 Series



Break Points

Temp	Multiplier
- 40	3
10	1
85	1
125	2

Pressure Error Band



Break Points

P	Limit (kPa)
20	+/- 2.1
40	+/- 1.2
94	+/- 1.2
105	+/- 1.5

FIGURE 2.3 Error band for MAP sensor.

Oil Pressure. Oil pressure on automobiles has traditionally been measured by the deflection of a rubber diaphragm which closes a set of contacts (switch) providing a lamp indication with low oil pressure or moves a potentiometer to provide an analog signal for a gage.

A replacement for the conventional electromechanical oil pressure sending unit is an electronic device such as the one designed by Chrysler's Acustar Division. In addition to a silicon

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piezoresistive pressure sensor, the unit contains transient protection circuitry, signal amplification for the sensor output, and output drivers for both an electromagnetic gauge and a fuel pump. The FET output drivers are capable of handling 10 A based on the heat dissipated though a heatsink that is integral to the sensor package.

The unit utilizes a supply voltage from 9 to 16 V and operates over a media temperature range of −40 to +150 °C. The overall accuracy is ±3.25 percent with linearity ≤ ±0.25 percent over the entire operating pressure range of 200 psi. The switch point for the low pressure indication is 4 psi ± 1.5 psi.

The sensor package was specially designed for easy assembly. The housing interfaces to the sensor with an extremely reliable O-ring seal that can withstand a burst pressure over 400 psi. Special materials were used for both the package and the protective gel that covers the sensor, which allow it to survive qualification tests with over 1 million pressure cycles, including portions conducted at high temperatures. This exceeds the number of cycles that can be achieved with traditional diaphragm-driven potentiometers that have been used for providing the indication of oil pressure. The sensor has been designed for a 10-year/100,000-mile life that could be required for future vehicle warranties.

Media Compatibility in Automotive Measurements. Pressure sensors frequently have to interface with an environment that is more demanding than other electronic components. For example, the measurement of engine oil pressure, transmission oil pressure, fuel pressure, and so on, or fluid level (oil, gas, coolant, etc.) requires the sensor package to be exposed to one or more fluids that are detrimental to the operation of semiconductor circuitry. Each of these media interface problems is addressed separately, depending on the application. Automotive cost requirements usually limit the usage of stainless steel as the isolation technique. Instead, more cost-effective protective polymers and chemically tolerant plastic and rubber materials have been developed for sensor packages.

2.2.2 New Applications for Pressure Sensing

The list of potential applications for sensing pressure in the automobile includes several new applications. These measurements are frequently made during the development of new vehicle systems. Their actual use on the vehicle is determined by factors such as cost, legislated requirements, need for diagnostics, and value added to the system. Applications in this section will identify areas of concern, range of pressure measurement, and factors that affect the usage of a pressure sensor.

Transmission Oil Pressure and Brake Pressure. Transmission pressure is required as an input in computer-controlled transmission shift points. This pressure can be measured with sensors similar to those developed for engine oil pressure.

Pressure in a hydraulic system, such as the master cylinder of an antilock brake system (ABS), is much higher than transmission oil pressure typically requiring a sensor with minimum rating of 500 psig. Pressures in other locations in the ABS system can be lower. The dynamic pressures in brake tubing can be of interest during the development phase of passenger vehicles and may be of interest in heavy duty commercial vehicles. These pressures can be below 150 psig.

The ABS system controls front and rear tire slip. Tradeoffs that exist in developing an ABS system for a particular vehicle include stopping deceleration to achieve the shortest possible stopping distance versus more steering control. Increased yaw stability can be obtained by reducing the deceleration rate of the rear wheels. The addition of traction control to the system improves stability during acceleration and provides independent control of each wheel during a variety of driving maneuvers for improved vehicle performance.

Passenger vehicles may have a single pressure sensor to monitor the pressure in the hydraulic system. One system, General Motors' ABS-VI, provides information on the brake pressure by detecting the current going to motors in the system. For the ABS-VI system, a pres-

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sure sensor is not required to provide optimum brake pressure at each wheel. However, other systems rely on the rate of brake application and release to control lockup. Commercial vehicles may have several sensors for sensing brake pressures. Sensors close to brake cylinders report the actual pressure, which is compared to the reference value stored in the control unit.

Tire Pressure. The continuous monitoring of tire pressure offers increased fuel economy and safety to passenger cars or commercial vehicles. Underinflated tires create excessive rolling friction and therefore decrease fuel economy. Overinflated tires have excessive stress that can result in failure during operation. Improperly inflated, either over- or underinflated, tires have uneven wear patterns which decrease tire life. Available tire pressure systems consist of a tire pressure sensor (or switch) at each wheel, wheel speed indicator, temperature sensor, a radio frequency transmitter, electronic receiver/controller, and a display unit. The dashboard display provides an indication to the driver that the tires are improperly inflated. Tire pressure increases with temperature approximately 1.5 psi for every 10 °C of tire air temperature rise, so the system must provide correction for this effect. Abrupt increases in temperature and pressure can be sensed by these systems and provide a warning of eminent tire failure providing an additional safety factor.

Another tire pressure system utilizes a separate hand-held reader to easily verify the proper tire inflation when the vehicle is stationary. Yet another commercial vehicle system for trucks with dual tires operates while the vehicle is stationary and employs a visual indication for the driver that adequate pressure exists. This system provides a single fill point for the dual tires, maintains equal pressure under normal conditions, and provides an isolation valve in the event that a blowout or slow leak develops in one tire.

EGR Pressure. EGR (exhaust gas recirculation) back pressure and a pressure differential exist across the EGR valve used to control NO_x emissions in the engine control system. The valve is modulated by a vacuum which lifts a pintle from its seated position to allow exhaust gas to be recirculated. A change in vacuum pressure from 50 to 90 mm Hg is sufficient to fully open the valve, and a pressure differential across the valve of 200 mm Hg is typical. Pressure measurements are made during the development phase to determine system operating characteristics. However, a position sensor is typically used to measure the EGR valve's position and control NO_x emissions during normal vehicle operation.

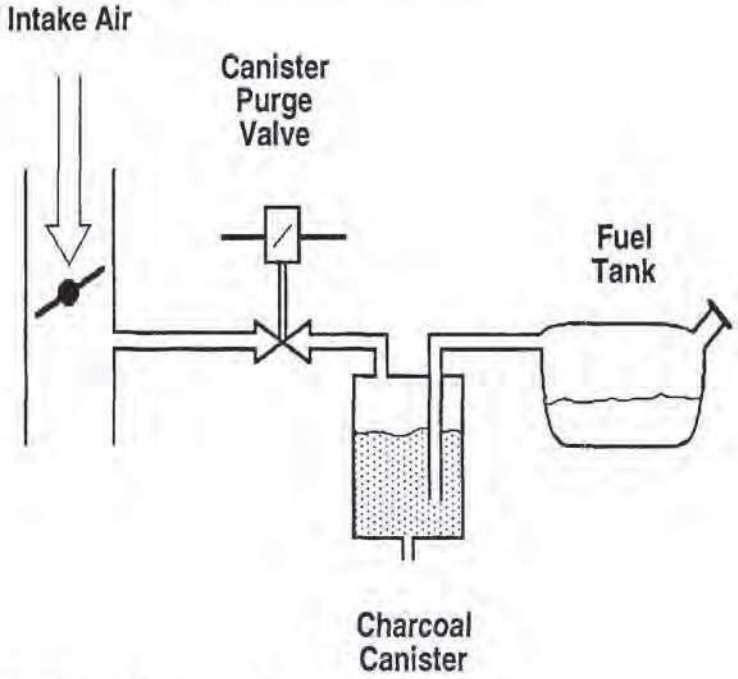

FIGURE 2.4 Canister purge system.

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Fuel Rail and Vapor Pressure. Evaporative emissions that occur when the engine is off are currently stored in an activated charcoal canister of about 850 to 1500 cc until the engine is running, as shown in Fig. 2.4. The vapors are then consumed by the combustion chamber and catalytic converter. One implementation of on-board vapor containment of refueling hydrocarbons (on-board refueling vapor recovery or ORVR) would require refueling canisters on the vehicle that could be three to four times the volume of existing canisters. If leaks need to be detected in this system, a diagnostic pressure sensor may be required.

One approach to fuel routing, employed in the 5.9-liter Dodge Magnum engine, is to mount the fuel filter and pressure regulator at the fuel tank. The fuel pump is mounted inside the tank. Therefore, since only a fuel supply line to the fuel rail and a line to the evaporative canister are necessary, the fuel return line is eliminated. This system maintains lower fuel tank temperatures, resulting in lower evaporative emissions.

Monitors required for on-board diagnostic (OBD) systems per California Air Resources Board's (CARB's) OBDII legislation were originally targeted to be phased in between model year 1994 and model year 1996. A Bosch fuel injection system with on-board diagnostics is shown in Fig. 2.5 that identifies a differential air pressure sensor for tank vapor pressure.

Overpressure Occurrences. Fuel supply pressures in automobile fuel injection systems normally operate at pressures below 75 psi; however, fuel pumps develop pressures up to 3200 psi to open injectors. Pressure spikes can be reflected back through the fuel supply system that measure up to 300 psi during each fuel injection pulse.

Overpressure created by backfire can also apply a positive pressure of 75 psi and higher to the intake manifold absolute pressure sensor. Techniques used to prevent failure from over-

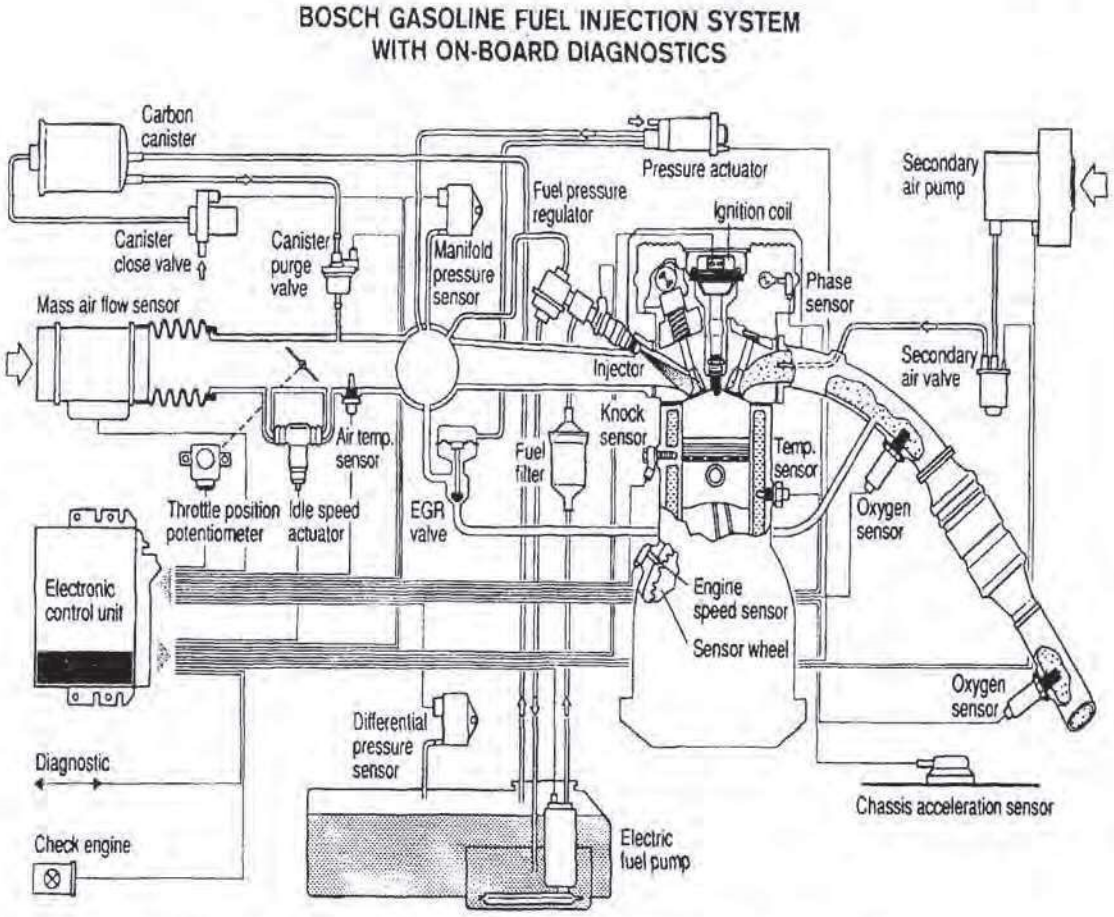

FIGURE 2.5 Fuel vapor control in electronic fuel injection system. *(Courtesy Robert Bosch, GMBh)*

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pressure include overpressure stop built into the transducer, mechanical pulse filtering, and a sensor designed to operate within the overpressure range.

Mechanical stops have been a traditional protection technique for mechanical pressure sensors. This is possible where the amount of diaphragm deflection is large. Silicon pressure sensors have a modulus of elasticity that is the same as steel (30×10^6 psi) and a yield strength (180,000 to 300,000 psi) that is higher than steel, allowing high overpressure without diaphragm damage. However, the sensor package itself must be designed to handle the maximum pressure safely.

Snubbing, or mechanical filtering, is commonly used for static pressure measurements. A small diameter tube reduces the dynamic variation in applied pressure. If dynamic measurements are desired, the ac component of the desired signal may also be attenuated.

Increasing the diaphragm thickness of the sensor to safely handle the full range of pressure within normal operating range will also result in a lower sensitivity.

Alternate Fuel and Alternate Engine Implications to Pressure. Legislation that requires a percentage of the vehicles sold in California to be LEV (low emissions vehicles) and even ZEV (zero emissions vehicles) is increasing the demand for alternate fuel and electric vehicles. Among the alternate fuel vehicles, CNG (compressed natural gas) and hydrogen cells most likely would require sensors for pressure measurements. CNG is pressurized at 3000 psi and the distribution system includes pressure regulators, a transducer, valves, and idle air solenoids. Before the natural gas enters the engine, a regulator reduces the fuel pressure to near atmospheric pressure. Sensing may be required in both low- and high-pressure portions of the system. Development of alternative engines, such as the two-stroke engine for vehicle applications, will utilize electronics for control functions similar to four-cycle engines. However, the range and necessity for pressure measurements will differ from four-cycle engines. The pressure range for direct fuel injection is considerably higher for a two-stroke engine. The need to control the oil pump may necessitate pressure sensing in two-stroke systems as well.

Hydrogen fuel cells are another potential source of energy for use in electric vehicles. In one design, the proton-exchange membrane (PEM) design, a turbocompressor is used to pressurize the system and maintain hydration of the membrane. A pressure of at least three atmospheres (0.3 MPa) is required to remove the water. This pressure or the pressure drop across the membrane may need to be monitored during operation.

2.2.3 Other Applications for Pressure Sensors

Pressure sensors can be used on vehicles for measuring flow through pressure differential, or delta-P, measurements and for determining liquid level.

Delta-P (Flow-Sensing) Measurements. Applications on the vehicle for flow sensing include mass air flow; heating compartment flow; oil, fuel, and cooling liquid flow; and vehicle flow in an air stream. Mass air flow is typically accomplished by hot-wire anemometer or Karman vortex flow meters which do not use pressure-sensing techniques. Other vehicle flow requirements, including the pressure drop across the air filter, could be sensed and monitored by a differential pressure sensor. In addition to requirements such as media compatibility (Sec. 2.2.1), the lower-level signals require higher-sensitivity pressure sensors and/or additional amplification and must tolerate faults that could apply full line pressure to only one side of the sensor.

One of the more interesting applications of differential pressure measurements applied to flow analysis is the flow of the vehicle itself relative to crosswinds. A rear-wheel steering system developed by Daimler-Benz uses two pressure sensors to measure the pressure caused by wind on the vehicle's sides. An electronic control unit analyzes the pressure difference and inputs from other sensors, and alters the rear-wheel setting according to the wind strength. The system that measures the crosswinds directly is faster than yaw sensors, which are reactive and measure the change in attitude and direction of the vehicle.

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Other laboratory measurements of airflow and crosswind force have also been made by Daimler-Benz that utilize 10 differential pressure gages with a range of ±3700 kPa. All pressure sensors were connected to a single pressure vessel to have a common reference. The reference pressure was measured by a 100-kPa absolute pressure sensor. The measurements were used to determine aerodynamic forces and moments and to compensate for wind effects in an active steering system.

Fluid Level Sensing. Various liquid levels can be measured in a vehicle, as shown in Table 2.4. All of these requirements, except fuel level, could be satisfied by a switch that simply detects that a predefined minimum level of liquid has been reached so that a driver indication can be provided. This can be accomplished by directly illuminating a dash lamp or through a microcontroller in a body computer which activates an output driver.

TABLE 2.4 Liquid Level Measurements

Level	Type	Range
Engine oil	Switch	38.1 cm of water
Transmission oil	Switch	30.5 cm of water
Coolant	Switch	61 cm of water
Windshield washer fluid	Switch	30.5 cm of water
Battery	Refraction switch	5.1 cm below reference
Power steering fluid	Switch	7.6 cm below reference
Brake fluid	Switch	30.5 cm of water
Fuel	Sensor and switch	38.1 cm of water

Sensing the fuel level has traditionally been performed by a float to sense the fluid level and a variable resistor with the wiper arm connected to the float. Configuration for the sensor depends upon the specific tank for which it was designed, necessitating a unique sensor for each vehicle. Manufacturers with several different vehicle models have the additional impetus to replace the existing techniques with a nonwearing, more accurate, self-calibrating electronic alternative. However, media compatibility for fuel level is among the harshest requirements for a pressure sensor. In addition to gasoline, oxygenated fuels containing ethanol, methanol, benzene, MTBE, engine additives, and even sour gas must be tolerated by the sensor. Nonintrusive differential sensors isolate the liquid from the sensor interface but must still tolerate fuel vapors. Also, the sloshing of the fuel in a vehicle's tank requires a time amplitude filter to smooth out the indication provided to the driver.

2.2.4 Combustion Pressure

The direct measurement of combustion pressure is being investigated for detecting misfire to meet CARB OBDII requirements. The high pressure (≥16 MPa) and temperature ranges combined with other environment factors make the design of a pressure sensor for this application extremely expensive. As a result, other techniques are being developed as alternatives to direct pressure measurement. These technologies include optical, fiberoptics measuring luminous emissions from combustion, and noncontact torque sensors. Section 2.3.7 explains a fiber optic technique.

The operation of the reciprocating-piston, internal combustion engine is represented by a constant volume process and the engine power cycle is analyzed by using pressure-versus-volume and pressure-versus-crank angle diagrams. To obtain these measurements in a laboratory environment a number of techniques have been developed. Direct (in-cylinder) pressure measurements have been performed with small diameter piezoresistive sensors placed in (or near) the sparkplug and piezoelectric washers placed under the spark plug. A high natural fre-

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quency is required for these sensors based on the dynamic measurement involved in the combustion process. Indirect measurements with shaft torque and optical phase shift are additional possibilities. The need to determine misfire due to component failure during vehicle operation is part of OBDII requirements. A sensor used on production vehicles will be required to survive the high pressure and temperature environment for the life of the vehicle, which could be 100,000 miles and 10 years. It must also have no need for periodic zeroing or calibration and be available at a low cost.

2.2.5 Other Pressure Measurements

An adaptive suspension system (see Chap. 17) can be accomplished with an air pressure controlled shock absorber damping, such as Mitsubishi's Active-ECS (Electronically Controlled Suspension). This system has two air pumps and nine solenoids that regulate air pressure based on inputs from sensors including an air pressure sensor in the rear of the vehicle that measures the passenger and cargo load. The driver can select soft, medium, or hard suspension. Another system utilizes an air reservoir charged to a pressure of 1 Mpa by a compressor. A pressure switch monitors when the pressure drops below 760 kPa to recharge the reservoir. Air springs operate at 300 kPa unloaded and at 600 kPa in the rear when fully loaded.

HVAC (heating, ventilating, and air conditioning) changes are occurring as manufacturers are required to convert from refrigerant CFC-12 to alternatives such as HFC-134a. The theoretical performance of these two refrigerants will mean about a 6 percent loss in efficiency, compressor discharge pressure that is 175 kPa higher, and a discharge temperature that is about 8 °C lower. Measuring the compressor discharge pressure (almost 1900 kPa for the HFC-134a system) is desirable for electric load control as vehicles add more requirements to the 12-V charging system. Also, the effect on engine performance and fuel economy when the A/C is used could make the refrigerant pressure sensor a standard vehicle sensor in the future. An absolute sensor used to measure gage pressure of the refrigerant provides a deadhead effect to prevent refrigerant loss in the event of a sensing diaphragm failure.

The measurement of the pressure developed when the air bag is inflated is part of the evaluation, qualification, and lot acceptance criteria of air bag inflating techniques. Time-to-peak pressure and peak tank pressure measurements require measurements in the tens of milliseconds range. Inflated bag pressures are in the range of 100 kPa or less. Hybrid inflators use a stored inert gas, such as argon, in place of sodium-azide propellant that requires a squib for ignition. The hybrid uses a pressure sensor to monitor the status of the stored gas.

Special heavy duty/commercial truck measurements require pressure measurements that are quite different from those made on passenger cars. Accumulator-type fuel injection systems for direct injection diesel engines have fuel pressurized to 20 to 100 MPa in the accumulator by a high-pressure pump. The accumulator pressure is monitored in this approach to reduce particulates. Another method to reduce diesel particulates utilizes a ceramic fiber as a filter in a canister. A pressure sensor monitors the backpressure and allows the full filter to be regenerated by burning off the accumulated particulates in the filter. A heater element in the trap has power supplied from the power-switching module. A temperature approaching 1300 °F (700 °C) is reached inside the filter cartridge to incinerate the particles.

Lumbar support systems utilize a pressurized system with a pressure sensor ($\leq$7.5 psig) as the feedback element controlling the air pump to provide additional support to the driver's lower back in luxury vehicles. Pressure-sensitive grids have been used in the development process to automatically measure up to 3600 contact points for visual display and weight distribution analysis.

2.2.6 Partial Pressure Measurements

The oxygen (or lambda-) sensor in engine control systems is a chemical sensor that utilizes partial pressures to provide a feedback signal for the closed-loop control system. Lambda is

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defined as the actual air/fuel ratio divided by the stoichiometric (14.6) fuel ratio. The operation of the oxygen sensor is defined by the Nernst equation: $U_L = RT/4F \cdot \ln(P_{O2}''/P_{O2}')$, where U_L is the unloaded output voltage of the sensor, R is the universal gas constant, T is the absolute temperature, F is the Faraday constant, P_{O2}'' is the oxygen partial pressure of the air (about 2.9 psi), and P_{O2}' is the equilibrium partial pressure of the oxygen in the exhaust gases. Equilibrium occurs due to the catalytic activity of the platinum electrodes used to coat the inside and outside of the Y_2O_3 stabilized ZrO_2 ceramic electrode. The oxygen partial pressure changes by a factor of 10^7 at 900°C (or 10^{19} at 500°C) when the exhaust gas changes from a reducing environment (lambda = 0.999) to an oxidizing environment (lambda = 1.001).

2.3 TECHNOLOGIES FOR SENSING PRESSURE

A number of technologies have been used for on-vehicle measurements of static and dynamic pressure: diaphragm-potentiometer, linear variable differential transformer (LVDT), aneroid, silicon or ceramic capacitive, piezoresistive strain gage, piezoelectric ceramic or film, and optical phase shift (combustion pressure). Recent advances in sensing have focused on transducers that provide an electric signal easily interfaced to microcontrollers. Mechanical devices are frequently used in the laboratory for calibration and component development or on the vehicle during the development phase of the vehicle systems. Common mechanical devices include the Bourdon tube, bellows, diaphragms, deadweight gage, and manometer.

The Bourdon tube is a curved or twisted, flattened tube with one end closed that acts as a force collector. When pressure is applied at the open end, the tube tends to straighten and the resulting motion is used as an indication of the applied pressure.

The bellows, or pressure capsule, is a chamber that expands with applied pressure. Absolute pressure can be measured by sealing a reference pressure (e.g., vacuum) inside a closed unit and applying pressure to the outside. The movement of the chamber is proportional to the applied pressure.

Diaphragms are the most common force collector used in modern pressure sensors. The diaphragm material can be rubber, elastomer, stainless steel, silicon, ceramic, or even sapphire. Diaphragm shapes are circular or square and can be supported or clamped around their periphery.

A deadweight tester or piston gage can withstand extreme pressure changes and high overpressure occurrences. The piston is sealed in a cylinder using O-ring or Teflon seals. Pressure on the piston causes a deflection that can be measured by position-sensing techniques. Precision weights allow calibration for high-accuracy measurements. The deadweight tester is one of the few pressure-sensing techniques that measures pressure in terms of its fundamental units—force and area. Errors associated with the measurement are air-bouyancy corrections, gravity error, surface tension, fluidhead, and thermal expansivity. These errors are normally small but should be taken into account when high accuracy is required.

The manometer is used both as a pressure-measuring instrument and a standard for calibrating other instruments. Its simplicity and inherent accuracy result from it being the measurement of the height(s) of a column of liquid. Three basic types of manometers are the U-tube, well (cistern), and slant-tube.

Other measurement devices including McLeod, Pirani, Alphatron, and thermocouple gages which can measure vacuum in the range of 10^{-5} mm Hg.

Sensing techniques that provide a transducer for conversion from mechanical to electrical units include resistive, LVDT, capacitive, piezoresistive, and piezoelectric.

2.3.1 Potentiometric Pressure Sensors

Prior to electronic engine control systems, carburetor dashpots and distributor vacuum advance units used the distance that a rubber diaphragm traveled when pressure was applied

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as a mechanical indication of pressure. A diaphragm which moves a potentiometer (resistor with a sliding element or wiper) provides an electric signal that can be applied to a remote gage such as an oil pressure gage. Potentiometric sensors inherently have some level of noise and wear associated with their operation due to the contact of the wiper to the resistive element. Stiction or static friction is also a potential concern with these devices, especially if control of ≤0.5 percent of the total resistance is required. The finite resolution of wirewound potentiometers is overcome by the use of newer thin-film plastic resistor designs.

2.3.2 Linear Variable Differential Transformer

One of the earliest pressure inputs for engine control systems was provided by the LVDT pressure sensor. The principle of operation is demonstrated in Fig. 2.6. An LVDT pressure sensor consists of a primary winding and two secondary windings positioned on a movable cylindrical core. The core is attached to a force collector which provides differential coupling from the primary to the secondaries resulting in a position output that is proportional to pressure.

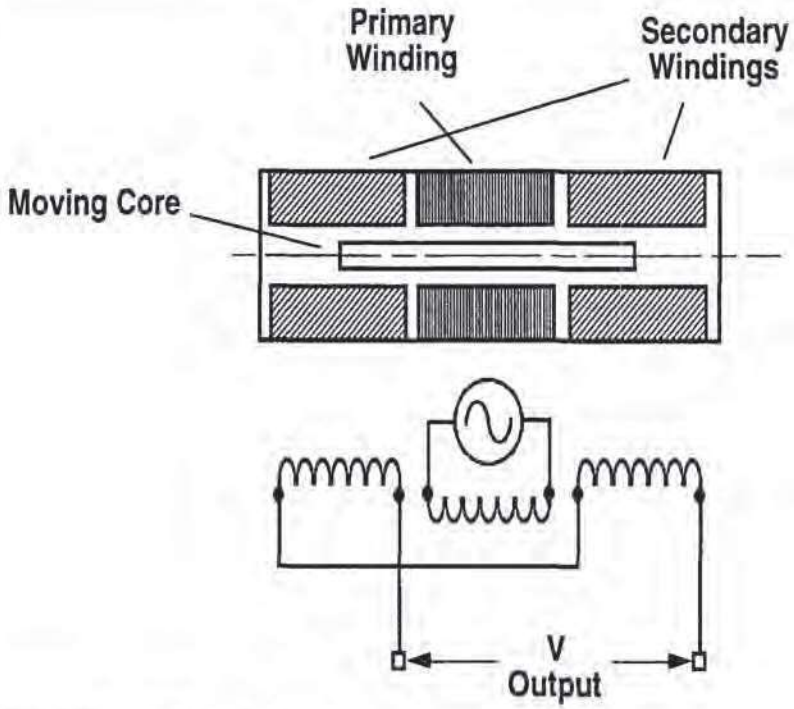

FIGURE 2.6 LVDT pressure sensor.

An alternating current is used to energize the primary winding, which results in a voltage being induced in each of the secondary windings. The windings are connected in series opposing, so the equal but opposite output of each winding tends to cancel (except for a small residual voltage called the null voltage). A pressure applied to a Bourdon tube or diaphragm causes the core to be displaced from its null position and the coupling between the primary and each of the secondaries is no longer equal. The resulting output varies linearly within the design range of the transducer and has a phase change of 180° from one side of the null position to the other. Since the core and coil structures are not in physical contact, essentially frictionless movement occurs.

Electronic devices necessary to signal condition the output of an LVDT consist of an oscillator for the supply voltage, circuitry to transform the constant voltage to a constant current, an amplifier with high input impedance for the output, a synchronous demodulator, and a filter with characteristics designed for quasistatic or dynamic measurements.

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2.3.3 Aneroid Diaphragms

Another early design for sensing automotive manifold pressure consisted of dual sealed aneroid diaphragms. The diaphragms were bonded and sealed with a vacuum inside each unit to a metallized conductive ring on opposite sides of a ceramic substrate. The substrate served as the fixed plates of two separate capacitors. Manifold vacuum was applied to one chamber and the second served as a reference for compensating and signal conditioning that minimized common mode errors due to vibration and shock.

2.3.4 Capacitive Pressure Sensors

Capacitive pressure sensors have one plate that is connected to a force collector (usually a diaphragm), and the distance between the plates varies as a result of the applied pressure. The nominal capacitance is $C = Ae/d$, where A is the area of the plate, e is the permittivity, and d is the distance between the plates. Two common capacitive pressure sensors used in automotive applications are based on silicon and ceramic capacitors.

Silicon. A silicon capacitive absolute pressure (SCAP)-sensing element is shown in Fig. 2.7. The micromachined silicon diaphragm with controlled cavity depth is anodically bonded to a Pyrex® glass substrate. Feedthrough holes are drilled in the glass to provide a precise connection to the capacitor plates inside the unit. The glass substrate is metallized using thin-film deposition techniques. Photolithography is used to define the electrode configuration. After attaching the top silicon wafer to the glass substrate, the drilled holes are solder-sealed under vacuum to provide a capacitive-sensing element with an internal vacuum reference and solder bumps for direct mounting to a circuit board or ceramic substrate. The value of the capacitor changes linearly from approximately 32 to 39 pF with applied pressure from 17 to 105 kPa. The capacitive element is 6.7 mm × 6.7 mm and has a low-temperature coefficient of capacitance (−30 to 80 ppm/°C), good linearity (≈1.4 percent), fast response time (≈1 ms), and no

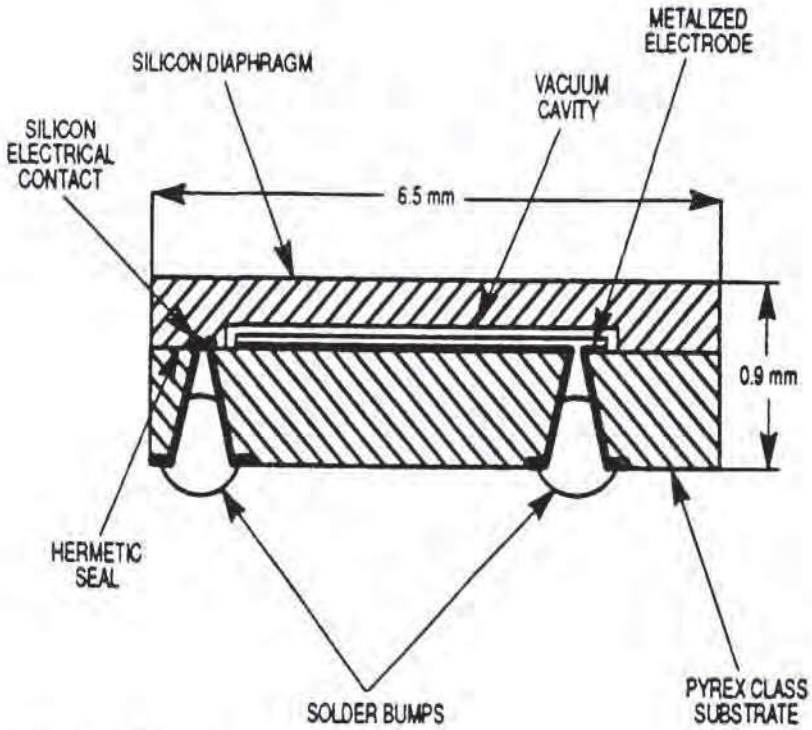

FIGURE 2.7 SCAP sensor.

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exposed bond wires. The output of the sensor is typically signal-conditioned to provide a frequency variation with applied pressure for easy interface to microcontrollers.

Surface micromachining and bulk micromachined silicon-on-silicon techniques (see Sec. 2.3.5) have also been used to build silicon capacitive pressure sensors. These approaches also address the addition of signal-conditioning electronics on the same silicon structure.

Ceramic. The ability to make thin diaphragms from ceramic material combined with thin-film deposition to provide metal plates and connections has been used to manufacture ceramic pressure sensors. Their operation and signal-conditioning requirements are similar to the silicon capacitive sensor described in Sec. 2.3.4.

2.3.5 Piezoresistive Strain Gage

Strain-gage pressure sensors convert the change in resistance in four (sometimes in two) arms of a Wheatstone bridge. The change in the resistance of a material when it is mechanically stressed is called piezoresistivity.

The open-circuit voltage of an unbalanced Wheatstone bridge is given by $V_O = \mathbf{E}[(R1*R3 - R2*R4)/(R1 + R2)(R3 + R4)]$, where V_O is the output voltage, **E** is the applied voltage, and $R1$ through $R4$ are the resistive elements of the bridge. Additional variable resistive elements are typically added to adjust for zero-offset and sensitivity, and to provide temperature compensation.

Different approaches to piezoresistive strain gages range from traditional bonded and unbonded to the newest integrated silicon pressure sensors.

Bonded and Unbonded Strain Gages. The bonded resistance strain-gage pressure sensor consists of a filament-wire or foil, metallic or semiconductor, bulk material or deposited film bonded to the surface of a diaphragm. Pressure applied to the diaphragm produces a change in the dimension of the diaphragm and, consequently, in the length of the gage, and, therefore, a change in its resistance ($R = \rho\, L/A$). The change per unit length is called strain. The sensitivity of a strain gage is indicated by gage factor

$$GF = \Delta R/R \div \Delta L/L = 1 + 2\mu + \Delta\rho/\rho \div \Delta L/L \tag{2.1}$$

Foil strain gages have a negligible piezoresistive effect and their gage factor is usually between 2 and 3.

When a pressure sensor is used for measuring an applied force it is called a load cell.

Integrated Silicon Pressure Sensors. The GF for a strain gage is improved considerably (to about 150) by using a silicon strain gage. In addition to the conventional Wheatstone bridge, silicon processing techniques, and the relative size of piezoresistive elements in silicon enable the design of a unique piezoresistive sensor. The sensor signal can be provided from a single piezoresistive element located at a 45° angle in the center of the edge of a square diaphragm which provides an extremely linear measurement. The offset voltage and full scale span of the basic sensing element vary with temperature, but in a highly predictable manner. In addition to the basic sensing element, an interactively laser-trimmed four-stage network has also been integrated into a single monolithic structure (Fig. 2.8). The size of the silicon die, including the diaphragm, sensing element, and signal-conditioning electronics, is only 0.135 in by 0.145 in. The die is attached to the six-terminal package through the use of a stress-isolating layer of RTV (room temperature vulcanizing) silicone. This approach allows a minimum of external components for amplification to provide a usable output signal.

Two silicon wafers are used to produce the absolute piezoresistive silicon pressure sensor (Fig. 2.9). The top wafer is etched until a thin, square diaphragm, approximately one mil in thickness, is achieved. The square area is extremely reproducible as is the 54.7° angle of the cavity wall based on the characteristics of bulk micromachined silicon. The top wafer is

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FIGURE 2.8 Silicon pressure sensor with integrated electronics. *(Courtesy Motorola, Inc.)*

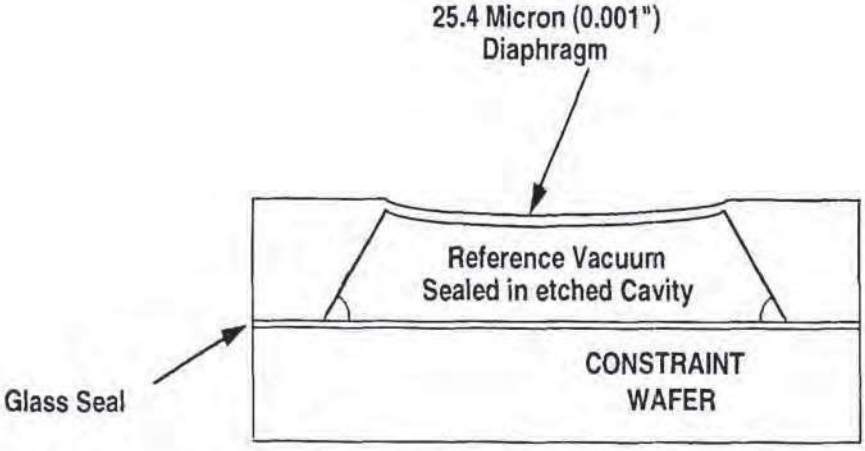

FIGURE 2.9 Cross section of piezoresistive silicon pressure sensor for measuring absolute pressure.

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attached to a support wafer by a glass frit to provide a structure which is isolated from mounting stresses.

The bulk micromachining process used to form the diaphragm and the etched cavity in the majority of silicon pressure sensors is a chemical etching process that allows a thin (0.001-in) mechanical structure—the diaphragm—to be precisely etched from a silicon wafer that is approximately 0.015 in thick. Hundreds of sensors can be formed simultaneously on a 4-in (100-mm) diameter silicon wafer, and several wafers can be batch-processed to yield thousands of sensors in a single lot. Silicon pressure sensors can also be achieved by using surface micromachining techniques. In these sensors, a layer of sacrificial material (usually an oxide) is grown on top of a silicon wafer, and material such as polysilicon is then deposited on the sacrificial layer and patterned to achieve a particular structure. The sacrificial material is removed by a chemical etchant. Both bulk and surface micromachining techniques can be combined with semiconductor processing techniques to provide additional circuitry on the same monolithic structure. A number of new terms are used relative to silicon pressure sensors that are defined in the glossary to this section.

Both bulk and surface micromachining, discussed previously, are performed at the wafer level. A polysilicon thin-film sensor that consists of a thin film of silicon that is doped with boron and vapor-deposited over a stainless steel diaphragm is shown in Fig. 2.10. A thin deposited layer of silicon dioxide insulates the silicon from the stainless steel diaphragm. Silicon nitride is used to cover the strain-sensitive elements. Silicon-on-insulated-stainless-steel (SOISS) sensors are not formed using silicon wafer techniques, but they use batch-processing techniques and are inherently suited for harsh environments.

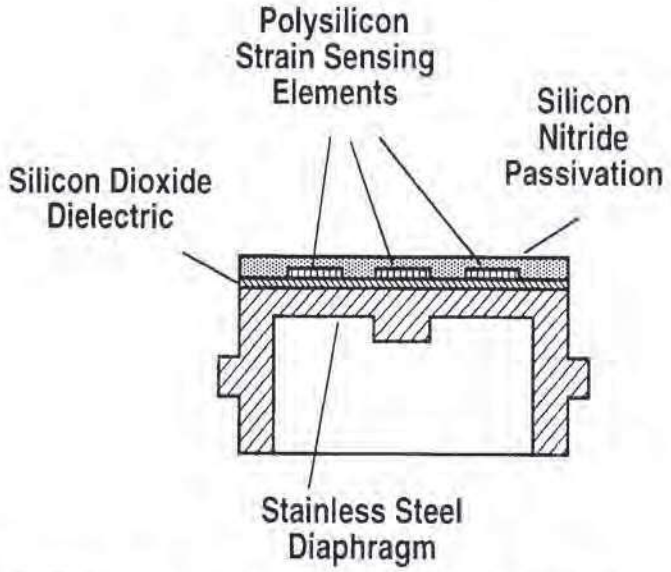

FIGURE 2.10 Polysilicon pressure sensor on stainless steel diaphragm.

2.3.6 Piezoelectric Pressure Sensors

A piezoelectric sensor produces a change in electric charge when a force is applied across the face of a crystal or piezoelectric film. The inherent ability to sense vibration and the necessity for high-impedance circuitry are taken into account in the design of modern piezocrystal sensors. Transducers are constructed with rigid multiple plates and a cultured-quartz sensing element, which contains an integral accelerometer to minimize vibration sensitivity and suppress resonances. A typical unit also contains a built-in microelectronic amplifier to transform the high-impedance electrostatic charge output from the crystals into a low-impedance voltage signal. Units made in stainless steel housings have an invar diaphragm laser welded to seal the

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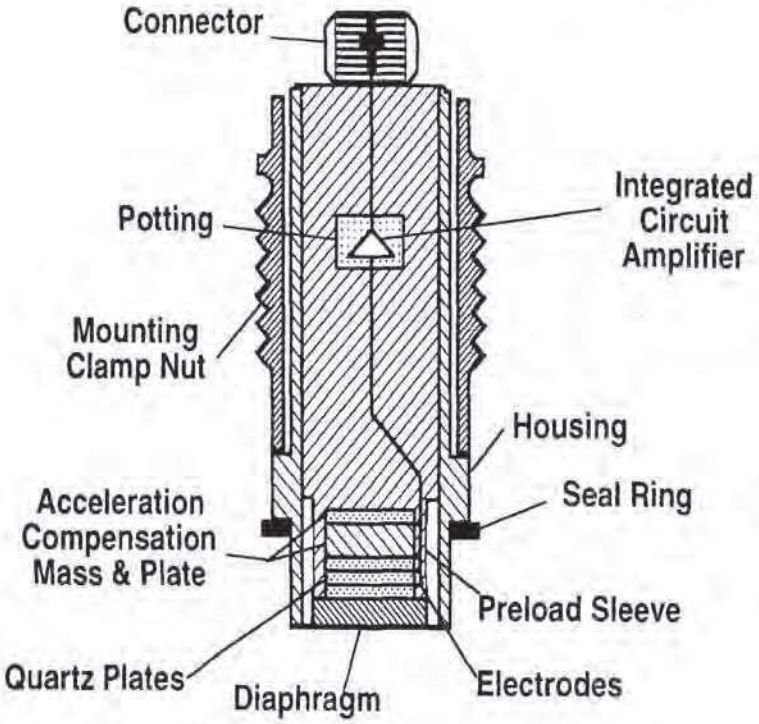

FIGURE 2.11 Piezoelectric pressure sensor.

sensing elements inside the package. Figure 2.11 shows the cross section of a piezoelectric pressure sensor.

More recently, piezo film sensors, which produce an output voltage when they are deflected, provide a very inexpensive method for pressure measurements. One approach has the piezo film cemented to a metallic dimple substrate with the dimple pointed toward the high-pressure source. As the pressure rises, a point is reached when the dimple snaps in the opposite direction and the movement is sufficient for the piezo film to generate a transient voltage.

Surface micromachining techniques have also been combined with piezoelectric thin-film materials, such as zinc oxide, to produce a semiconductor piezoelectric pressure sensor.

2.3.7 Fiber Optic Combustion Pressure Sensor

For extremely high pressure, or pressure measurements at high temperatures, different pressure measurement techniques are used. Figure 2.12 shows an alternative to traditional pressure-sensing techniques that is being developed to sense production vehicles' combustion

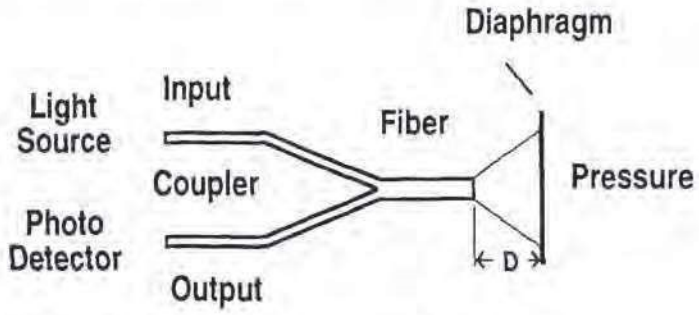

FIGURE 2.12 Fiber optic combustion pressure sensor.

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pressure. The fiber optic pressure sensor can withstand temperatures (up to 550 °C) that are well above the normal range for piezoelectric sensors. Furthermore, the design has a normal pressure range of 0 to 1000 psi and overrange capability of 3000 psi.

The sensor's operation is the result of a light source input to an optical fiber coupler and a photodetector at the receiving end of the coupler. Light exits the optical fiber as a diverging cone which illuminates a diaphragm. The maximum angle is determined by an aperture. The amount of light that is returned to the sensor fiber after it is reflected from the diaphragm depends upon the gap D between the fiber and the diaphragm. The diaphragm can be sized to allow the sensor to be integrated into a spark plug for easy access to the combustion pressure of each cylinder. Accuracy within 5 percent has been demonstrated within the 550 °C operating temperature range.

2.3.8 Pressure Switch

A pressure switch can be simpler and more cost effective than a pressure sensor for an application that only requires detecting a single pressure level. Sufficient motion of the force-collecting diaphragm (e.g., elastomer, Kapton®, fluorosilicon) allows a spring to be compressed and a set of contacts to be closed in a traditional mechanical switch. The design of the contacts may allow several amperes to be switched.

Converting the output of any of the electric sensors in Sec. 2.3 to a threshold-sensing level requires additional circuits, including an electronic switch, such as a power FET, to conduct the current. The sensor can have multiple switch points depending on the amount of additional circuitry that is provided.

2.3.9 Pressure Valves/Regulators

Pressure is frequently controlled in automotive applications by pressure regulators or valves. The actuation of these mechanisms can be a result of applied pressure to a mechanical structure such as an integral piston or relief valve held closed by a spring force, or an electric signal generated from a sensor and subsequent activation of a solenoid, which opens a valve or moves a pintle in an orifice to change the pressure. The thermostat in the engine cooling system allows flow based on a minimum temperature being achieved. It must operate independently of the pressure variations in the cooling system. A common solution is an expansion-element thermostat which actuates a valve to redirect the flow of coolant into a radiator bypass line when the control temperature is reached.

Extremely small and precise silicon-based regulators, and even pumps, are possible using micromachining techniques. Figure 2.13 shows a silicon Fluistor™ (or fluidic transistor) microvalve that is approximately 5.5 mm by 6.5 mm by 2 mm. The valve is actually a thermopneumatic actuator which accepts an electric input. The cavity is etched in the middle silicon chip by bulk micromachining described in Sec. 2.3.4 and filled with a control liquid. When the liquid is heated, the silicon diaphragm moves outward over the valve seat. This approach has demonstrated a dynamic range of 100,000:1 controlling gas flows from 4 µlpm to 4 lpm at a pressure of 20 psid.

The microvalve combined with a pressure sensor and electronic feedback loop provides a solid state pressure regulator. It has potential for usage in both gas and liquid flow control applications on future vehicles. The integration of EGR and idle-air control (IAC) has already been accomplished in a somewhat conventional (patented) manner. A feedback-controlled valve with two inlets and a single outlet orifice eliminate stepper motor programming in the engine controller and only one calibration curve is needed for both EGR and IAC functions. The combination of this approach to control systems and newly developed technologies, such as the silicon microvalve, will allow additional advances in vehicle performance, efficiency, and control.

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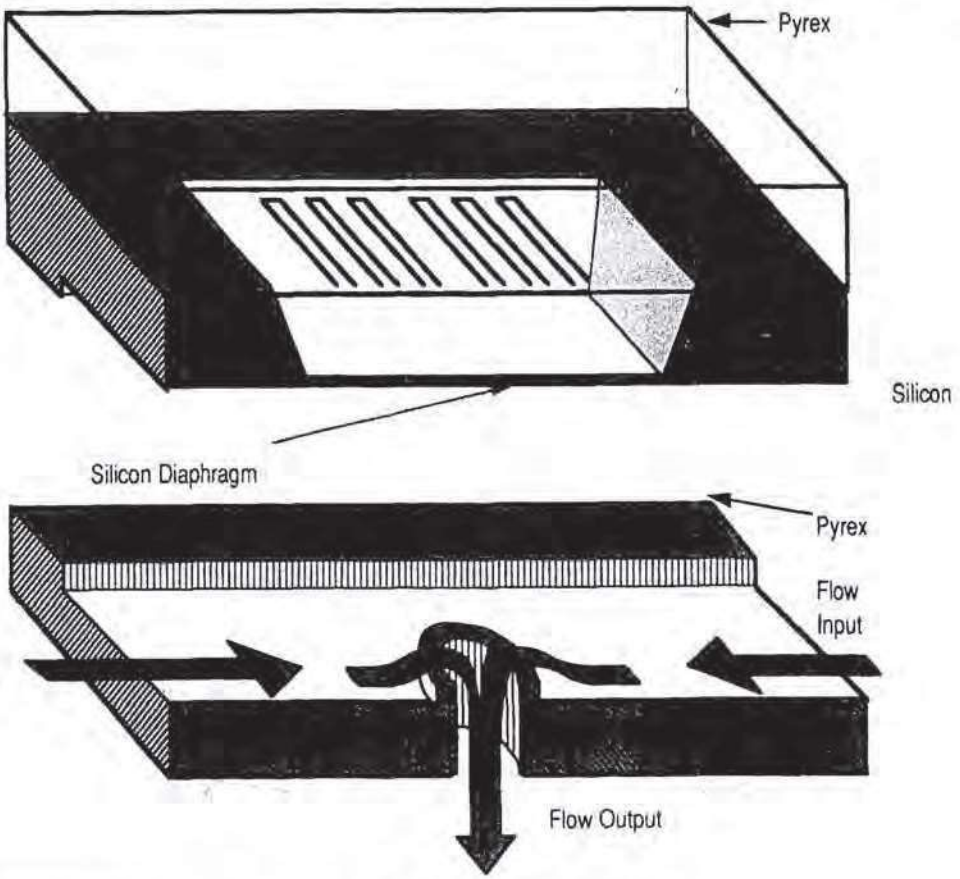

FIGURE 2.13 Silicon microvalve. *(Courtesy of Redwood MicroSystems, Inc.)*

2.4 FUTURE PRESSURE-SENSING DEVELOPMENTS

The different types of pressure measurements, different technologies for measuring pressure, and potential pressure measurements in automotive applications have been explained in this chapter. In addition, alternatives to making pressure measurements, such as indirect sensing and the use of pressure regulators, have been discussed. The use of semiconductor technology applied to sensing applications is producing sensors with inherently more decision and diagnostic capability that can communicate bidirectionally with host microcomputers in complex systems. The desire to directly produce a signal that is compatible with microcomputers rather than requiring analog signals to be converted to digital format through A/D converters is spurring development activity that could affect future automobile systems. Furthermore, recently developed fuzzy logic and neural network approaches to control systems and multiplexing of sensor outputs for use in several systems will make previously cost-prohibitive sensing applications a reality.

Increased and recently initiated sensing activity from industrial organizations such as SAE, the American National Standards Institute (ANSI), and the Institute of Electrical and Electronics Engineers (IEEE) should provide a greater level of understanding, common terminology, and improved specifications and test procedures for the numerous approaches that can be taken to sense pressure in automotive applications.

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GLOSSARY

Altimetric pressure transducer A barometric pressure transducer used to determine altitude from the pressure-altitude profile.

Diaphragm The membrane of material that remains after etching a cavity into the silicon sensing chip. Changes in input pressure cause the diaphragm to deflect.

Error band The band of maximum deviations of the output values from a specified reference line or curve due to those causes attributable to the sensor. Usually expressed as "±% of full-scale output." The error band should be specified as applicable over at least two calibration cycles so as to include repeatability and verified accordingly.

Linearity error The maximum deviation of the output from a straight-line relationship with pressure over the operating pressure range. The type of straight-line relationship (end-point, least-square approximation, etc.) should be specified.

Operating pressure range The range of pressures between minimum and maximum pressures at which the output will meet the specified operating characteristics.

Overpressure The maximum specified pressure that may be applied to the sensing element of a sensor without causing a permanent change in the output characteristics.

Piezoresistance A resistive element that changes resistance relative to the applied stress it experiences (e.g., strain gauge).

Pressure error The maximum difference between the true pressure and the pressure inferred from the output for any pressure in the operating pressure range.

Pressure sensor A device that converts an input pressure into an electric output.

Ratiometric (ratiometricity error) At a given supply voltage, sensor output is a proportion of that supply voltage. Ratiometricity error is the change in this proportion resulting from any change to the supply voltage. Usually expressed as a percent of full-scale output.

Response time The time required for the incremental change in the output to go from 10 to 90 percent of its final value when subjected to a specified step change in pressure.

Temperature error The maximum change in output at any pressure in the operating pressure range when the temperature is changed over a specified temperature range.

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CHAPTER 3
LINEAR AND ANGLE POSITION SENSORS

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3.1 INTRODUCTION

Position sensors of one form or another are an integral and necessary part of the modern automobile. Position sensors range in technology from the ubiquitous microswitch warning to the driver of a door ajar to linear variable differential transformers (LVDTs) used in sophisticated active suspension systems. Whether as monitors or as critical parts of safety systems, market and legislative pressures for longer warranties and lower emissions are opening avenues for a wide range of sensing technologies to find a place in the modern automobile.

The automotive systems designer must take into account many factors when choosing the appropriate technology for an application. Each sensor type has its own vocabulary, and it is important when making comparisons to understand how a figure of merit for one sensor relates to that of another. It is equally important to understand how the choice of output signal format, whether digital or analog, can affect the resolution of measurement and subsequently the performance or stability of an automotive system.

The purpose of this chapter is to give an overview of position sensor technologies currently used and available for use in automobiles and to compare their characteristics and suitability for particular applications. Consideration is given to the interfacing requirements of each type of sensor with an emphasis on the advantages and disadvantages of each method as they apply in the automotive environment. Where appropriate, descriptions of applications of the various sensor types in automobile applications are given. Other available technologies and technologies in development which have desirable characteristics for automotive applications are also discussed.

3.2 CLASSIFICATION OF SENSORS

Sensors may be classified in many different ways. From the perspective of a system designer, the basic questions are: What kind of information does the sensor provide and how is the sensor used? For the purposes of this discussion, a position sensor is defined as an electromechanical device that translates position information into electric signals. Sensors can be grouped into two basic categories.

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3.2.1 Incremental or Absolute

Position information can be presented in two different ways. Incremental position sensors measure position as the distance from an arbitrary index or zero. Alternatively, position information may be provided that gives an unambiguous or absolute measure of the distance from a well-defined index.

Incremental sensors usually rely on some method of pulse counting. One pulse in the sequence is designed to be wider or of opposite polarity than the others so that it may be used as a nominal zero. A typical optical angle encoder consists of a glass disk marked with a number of equally spaced radial opaque lines and transparent gaps. The disk is illuminated on one side and a light sensor and associated electronics on the other side detect the passage of dark lines and gaps and generate corresponding electric pulses. Dedicated electronics built into the sensor or a remote microcontroller can be used to count the pulses. A zero is established by detecting the wider pulse, known as *North Marker* in optical encoder terminology, and then resetting the pulse counter. The advantage of this data format is that few wires are required to carry the information. Typically, four or five wires would be required depending on the exact details of the format (see Sec. 3.3.2). The biggest disadvantage of incremental sensors is that at power-up the system has no position information and requires a mechanical indexing cycle to find the marker pulse. Another disadvantage is that the system is prone to the effects of noise, which may lead to erroneous counts.

In contrast, absolute position sensors produce an unambiguous output at power-up. Each position or angle has a unique value. The output may be a voltage or frequency or other analog of the input position. Potentiometers are often used in applications requiring this characteristic. Many absolute position sensors have binary digital outputs. The digital formats vary depending on the construction of the sensor. Some optical encoders use Gray code to avoid ambiguities at code transitions. Other sensors, such as resolvers, do not directly produce a digital output but are almost always used with an analog-to-digital converter that may output in parallel or serial form one of the common formats—for example, two's complement or offset binary.

3.2.2 Contact or Proximity

Position sensors are designed to detect the position of components of mechanical systems by either being directly coupled by some shaft or linkage, as in the case of potentiometers or optical encoders, or by some noncontact or proximity means. Environmental issues are often a key influence in the choice of sensor for a given application. High levels of vibration, particularly in small engine applications, may cause rapid wear of the conductive track of a throttle-position-measuring potentiometer. Dirt and dust usually exclude optical sensors from underhood applications due to rapid degradation of the optical path.

The most common form of proximity sensors are based on various methods of magnetic field detection. A device based on magnetic field sensing principles may be more easily isolated from the destructive effects of the harsh environment encountered in many automotive applications.

3.3 POSITION SENSOR TECHNOLOGIES

3.3.1 Microswitches

The simplest form of contact sensor is a switch. Contact position sensors may be as simple as the microswitches that operate anything from brake lights to courtesy lights in the automobile. Many applications of microswitches in position sensing are as limit switches, usually

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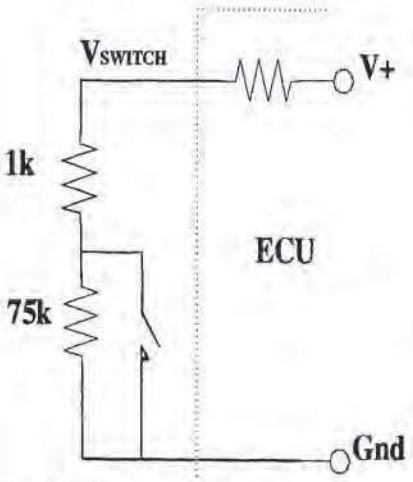

FIGURE 3.1 Diagnosable switch.

wired to limit or warn of the extent of travel of a mechanical component by disconnecting power to an electric motor or by operating an indicator lamp. In some cases, for safety reasons, it is desirable to be able to detect fault conditions that would make the switch inoperable. In some applications, it is possible to connect the switch as shown in Fig. 3.1. In this case, a diagnostic circuit measuring the voltage, V_{SWITCH}, can differentiate between the normal conditions of switch open or closed and can also determine if the switch is disconnected or if V_{SWITCH} is shorted to either power supply.

An undesirable characteristic of switches is that the contacts may bounce on closing. If it is important in the application that the first switching edge is detected, then a simple switch-debouncing logic that rejects noisy signals can be used. If a microcontroller is used to monitor the switch output, then debouncing can be accomplished by software means. This may be a better solution in applications subject to shock or heavy vibration, which may cause occasional false switching. In these cases, a microcontroller can be configured to poll the switch over some period of time and report switch closure only if a number of consecutive readings are the same.

3.3.2 Optical

Optical angle encoders for incremental shaft angular position measurement are constructed of a disk with a series of transparent and opaque equally spaced sectors. The disk can be made of glass for precision applications. Mylar film and metal disks offer high and medium resolutions, respectively, at low cost. The encoder disk is illuminated on one side and light sensors on the other side detect the passage of light and dark sectors as the disk is rotated. (Low-resolution versions such as the Hewlett-Packard HRPG series use an alternative reflective technology.) Most encoders have two sets of light sources and detectors offset by half the width of a sector. Figure 3.2 shows the relationship between the outputs of the light sensors as the encoder is rotated. This format is often referred to as "A quad B," since the signals are in quadrature. The passage of one pair of light and dark sectors over a detector is referred to variously as one cycle, one count, one line or 360 electrical degrees (°e). Encoder resolutions range from around 16 counts per revolution (CPR) for low-cost applications to over 6000 CPR for precision position control systems. Most encoders also include a third signal for use as an index or reference pulse. The index, or North marker as it is sometimes called, occurs once per revolution. The pulse width is usually equal to 90 °e.[1]

Four separate states, each of 90 °e, can be derived from the A and B outputs using integrated circuits available from a number of vendors. This allows a resolution of four times the number of lines on the encoder disk to be achieved. These ICs also determine the direction of rotation of the encoder by observing which output leads the other. By convention for clockwise rotation, the low-to-high transition of A leads the low-to-high transition of B. Control circuitry can be added to improve noise immunity by only allowing valid next states to be counted.

Incremental angle encoder accuracy specifications fall into two categories. The angular position accuracy is the difference between the actual shaft angle and the angle indicated by the encoder. This error is normally expressed in degrees or minutes of arc. The second category includes specifications for the symmetry and repeatability of individual cycles; these are usually

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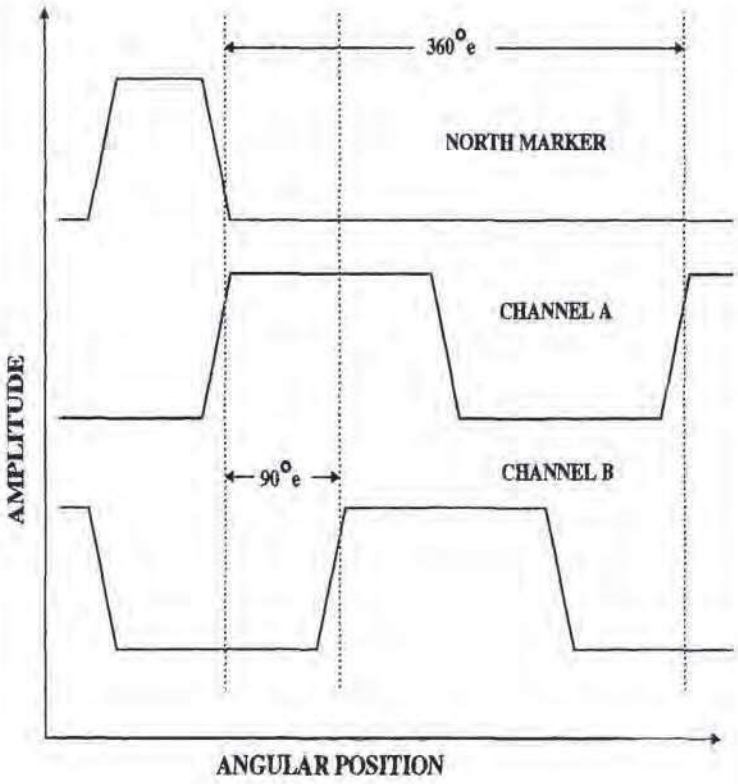

FIGURE 3.2 Encoder outputs.

expressed in electrical degrees. Typical characteristics are detailed in Fig. 3.3 and Table 3.1 Errors are caused by eccentricity and axial play of the code wheel and manufacturing defects in the lithography or etching of the code wheel. Modular encoders consisting of a light source and sensor head are available which use a collimated light source and an array of integrated photodiodes to minimize the effects of these error sources. Differential connection of the photodiodes ensures insensitivity to errors caused by light source variability due to environmental or other factors. A further source of error can occur if the encoder is rotated at high enough speeds that the rise and fall time of the digital outputs significantly affects the pulse width. The light sensor bandwidth usually determines the maximum rotational speed of the sensor. Typical bandwidths are below 100 kHz, which would limit the speed of a 100-CPR encoder to 1000 rpm.

Linear incremental optical encoders are available from many vendors. These allow direct measurement of linear motion. Modular sensor/emitter heads are available that can be used in these applications. The technology is basically the same as incremental angle encoders and the terminology used to describe specifications is the same as for angle encoders. Linear encoders are described in terms of their count density or resolution in counts per mm or mm

TABLE 3.1 Incremental Encoder Specifications

	Minimum	Typical	Maximum	Units
Position error		10	40	min of arc
Cycle error		3	10	°e
Pulse-width error		7	30	°e
Phase error		2	15	°e
State-width error		5	30	°e
Index pulse width	60	90	120	°e

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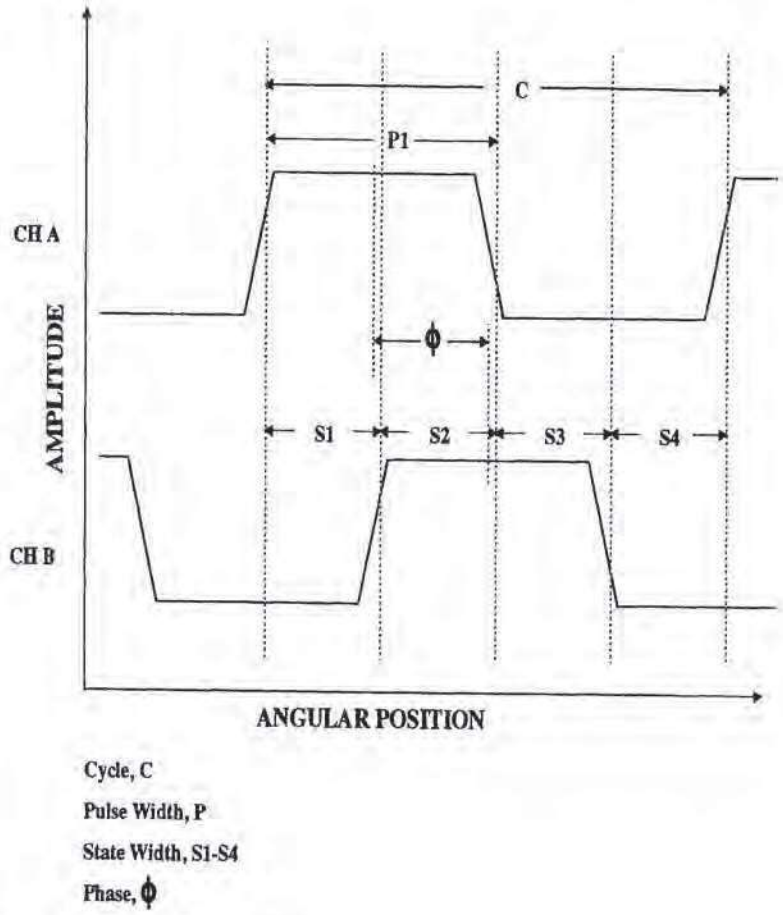

FIGURE 3.3 Encoder definitions.

per count. Line counts range up to approximately 8 per mm, allowing an ultimate linear resolution of around 30 μm.

If it is important to have an unambiguous measure of position as soon as power is applied to a system, then an absolute encoder must be used. Absolute optical encoders are manufactured with resolutions from one part in 2^6 to one part in 2^{16}. The data format can be binary, binary-coded decimal (BCD), or Gray code. An absolute angle encoder is divided into equal sectors which are arranged so that adjacent sectors contain consecutive digital words. The binary bits of each word form N concentric tracks on the encoder disk, where N is the digital word length. N sets of light sources and photodiodes detect the parallel word representing the input shaft angle.

Absolute optical encoders often use Gray code to eliminate code transition errors. In a natural binary sequence between zero and full scale on the disk, all the bits of the digital word change state together. Any misalignment of the code wheel and the light sensors, or sensor-to-sensor misalignment, will cause false codes to be generated. This could be disastrous for a position control system since a misread code could indicate an angle up to 180° away from the correct angle. Gray coding eliminates this problem. Gray code is a unit distance code; consecutive codes differ by only one binary bit. If a code transition is misread, the largest error will be one least significant bit of the digital word.

.3.3 Potentiometric

Potentiometers are widely used as position sensors in automotive applications such as throttle and accelerator pedal position measurement. The automotive industry increasingly

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demands low-cost mechanically and electrically rugged sensors to provide control or measurement of position in the modern automobile. This has resulted in the development of potentiometers that are capable of operational life far in excess of the life of the average car, and in some cases capable of continuous rotational speeds of above 1000 rpm for more than 1000 hours.[2]

Potentiometers can be constructed using a wire-wound track. The resolution of these potentiometers is determined by the number of turns of wire used to wind the track. The resolution of rotary wire-wound potentiometers is often quoted as the number of turns per degree and can be anywhere between 1 (1° per turn) and 7 (8.5 arcmin per turn). The track resistance is proportional to the number of turns used and can be in the range of 10 ohms to 100 kilohms, with a tolerance of approximately 5 percent. Wire-wound potentiometers have advantages where low-value variable resistors are required but do not excel in linearity, resolution, or rotational life which can be as low as 10^5 revolutions. Potentiometers for position-sensing applications are constructed using a resistive track of conductive material, usually a graphite and carbon black doped plastic, and a collector track molded on some supporting substrate. A drive shaft or pushrod draws precious metal multifingered wipers along the tracks. Wiper damping is usually included to make the potentiometer insensitive to vibration. Potentiometers of this type are manufactured with a range of resistance from around 500 ohms to 20 kilohms with a tolerance of 10 to 20 percent (Table 3.2). Potentiometers of this type are capable of excellent linearity and very high resolution.

TABLE 3.2 Potentiometer Specifications

Parameter	Minimum	Maximum
Electrical travel	90°, 10 mm	360, 3000
Nominal resistance	500 ohms	20 kilohms
Resistance tolerance	10%	20%
Resistance temperature coefficient (TC)		500 ppm/°C
TC of V_{out} in voltage divider mode		5 ppm/°C
Linearity error	0.01%	1%

Potentiometric sensors are used as voltage dividers. A reference voltage is applied across the resistive element and the wiper voltage is used as an absolute measure of the position of the actuator. Linear potentiometers are available in a wide range of lengths from 10 mm to 300 cm. Rotary potentiometers are usually restricted to 355° of useful range due to the dead band created by the track-end contacts. Some versions are available with true 360° operation. These use multiple wipers and dedicated electronics to eliminate the dead band.

All potentiometers are ratiometric sensors. That is, the wiper voltage at a given position is some fraction of the reference voltage applied across the resistive track. If the reference voltage is varied, the potentiometer output remains in the same ratio to the reference voltage. Sensor potentiometers, when properly terminated, maintain ratiometric operation over a wide range of temperatures with temperature coefficients typically less than 5 parts per million (ppm) per degree centigrade. Without special signal processing, ratiometricity is compromised at the end of the electrical travel of a potentiometer by the change in resistivity of the track as it joins the end contact and by any parasitic external resistance in series with the track. Figure 3.4 shows the effective limitations on the potentiometer at its endpoints.

Ratiometricity is a very desirable characteristic for a sensor that is used with comparators or analog-to-digital converters. For example, if the same reference voltage that powers the sensor is used as the reference for an analog-to-digital converter, then the measurement system will be insensitive to the absolute value of the reference voltage. A given shaft angle will always be reported as the same digital code. In most automotive control systems, analog-to-digital converters (usually on board a microcontroller) use the regulated 5-V engine controller

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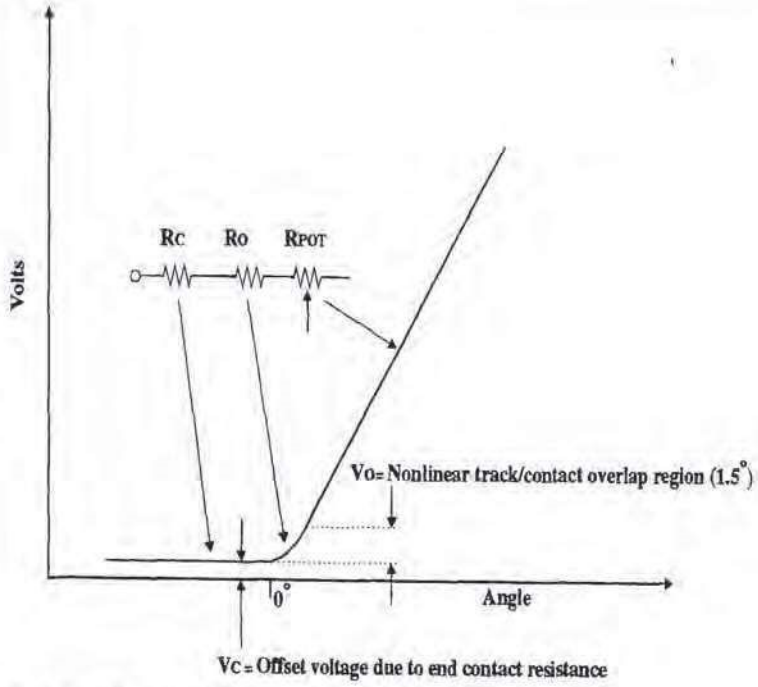

FIGURE 3.4 Potentiometer endpoint nonlinearity.

(ECU) power supply as reference to avoid the additional cost of a separate voltage reference chip. It is desirable that the same voltage, perhaps buffered to isolate the control module from accidental shorts, is used as reference by any ratiometric sensors in the automobile.

Potentiometers are subject to a number of sources of error, of which linearity is the most important. The linearity error is the difference between the actual transfer function of the potentiometer and the ideal transfer function (output voltage change versus mechanical travel) as a percentage of the applied reference voltage. Linearity specifications between 0.03 and 1 percent are available, with sensor cost inversely proportional to linearity. Microlinearity can be an important indicator of the suitability of the potentiometer for use in accurate control systems where large changes in the local gradient of the transfer function may cause instability. Ratiometricity, linearity, and offset errors can be caused by improperly loading the wiper of the potentiometer. The maximum error is at the center of travel of the wiper. If the load is a constant current, such as the input current of a buffer amplifier, a voltage will be developed across R_{EXT} that will cause an offset error at the extremes of travel of the wiper and an additional linearity error at the center of travel. Sensor potentiometers are usually specified with some maximum wiper current (100 nA, typically) to eliminate these errors. Plastic track potentiometers are capable of resolutions better than 0.001 percent of travel. This is primarily limited by the homogeneity of the resistive track material and hysteresis caused by limitations in the mechanical construction of the potentiometer related to bearings, wiper stiffness, and coefficient of friction of the track.

Plastic track sensor potentiometers are capable of operational life in excess of 10^7 revolutions for a rotary sensor or 10^7 strokes for a linear sensor. Unfortunately, no universal standards are available defining test conditions, and these may vary from vendor to vendor. Generally, two types of test are carried out. Dither testing simulates conditions which may exist in control applications or areas with high levels of vibration. The wiper is moved over a small proportion of the travel, say 1 or 2°, at a test frequency of 100 Hz. Information about contact resistance and local gradient changes in the potentiometer transfer function can be gathered rapidly using this technique. A change in gradient (ohms/percent of travel) relative to the mean gradient of the potentiometer can be equated to a change in loop gain in a con-

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trol system. Sensitive systems may become unstable at worn points in the potentiometer track due to relative gradient errors.

A second method of potentiometer reliability testing is to repeatedly move the wiper at around 10 Hz over a large proportion of the available range. An excursion from 0 to 50 percent of the available travel will result in the maximum change in linearity error over a large number of cycles, since only one-half of the track is subject to wear. The criteria for failure of a potentiometer will be very application-specific and may, for example, be a doubling in linearity error. It is important to work with the potentiometer vendors to understand how their specifications can be extrapolated to make a prediction of operational life.

3.3.4 Magnetic

By far the largest category of position sensors relies on electromagnetic induction principles. This group of sensors can be broken into subgroups depending on the details of the employment of the phenomenon. Other sensors in this category rely on materials with magnetoresistive or magnetostrictive properties. Electromagnetic sensors have a number of advantages over other technologies. In general, this class of sensors measures or responds to changes in the relative position of components in a magnetic circuit. The components are always separated by an air gap and are not subject to friction wear. In many cases, it is possible to construct rugged sensors that are insensitive to the harshest automotive environments.

Variable Reluctance. The reluctance of a magnetic circuit determines the magnetomotive force (amp turns) required to produce a flux of a given value.[3] Variable reluctance devices operate by sensing changes in the reluctance within a magnetic circuit. In most cases, the reluctance change is caused by a change in the length of an air gap. The change in reluctance causes a change in the magnetic flux which induces a voltage in an output signal coil. The voltage induced is typically a bipolar pulse shape whose amplitude is proportional to the rate of change of flux (Faraday's law).

$$V = \left(\frac{d\Phi}{dt} \right) \tag{3.1}$$

This sensor technology cannot be used at zero speed since, if the rate of change of flux is zero, then the output will be zero.

In automotive applications, variable reluctance sensors are used to detect the position and speed of rotating toothed or slotted wheels in crank-, cam-, and wheel-monitoring applications. An easily magnetized or "soft" magnetic core or bobbin wound with a sense coil is magnetized by a strong permanent magnet such as samarium cobalt (Sm_2Co_{17}). The sense end of the core is placed in close proximity to a toothed gear wheel. The flux change that occurs when a tooth edge passes the sensor causes a voltage to be induced in the coil. Remote signal-conditioning electronics associated with the ECU are used to amplify the signal and produce a signal that a microcontroller can interpret as a position increment. An alternative construction[4] uses a coaxial pole piece to improve the magnetic circuit. This construction is particularly suited to sensing holes or apertures in a sense wheel. Sensors that detect slots and are positioned in close proximity to the target with a small air gap work at low reluctance and are less likely to be disturbed by interfering fields than sensors configured to detect teeth at a low mark space ratio.

Variable reluctance sensors are prone to a number of sources of error. Vibrations or resonance sometimes exacerbated by the attractive forces between the sensor and the target can seriously degrade the signal-to-noise ratio of the device. The sensors' target is usually a rotating ferromagnetic wheel or gear. Eddy currents will be generated by the movement of the wheel in the magnetic field of the sensor. This may lead to false readings from the sensor. In some refinements of variable reluctance sensors, the holes or apertures in the wheel are filled with an electrically conductive nonmagnetic material to homogenize eddy currents.[4]

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Significant advantages of variable reluctance sensors in the automotive environment are their simple rugged construction and low cost. Additionally, they have a wide operating temperature range and require only two wires for operation. Variable reluctance sensors can also be used as variable inductance sensors by exciting the sense coil with alternating current and employing inductance-measuring means in the signal-conditioning electronics.

Hall Effect. Electric current is carried through the motion of electric charge. If a conductor is moved through a magnetic field with velocity v, the charges in the conductor will experience a force (Lorentz force) in a direction perpendicular to both the direction of motion and the magnetic field. This gives rise to an electric field of strength:

$$\mathbf{E} = v\mathbf{B} \tag{3.2}$$

The charges will move and a surface charge will develop on the conductor until an electrostatic field forms which counterbalances the electric field due to motion, $v\mathbf{B}$. A voltage due to the movement of charge can be detected with a voltmeter. The voltage is proportional to the field **B** and the velocity and length of the conductor. The result of this effect in thin films of material was first described by Hall over 100 years ago. When he passed current through a rectangle of gold foil in the presence of a magnetic field perpendicular to the plane of the foil, a voltage could be measured across the other axis of the foil.

Devices can be constructed using semiconductor materials which can utilize this effect to detect the strength of magnetic fields. Figure 3.5 illustrates the construction and operation of a silicon Hall effect device. A voltage is amplified across one axis of a thin block of high-resistivity n-type epitaxial material. In the presence of the field **B**, charges move in the direction of the arrow. A voltage directly proportional to **B**, the current density in the silicon and the Hall coefficient (scattering factor) can be measured at the point shown. The sensitivity is low and amplification is required to render a useful signal. For example, with a current of 10 mA flowing in an n-type silicon epitaxial layer 1 μm thick with a doping level of $10^{15}/cm^3$ and a field of 100 mT, a voltage difference of approximately 30 mV will be measured at 25 °C. Offsets caused by resistivity gradients, piezoelectric effects from packaging stress, and contact misalignment can amount to 10 mT or more. Layout techniques, such as cross-coupled structures to minimize the effects of resistivity gradients, can significantly improve offsets. Careful alignment of the Hall cell layout with crystal axes can mitigate piezoelectric effects. Silicon Hall effect devices are insensitive to magnetoresistive effects as the field strengths encountered in most applications have good linearity with errors of <0.1 percent for fields from 0 to >100 mT.[5]

The Hall voltage is strongly temperature dependent and, with constant current bias, is proportional to the magnetic field, the bias current, the carrier concentration, the scattering factor, and a constant G, which is a function of the geometry of the device.

$$VH = GI\mathbf{B}\left(\frac{r}{\text{qnt}}\right) \tag{3.3}$$

A typical silicon Hall device will exhibit a temperature coefficient of the Hall voltage of approximately 1000 ppm/°C under these bias conditions. The temperature dependence can be reduced with a current source, the temperature coefficient of which is designed to compensate for the Hall voltage TC. In this way, the sensitivity of a Hall effect device can be controlled within 1 or 2 percent over the range of temperatures normally encountered in automotive wheel position and speed applications. The temperature coefficient of the compensated device can be matched to the magnetic circuit if necessary; a typical requirement might be to provide a residual TC of 200 ppm/°C to compensate for the TC of a Sm_2Co_{17} magnet.

Hall effect devices can be constructed from semiconductor materials other than silicon—for example, gallium arsenide (GaAs). GaAs offers higher carrier mobility and some promise for higher temperature operation than silicon. Silicon has the advantage of low cost and the availability of integrated circuit processing techniques that can be used to integrate Hall effect devices with sophisticated signal conditioning. Dielectrically isolated silicon processes,

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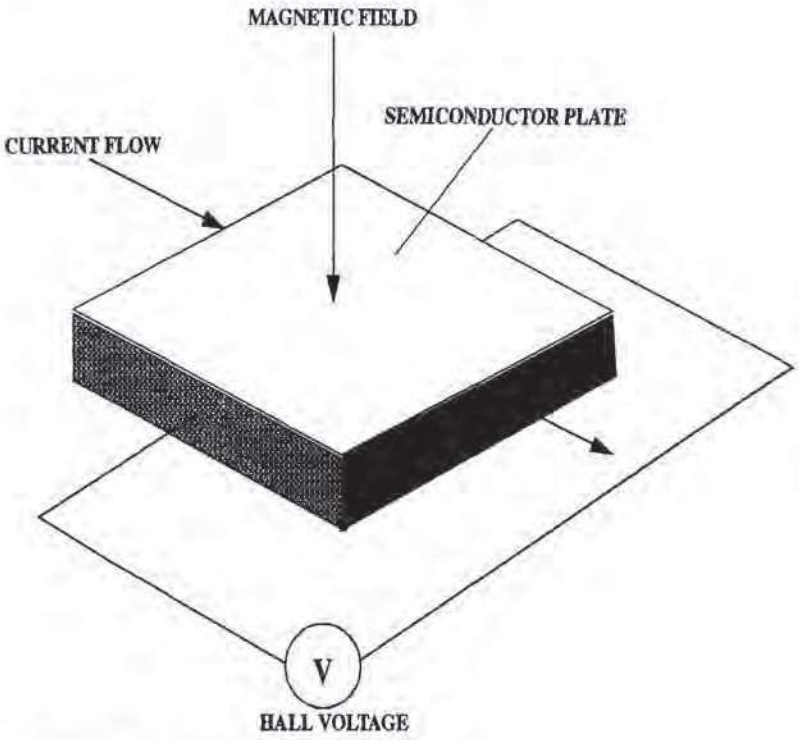

FIGURE 3.5 Hall effect device.

combining integrated circuit techniques with low leakage device isolation, can equal or better the high temperature performance of GaAs.

Hall effect integrated circuits are best categorized in terms of their output characteristics. Analog output devices are usually designed to provide a voltage output that is proportional to the applied magnetic field and also to the power supply voltage. An output ratiometric to the supply allows the device to be easily interfaced to analog-to-digital converters. Analog output devices can be used to construct noncontact absolute position transducers, where the Hall effect device measures a varying field which is designed to be proportional to an angle or linear position. Sensors such as these have no wearing parts other than bearings and can have significant reliability advantages over potentiometers in applications such as throttle-position measurement applications.

Digital output devices are used to construct limit switches or incremental position sensors. The Hall device can be designed to detect homopolar or bipolar fields. Important specifications for digital output devices are operate and release points and the differential between them. The operate point is the maximum field that must be applied to turn the output ON; where ON may be a current-sourcing or current-sinking function. The release point is the minimum field that will guarantee that the sensor is OFF. The differential is the difference between the actual operate and release points. The differential is built in to provide some hysteresis or noise margin to prevent false triggering, particularly at low rates of change of field. The differential may be considerably smaller than the difference between the specified operate and release points. Unipolar devices are specified with operate and release points of the same sign. Bipolar devices are specified with a positive operate point and a negative release point. A caution here is that some devices specified as bipolar do not always require a change of phase of field to operate and release; truly bipolar devices always do.

High-performance Hall effect ICs employ various circuit techniques to improve sensitivity.[6,7] Differential Hall sensors designed for use as gear wheel position sensors use two Hall cells ideally separated by half the gear tooth pitch. This kind of sensor is capable of detecting small changes in unipolar fields. Differential sensors produce an output pulse whose width

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depends on the rate at which the gear tooth passes the sensor. At very low and very high speeds a very small mark space ratio output results. At high speeds, the timing of the output will be delayed from the mechanical event by a significant proportion of the tooth pitch. A second method is to use a filter circuit to determine the average value of an alternating field and then detect variations from the average value. This method also eliminates any offset that the sensor may have. This method more accurately tracks the mechanical stimulus. A disadvantage is that the filtering function imposes a lower limit on the speed that can be tracked. The devices detailed in Refs. 6 and 7 have lower limits of around 4 Hz. An additional limitation is that the sensor may fail to operate with a high mark space ratio stimulus since the average value of the input will be close to the value of the longest part of the cycle.

A typical Hall sensor application is shown in Fig. 3.6. The Hall device is assembled into a probe with a biasing magnet. The Hall device orientation will depend on its mode of operation, whether unipolar or bipolar. In all cases, the device is sensitive to fields perpendicular to the plane of the silicon surface. Figure 3.6 also compares output waveforms of the Hall sensor configurations discussed earlier as they would appear in this application.

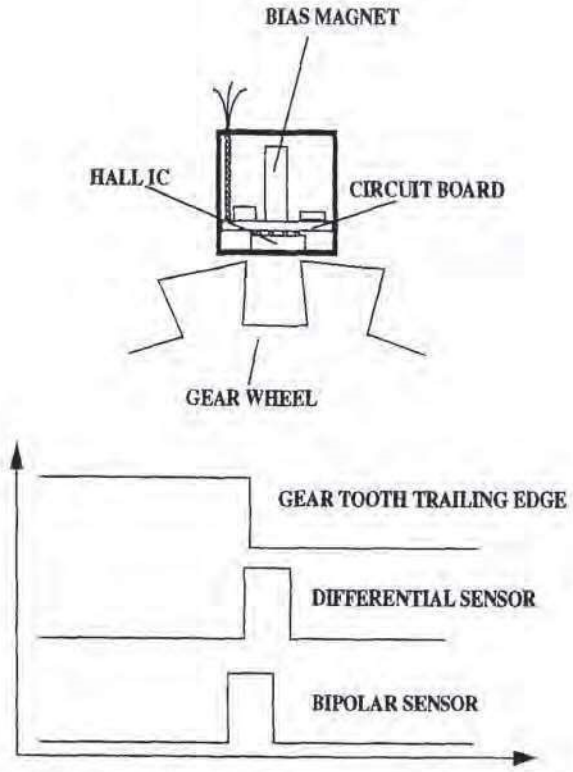

FIGURE 3.6 Hall probe gear position sensor.

Inductive Angle Transducers. Synchro resolvers, or simply resolvers, are absolute angle transducers. Due mainly to their construction, modern brushless resolvers offer the most rugged, reliable, and highest-resolution solution to angle sensing. Resolvers are often considered a high-cost transducer for automotive applications due to the high labor content in the production of most variants. Some designs[8] provide a cost-effective solution by employing sensing and output windings that can be produced on conventional armature-winding machines. Resolvers can be obtained either fully enclosed or as "pancake" devices, with the stator and rotor supplied separated to facilitate over shaft mounting. Resolvers are often referred to by their size. This is the diameter of the case of the device in inches, rounded up to the nearest 10th, and multiplied by 10. For example, a size 11 resolver will be a fraction less than 1.1 in in diameter. Resolver accuracies are specified in arc min. Typical values for

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accuracy lie in the range 7 arcmin, with more or less accurate versions available from some vendors.[9]

Resolvers are basically rotating transformers. The construction of a typical device and the output waveforms for a 360° rotation are shown in Fig. 3.7. An alternating voltage connected to the reference input provides primary excitation. The range of frequencies used can be 400 to 20 kHz depending on the construction of the resolver; most resolvers are optimized for the 2 to 5 kHz frequency range. The reference signal is coupled to the rotor via a transformer mounted at one end of the rotor shaft. A second rotor winding couples to two orthogonally oriented stator windings. The stator coils are wound so that as the rotor shaft rotates, the amplitudes of the outputs of the stator windings vary as sine and cosine of the shaft angle relative to some zero.

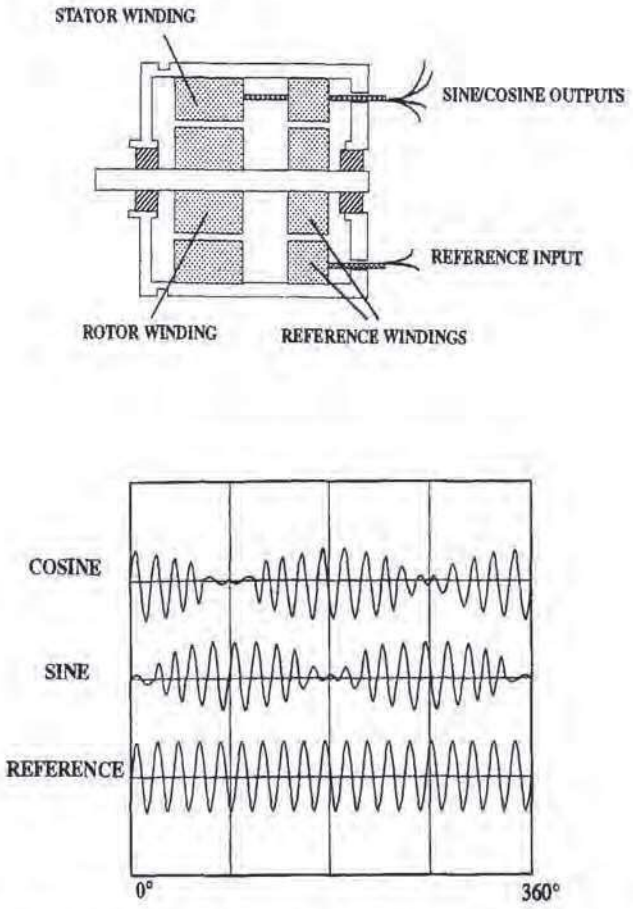

FIGURE 3.7 Resolver construction and output format.

By far, the most economical way of decoding the output of a resolver is to use an IC resolver-to-digital converter (R to D). A functional block diagram of a typical converter is shown in Fig. 3.8. The sine and cosine amplitude-modulated input signals from the resolver representing a shaft angle θ are multiplied by the cosine and sine, respectively, of the current value ϕ of the up/down counter. The resulting signals are subtracted giving:

$$VE = A \sin(\omega t) \sin(\theta - \phi) \tag{3.4}$$

where $A \sin(\omega t)$ represents the reference carrier.

This signal is synchronously demodulated and an integrator and voltage-controlled oscillator form a closed loop with the counter/multiplier, which seeks to null $\sin(\theta - \phi)$. When the

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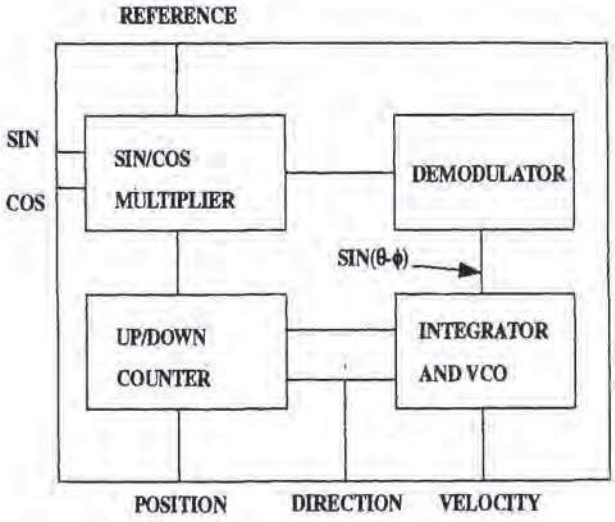

FIGURE 3.8 Tracking resolver-to-digital converter.

null is achieved, the counter value represents the resolver shaft angle within the rated accuracy of the converter. IC R-to-D converters are available that provide parallel or serial digital outputs with resolutions of from 10 to 16 bits and accuracies from 2 to 30 arcmin. Versions are available[10] that emulate standard optical encoder outputs for applications where absolute position measurement is not required but the environment is too harsh for an optical encoder. The system described is a type 2 servo loop which is characterized by zero position and velocity error (not including the limitations of the amplifiers in the IC). R-to-D converters of this type also provide a signal proportional to the angular speed of the resolver from zero to some upper limit, typically 1000 s of rpm, depending on the converter characteristics.

Inductive potential dividers are another class of transducers that are available in many variants.[11,12] A good example is the *rotary variable transformer* or ROVAT.[12] This device comprises a single coil wound on a circular ferromagnetic stator with a number of teeth wound as alternate polarity poles. The stator is excited with an AC signal of around 20 kHz. A rotor with a semicircular conductive screen on its inside surface encircles the stator. The screen reduces the flux linkage between the rotor and stator and the inductance of the screened portion of the stator is reduced, reducing the voltage drop across this portion of the stator. The voltage measured at a central tap on the stator is linearly proportional to the angle of the rotor. Further taps at 90° and 270° from the nominal zero allow a waveform to be measured with amplitude in quadrature with the signal measured at the center point. This allows a 360° absolute angle transducer to be realized, using decoding techniques similar to those which will be described later for the LVDT.

Inductive Linear Displacement Sensors. Shading ring or short-circuit ring sensors are absolute displacement sensors consisting of an E-shaped core with a winding on the central leg of the E. The winding is excited with high-frequency alternating current. An electrically conductive ring of Al or Cu is allowed to slide, maintaining an air gap along the central leg. The ring is attached to the mechanical component, whose position is to be measured. The ring is equivalent to a short-circuited secondary turn in a transformer. The ring has a shading effect, preventing any flux coupling between the legs of the core from its position along the central leg of the core to the open ends of the core (Fig. 3.9).[13] An inductance change can be measured at the terminals of the excitation coil. These sensors are usually used in a potential divider configuration with a reference inductance of similar construction to the main sensor connected in series with the main sensor. A reference alternating voltage is applied across the series-connected reference and sensor inductances, forming an inductive potential divider. The output is then proportional to the ratio of the inductances. This renders the sensor insensitive to tem-

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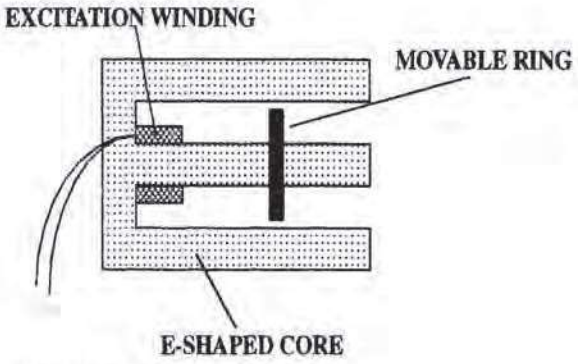

FIGURE 3.9 SCR sensor construction.

perature variations and allows easy adjustment of offsets. Signal-processing electronics can be used to rectify and filter the output and transmit the result to a remote control unit. An alternative construction is to replace the movable ring with an angled channel which can move, relative to the E-shaped core, in a plane perpendicular to the core. Again, the inductance of the sensor is proportional to the linear movement of the angled channel.

Another form of absolute linear displacement sensor is the linear variable differential transformer or LVDT.[14] LVDTs are rugged and reliable and capable of working in harsh environments. Suitable automotive applications include mounting inside hydraulic cylinders in suspension control systems.

LVDTs are constructed from a primary excitation coil positioned centrally on a cylindrical hollow former. Two identical secondary coils are positioned on either side of the primary. The coils have a common core which is free to move within the cylindrical former (Fig. 3.10). The secondaries are normally connected in series, with opposing phases such that with the core centrally positioned and coupling equally to each secondary, the voltage at the node common to both coils will be zero. With this connection, as the core is moved from one extreme of travel through the center to the other extreme, the output signal will vary from a maximum value in phase with the excitation through zero to a maximum value in antiphase with the excitation.

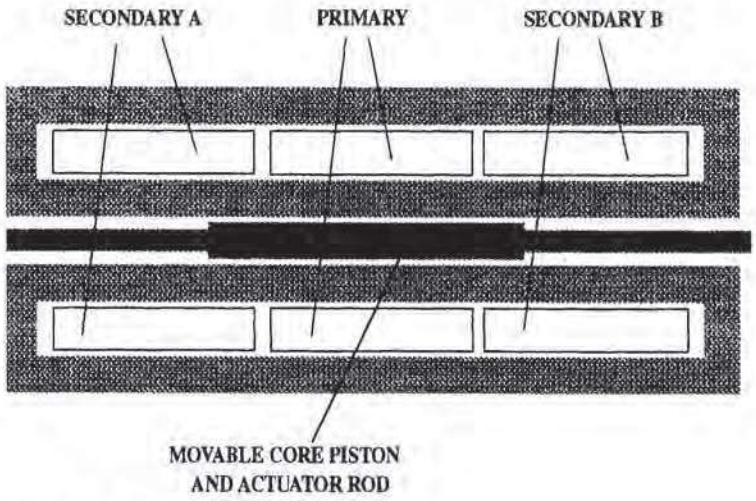

FIGURE 3.10 LVDT construction.

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LVDTs are designed to give a linear output within some tolerance, typically ±0.25 percent, over a specified proportion of the available stroke length. The distribution of turns on the secondary coils is carefully arranged to maximize linearity over the widest possible range. LVDTs are available that maintain good linearity with stroke lengths from ±0.05 to ±10 in.

LVDTs operate with effective transformer ratios of between 10:1 to 2:1. The range of primary excitation frequencies can be from 20 Hz to 20 kHz, depending on the construction of the device. Most LVDTs are optimized for the 2- to 5-kHz frequency range. The output signal from an LVDT can be decoded in several different ways and a number of analog and digital integrated circuit solutions exist for this purpose.[15] An example of a typical connection scheme using an LVDT-to-digital converter is shown in Fig. 3.11. In this example, it is assumed that the sum of the voltages across the series-connected secondaries $V_A + V_B$ is a constant over the range of displacements of interest. The majority of LVDTs in production meet this criterion; for those that do not, an additional nonlinearity will result. The IC decodes the function $(V_A - V_B)/(V_A + V_B)$ over the range $[(V_A - V_B)] \leq (V_A + V_B)/2$ into a 13-bit digital word that can be accessed via a three-wire serial interface. Additional bits indicate null and over or under range for signals outside the linear range. The ratiometric decoding scheme described here is insensitive to primary-to-secondary phase shifts, temperature, and any residual null voltage that the transducer may have due to stray capacitive coupling.

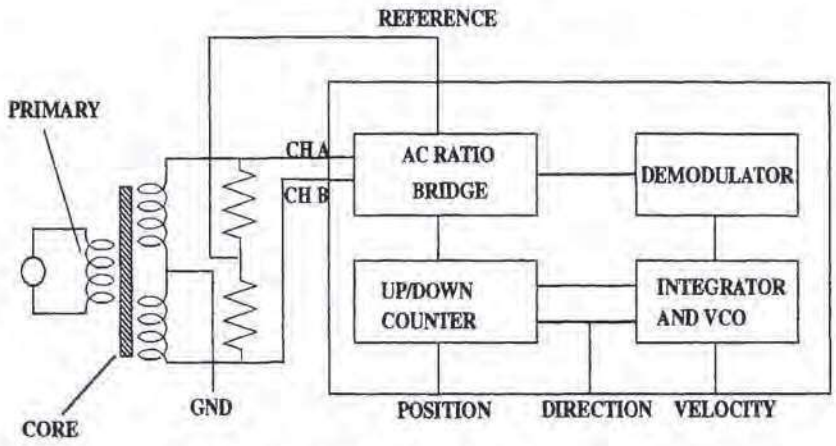

FIGURE 3.11 Tracking LVDT-to-digital converter.

Analog methods of decoding utilize the same basic algorithm as the converter already described. An analog decoder senses the secondary output voltages and evaluates the ratiometric function introduced earlier. The decoder output is filtered and amplified to produce an output voltage proportional to the position of the movable core.

Magnetoresistive. An interesting group of sensors utilize the property of some FeNi alloys such that their resistivity is strongly affected by the presence of a magnetic field. The magnetoresistive effects of one of the useful alloys, Permalloy, which is 81 percent nickel and 19 percent iron, enables sensitive magnetic field sensors with full-scale fields of 5 mT to be built. The variation in resistance is around 2.5 percent for a field of this magnitude. The resistance decreases with increasing field strength; the relationship between field strength and resistance is very nonlinear, approximating a cosine-squared function. Using thin films of Permalloy deposited on a silicon substrate allows signal-conditioning electronics to be integrated with the sensor. Despite the nonlinearity of the phenomenon, accurate linear sensors can be constructed by using the sensor in a bridge arrangement together with flux nulling means, such as a servo-driven coil surrounding the sensor, to effectively operate the sensor at constant resistance. An alternative construction uses opposing "barber pole" thin-film elements.[16] An element is composed of a rectangular thin film of Permalloy overlaid with a series of shorting

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stripes of aluminum at 45° to the long axis. Two series-connected elements, which are mirror images of each other (reflected about the long axis), form a potential divider. Magnetoresistive sensors generally exhibit high sensitivity, but this leaves them prone to interference from unwanted fields and, therefore, they are unsuitable for some applications.

Magnetostrictive. Magnetostriction is a property of materials that respond to a change of magnetic flux by developing an elastic deformation of their crystal structure. Magnetostrictive linear displacement sensors utilize this phenomenon by launching a compression wave down a cylindrical waveguide using electromagnetic means, usually a current pulse. The waveguide passes through a movable permanent magnet ring at some distance from a receiver site. The compression wave generated at the magnet position travels to the receiver site at approximately 2800 m/s where it causes a change of flux and generates a voltage pulse in a sense coil. The time of flight of the pulse can be measured to determine the distance of the movable ring magnet down the wire. Transducers with stroke lengths in excess of 7.5 m are available that use this technique.

3.3.5 Other Technologies

A number of other technologies can be applied to position-sensing problems, limited only by engineering ingenuity. Some, like capacitive-sensing techniques, are not tolerant of the automotive environment due to sensitivity to humidity, vibration, or temperature or pressure extremes. Others, like resolvers of traditional construction, are sufficiently rugged but prohibitively expensive unless low-cost manufacturing techniques can be found. Occasionally, a nonobvious method finds a niche. An example is a fuel-level sensor disclosed by workers at Bosch,[17] which, in principle, could be applied as a position sensor. The device operates by exciting a metal rod with acoustic waves such that it resonates. One end of the rod is immersed in the fuel. The resonant frequency is a function of the depth of immersion and the fuel level can be determined by suitable electronics.

A significant influence in the selection of technologies for automotive use is the mandatory inclusion of safety systems. Microwave or laser-ranging techniques can be applied to anticollision systems to anticipate obstacles at nighttime or in poor-visibility driving conditions. These will be a ubiquitous component of automobiles in years to come.

3.4 INTERFACING SENSORS TO CONTROL SYSTEMS

All sensors, whether they have digital or analog outputs, provide measurement of real-world phenomena that are then interpreted by another system to either indicate a value, a warning, or close a control loop. It is vitally important that the integrity of the data is maintained by the proper choice of interface.

Cost and reliability in automotive systems are primary drivers in the choice of interface. For a given performance, the sensor that requires the fewer connections will always be selected. In some cases, such as LVDTs where the basic sensor requires 5 or 6 wires, it may be advantageous to locate the signal-conditioning electronics with the sensor and communicate the processed data to a remote controller via a simple serial interface. Interfacing incremental or serial binary data to a microcontroller is straightforward. In the case of incremental data, typically the mechanical system being monitored is moved until some limit or index is detected. Knowledge of the absolute position of the mechanical component is then known. A counter or register can be set to an initial nonzero value or reset to zero. As the motion is detected, pulses from the incremental sensor can be counted and stored as a measure of position. The indexing cycle must be performed each time power is applied. Binary serial data can be read into a register and used directly with no further processing.

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Analog-to-digital converters (ADCs) require some special considerations to optimize performance. Not least of these is grounding. In most applications, chassis ground returns cannot be used. Modern automobiles may have voltage drops of 1 V or more between the chassis at the ECU and the sensor site, due to return currents from electric equipment. This voltage is likely to be noisy with many transients and will certainly upset all but the crudest sensors.

Previous sections have discussed the advantages of ratiometric sensors that can use the same reference as the converter. The advantage is that a least-significant bit of the ADC is always a fixed percentage of the sensor span. This eliminates gain, offset, and temperature errors that may occur if separate references are used. Resolution and gain accuracy of a system can be further optimized by making certain that the span of the sensor output uses all of the available input span of the converter. Many ADCs include on board a microcontroller and use switch capacitor techniques to acquire the analog input values. These present a transient load to the sensor once or twice per conversion cycle. Some sensor outputs, particularly sensors with buffer amplifiers, require isolation from this transient to achieve rated accuracy. A simple technique is to use a simple RC filter on the output of the sensor. This limits the transient current that the sensor output sees and shunts the ADC input with a capacitor.

GLOSSARY

Absolute output sensor The sensor output is an unambiguous measure of position and is valid when power is applied.

Arcminute An angular measure. There are 60 arcminutes in 1 degree of arc.

Incremental sensor The sensor indicates changes in position. An additional position reference, such as a limit switch, is often used with this type of sensor.

Linearity error The amount by which the sensor output differs from an ideal characteristic. Usually expressed in percent.

Ratiometric output sensor An input stimulus causes the output to be a fraction of a reference voltage.

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CHAPTER 4
FLOW SENSORS

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4.1 INTRODUCTION

Measurement of flow rate is important to optimize the performance of several key engine control subsystems. Mass air flow sensors are replacing the indirect calculation of intake mass air flow for improved performance, driveability, and economy. New requirements for on-board diagnostics are opening new applications for flow sensing in the automobile.

If the parameter to be measured is a gaseous mass flow as opposed to a volume flow, this further focuses the sensing technology selection since only a few technologies inherently measure mass flow. For liquid flow, either a mass flow or volumetric flow approach may be used since the density of a liquid changes only a small amount with atmospheric pressure and temperature.

This chapter is intended to give the reader an understanding of where and why flow sensors are being specified for use in engine control systems and an understanding of the trade-offs among alternative technologies in particular applications.

4.2 AUTOMOTIVE APPLICATIONS OF FLOW SENSORS

4.2.1 Intake Air Mass Flow

Electronic fuel injection has almost universally replaced the carburetor in the auto engine. This is because it provides better performance and is the only way to meet government mandated emissions standards. To do fuel injection, the mass flow rate of air going into the engine must be determined. There are two competing approaches to determining the mass air flow rate. The first, *speed density*, calculates the mass flow rate by measuring engine speed (RPM), intake air temperature (T_a) and intake manifold pressure (P). The per-cylinder nominal displacement (V) is known, as is the gas constant of air (R_a). The engine's volumetric efficiency (η) may be modeled as a function of speed. Then, the mass flow rate ($\dot{m}_a$) is calculated as follows:

$$\dot{m}_a = \frac{(\mathrm{RPM}\, V \eta\, P)}{(R_a T_a)} \tag{4.1}$$

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By using a mass flow sensor, this calculation is eliminated and $\dot{m}_a$ is measured directly. The advantages of using a direct measurement include better accuracy under dynamic conditions because the manifold pressure changes more slowly than the mass flow rate. Also, no assumptions are made about engine displacement or volumetric efficiency, both of which affect the speed density calculation. Volumetric efficiency can change as the intake system becomes contaminated. Mass air flow sensors are presently being used on roughly 20 percent of the cars sold in the United States. They are not more widely used because they cost more than the pressure sensor needed to do the speed-density calculation. The largest drawback to using a mass flow sensor is that a wide dynamic range sensor is needed since the mass flow rate can change over a 100-to-1 range from idle to full throttle, whereas the manifold pressure only changes over a 5-to-1 range. Other important factors in sensor selection include resistance to contamination and particulate damage, accuracy, ability to measure reverse flow, and sensitivity to upstream and downstream ducting.

Fuel is injected to each cylinder on a sequential basis for optimum performance. This requires using the crankshaft sensor and camshaft sensor outputs to time the injection of fuel into the intake manifold at the proper point on the intake stroke. The fuel injector is fed with a constant pressure and is pulse-width modulated to control the amount of fuel injected. The calculation of the mass rate ($\dot{m}_f$) of fuel injected follows:

$$\dot{m}_f = \dot{m}_a \lambda \tag{4.2}$$

where $\dot{m}_a$ = mass air flow rate
λ = stoichiometric air/fuel ratio

4.2.2 Potential or Future Applications of Flow Sensors

Fuel Flow for Gas Mileage Measurement. Driver information systems that predict range and gas mileage need to know the amount of fuel flow. As seen from the preceding discussion of mass air flow measurement, the fuel flow is calculated from the air flow so that this data is already in the engine control computer. By simply summing the injector "on" time over a revolution or multiple revolutions, the fuel flow is known.

Alternatively, the fuel flow can be measured by taking the difference between the fuel coming into the fuel rail and that being returned. This approach could be subject to substantial error, however, due to the fact that these flows are purposely much larger than the net flow into the engine so that the fuel rail will be maintained at a constant pressure. Future fuel-handling systems may simplify the measurement by eliminating the return line and simply modulating the fuel pressure pump to maintain constant pressure. Then, the measured flow would be simply that flow going into the engine.

Exhaust Gas Recirculation Flow. Exhaust gas recirculation (EGR) is performed to reduce the emission of nitrous oxides (NO_x) by cooling the combustion process. If the EGR valve begins to clog or only partially opens, its flow will be reduced and emissions will increase. In the near future, OBDII legislation will require cars to have on-board diagnostics capable of determining when an emissions-related failure (such as that just described) occurs. Measurement of the flow is one way to diagnose a faulty EGR valve. Another way would be the use of an NO_x sensor to measure the emissions. However, no low-cost NO_x sensors have yet been developed.

Secondary Air Pump Flow. The secondary air pump is used to reduce the emissions of carbon monoxide (CO) and hydrocarbons (HC). Measurement of its flow rate is an approach to verifying that it is operating properly and doing its part to reduce emissions. Another way, of course, would be to directly measure the emissions of HC and CO in the exhaust. To date, however, there is no low-cost real-time means to do that. A way to verify air pump operation

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without using any additional sensors is to command the air pump full-on when the fuel injection is slightly rich of stoichiometry. The oxygen sensor output should switch from rich to lean if the air pump is operating properly.

Fuel Flow for Fuel-Air Ratio Feedback Control. Present engine control systems treat the fuel flow as a dependent variable, measuring the intake air flow and then operating the fuel injectors to meter the proper amount of fuel into the engine. This tacitly assumes that each of the injectors is precisely calibrated so that a given "on" time provides a given amount of fuel. Fuel injectors typically use a needle valve in an orifice to meter the fuel. The orifice area is proportional to the square of the diameter so that the fuel flow error will be proportional to two times the diameter tolerance. By measuring the fuel flow, the accuracy of fuel injection could be improved. Table 4.1 summarizes the performance requirements by application.

TABLE 4.1

Application	Measurement type	Range, kg/h	Accuracy, %
Intake air	Mass	10–1000	±4
Fuel flow	Mass/vol.	1–66	±10
EGR flow	Mass	30–100	±10
Air pump flow	Vol.	50	±20
Fuel flow	Mass/vol.	1–66	±4

4.3 BASIC CLASSIFICATION OF FLOW SENSORS

4.3.1 Energy Additive or Energy Extractive

Flowing fluid possesses energy, both potential and kinetic. One approach to flow measurement extracts energy from the flow. Alternately, energy may be added to the flow and its effect observed. The energy-additive approach typically is nonintrusive, so the act of measuring doesn't affect the flow. As might be expected, flowmeter selection involves a number of factors, as will be discussed later.

4.3.2 Measurement of Mass Flow or Volume Flow

Intake air measurement requires that the mass of air flowing into the engine be measured. This favors a mass-flow approach, since, otherwise, pressure and air temperature must be measured to calculate the mass flow from the volume flow. The mass flow rate ($\dot{m}_a$) is calculated as follows:

$$\dot{m}_a = \dot{V}_a \rho \tag{4.3}$$

where ρ = air density
V_a = volumetric flow rate

The density, in turn, is calculated as follows:

$$\rho = \frac{P}{ZR_aT_a} \tag{4.4}$$

where P = air pressure
Z = compressibility factor
R_a = gas constant for air
T_a = air temperature

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4.4 APPLICABLE FLOW MEASUREMENT TECHNOLOGIES

4.4.1 Gaseous Flow

Vane. The vane simply consists of a vane or paddle which is located in the flow duct and is restrained by a spring so that it blocks the duct with no flow. The deflection of the vane is thus proportional to flow. This deflection is read out by a potentiometer. The largest drawback of a vane sensor is that it increases the pressure drop in the intake tract, reducing the volumetric efficiency of the engine. This approach was used in the earliest engine control systems and is being replaced by technologies such as hot-wire air flow sensors which offer much lower pressure drop.

Thermal. This is the favored approach and is used in all engines currently being manufactured that employ direct measurement of the intake air mass. Depending on design details, it provides a nearly direct measurement of the mass flow and thus simplifies the engine control strategy. A variety of designs exists, from the straightforward hot-wire air flow sensor to more complex schemes. The basic idea is to heat a fine wire, and then as the gas flows past the wire, convection removes heat. The amount of heat removed can be measured with an electronic circuit and is proportional to mass air flow rate as the following equation shows:

$$\Delta P \cong \Delta T\,[C_t + (2\pi d C_v \dot{m}_a)^{1/2}]^* \tag{4.5}$$

where ΔP = change in electric power due to a given flow rate
ΔT = temperature difference between air and sensor
C_t = thermal conductivity of air
d = diameter of hot wire
C_v = thermal capacity of air
$\dot{m}_a$ = mass flow rate of air

Note that the first term of the equation isn't proportional to flow rate. Either this needs to be modeled and removed or the change in ambient air temperature needs to be minimized to accurately measure mass flow rate. A hot-wire air flow sensor and its control circuit is shown in Fig. 4.1. Control circuits typically either supply constant power to the heated element or

* From Joseph P. DeCarlo, *Fundamentals of Flow Measurement*, Instrument Society of America, 1984, pp. 173 and 176.

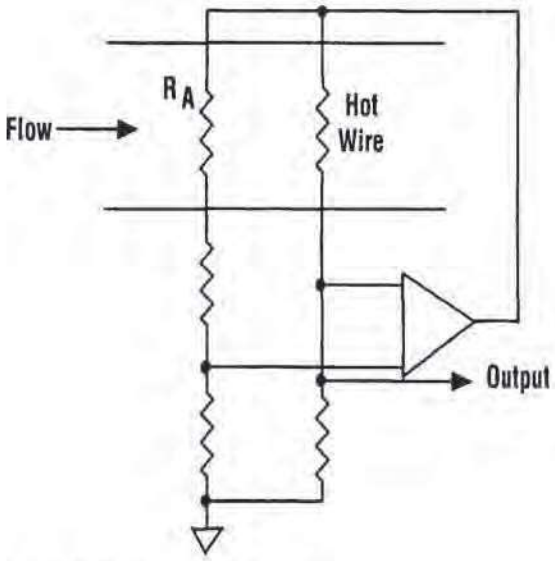

FIGURE 4.1 Hot-wire air flow sensor.

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operate it at a constant temperature delta above the ambient temperature. The latter is shown in Fig. 4.2 and is preferred because it simplifies temperature compensation.

One of the problems with the hot-wire sensor is that fine dust particles may pass through the air filter and, under full-throttle conditions, can impact the hot wire with sufficient force to break it. Particulate build-up is also a source of error and has been alleviated by placing the heated element in a bypass channel or by incorporating a burn-off cycle at power-on. Most of the development in hot-wire sensors has been to ruggedize them to withstand the automotive environment and to desensitize them to upstream and downstream flow anomalies. Figure 4.2 is an example of a bypass design for a hot-element mass air flow sensor. It uses a platinum wire wound on a ceramic mandrel and coated with glass as the sensing element. It is located in a bypass channel away from the main flow to reduce the likelihood of particulate contamination. The bypass exits into the main channel through slots which are intended to desensitize it to backflows and backfires.

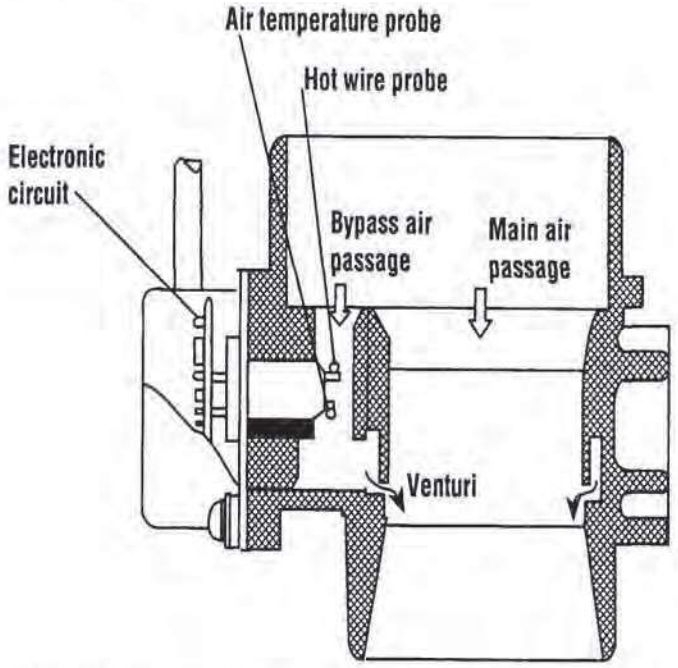

FIGURE 4.2 Bypass hot-wire air flow sensor. *(U.S. Patent 4,264,961)*

Backflow can occur in engines with four or fewer cylinders at low speed. It is most desirable for the sensor to measure the backflow, but most either don't measure it at all or rectify it, which makes the measured flow appear larger than it really is. This error is compensated by measuring the backflow on an engine and then using software to remove the nominal error. One of the issues with bypass designs is that upstream ducting of the air may affect measurement accuracy. A bend just ahead of the sensor will cause the air to move toward the outside of the bend and, depending on where the bypass is located, it may read either too low or too high. This effect is minimized by placing a screen or honeycomb in the sensor to straighten the flow.

Micromachined air flow sensors have been available commercially for several years and efforts are underway to adapt them to automotive applications. Their primary advantages include the low cost of the sensing element due to batch fabrication; excellent performance over temperature due to the close proximity of the heated and reference elements; the ability to measure reverse flows; low operating power due to the small size of the heated element; and fast response, again due to the small size of the heated element. Because of the use of integrated circuit manufacturing techniques, it is no more difficult to include additional resistors on the sensor chip than to simply replicate a hot wire. A calorimetric flow sensor may be constructed by separating the heater and sensor functions as shown in Fig. 4.3. The advantage

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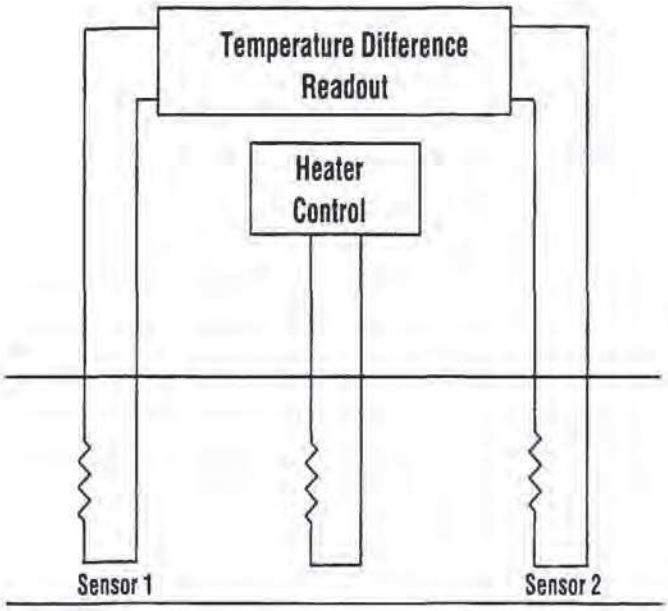

FIGURE 4.3 Calorimetric flow sensor.

of a calorimetric flow sensor is that it does measure the mass flow rate as the following equation shows:

$$\Delta P = \dot{m}_a C_p \Delta T^* \tag{4.6}$$

where ΔP = change in power due to a given mass flow rate
$\dot{m}_a$ = mass air flow rate
C_p = thermal capacity of air
ΔT = temperature difference between air and sensor

One of the issues with microstructure sensors is protection from damage due to particle impact and preventing build-up of contamination. This requires clever packaging.

Table 4.2 compares the main types of thermal mass air flow sensors.

Differential Pressure. A simple way to measure volumetric flow is to place an obstruction in a flow channel and measure the differential pressure drop across it. The flow is proportional to the square root of the differential pressure. This only works well for narrow flow ranges because to operate over a given flow range, the pressure sensor must operate over the square of that range. For the automotive intake flow range of 100 to 1, a pressure sensor with a range of 10,000 to 1 is required, which is not achievable except at high cost. An important advantage of this approach is that it is resistant to contamination, since the pressure sensor merely needs

* From "Fundamentals of Flow Measurement," Joseph P. Decarlo, Instrument Society of America, 1984, pp. 173 and 176.

TABLE 4.2

Type	Effect of contamination	Meas. rev. flow	Affected by ducting	Power used
Hot Wire	High*	Rectifies	Low	Medium
Hot RTD Bypass	Low	Ignores	High	High
Micro RTD	Low	Yes	Low	Low

* Burn-off cycle used to alleviate.

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to sense the pressure difference across the flow restriction (in the case of an orifice plate or venturi). The differential pressure approach could be suitable for some low-accuracy or low dynamic range applications such as EGR valve flow. Venturis (Fig. 4.4), flow restrictions (Fig. 4.5), and pitot tubes (Fig. 4.6) all operate on the same principle.

4.4.2 Liquid Flow

Differential Pressure. The preceding discussion on differential pressure sensing applies equally to liquid flows.

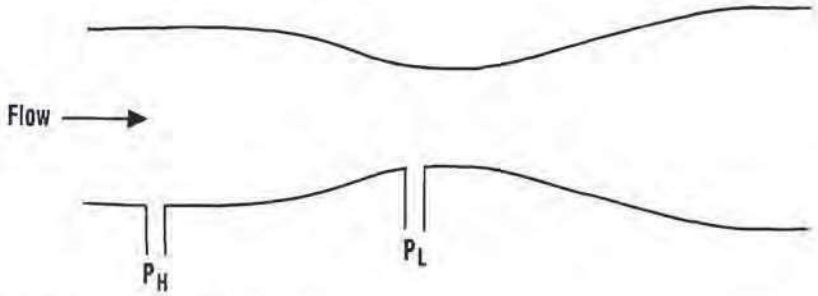

FIGURE 4.4 Venturi flow sensor.

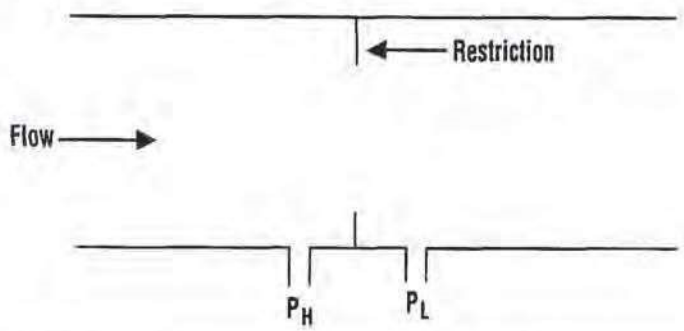

FIGURE 4.5 Flow sensor using a restriction to develop a differential pressure.

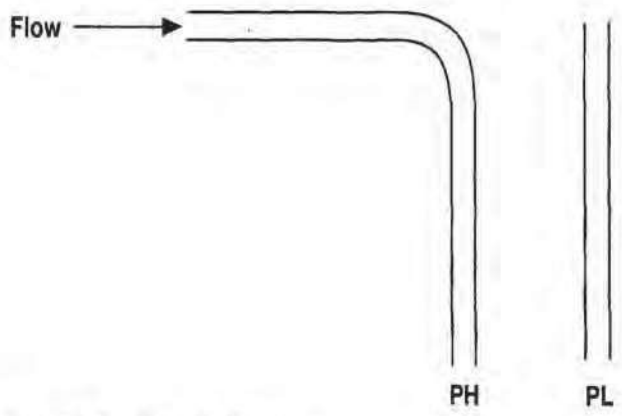

FIGURE 4.6 Pitot tube flow sensor.

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Turbine. A turbine blade placed in a flow channel can offer low restriction to flow, and by counting the speed of rotation it can also measure flow. It is analogous to the vane described previously except that it is more subject to wear since it is revolving, not merely deflecting. Use of a noncontacting means of counting revolutions (such as a Hall effect sensor) is recommended. This approach is well-suited to measurement of fuel flow.

Vortex Shedding. Oscillations may be induced in a fluid by placing an obstruction in the flow stream. The oscillations may be measured thermally, by pressure changes or using ultrasonics. This approach doesn't work well at low flow rates due to instability in the vortex shedding mechanism, so it is not suited to wide dynamic range applications such as intake air measurement. An example of a vortex shedding flow sensor is shown in Fig. 4.7.

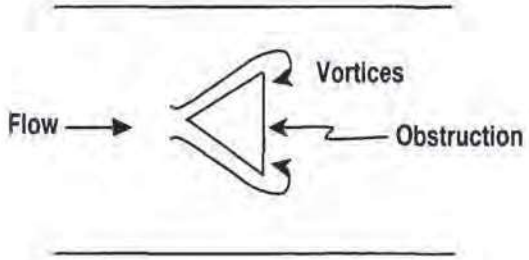

FIGURE 4.7 Vortex shedding flow sensor.

Other Technologies. There are a number of other technologies which are not well-suited to automotive applications, primarily due to cost considerations. A variety of flow sensors has been developed for industrial applications where performance is paramount and cost is secondary. These include the use of ultrasonics, gyroscopic effects, ionization of gases, and so on. These will not be discussed herein. Information on these technologies is given in the books by DeCarlo and Norton. See the list of suggestions for further reading.

GLOSSARY

Backflow The flow of air out of the intake system of an engine. This occurs at low speeds in engines containing only a few cylinders when all intake valves are closed at once.

Exhaust gas recirculation A process in which exhaust gases (containing primarily nitrogen) are returned to the intake system to reduce emissions by lowering the combustion temperature.

Micromachining Formation of very small three-dimensional structures in a semiconductor material.

Speed density A method of calculating the intake mass air flow rate by measuring engine speed and air density.

Stoichiometry The air-to-fuel ratio at which all the oxygen is consumed during combustion.

Volumetric efficiency The volume flow rate of air into the intake system divided by the volume rate of piston displacement.

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Robert E. Bicking received the B.E.E. and M.S.E.E. degrees from the University of Minnesota and has been involved with sensors nearly all of his 32 years in engineering. He is currently involved with the development of new automotive sensors at the Micro Switch division of Honeywell. He has been awarded three U.S. patents and is the author of over 24 technical papers. He is a member of the I.S.A., I.E.E.E., and S.A.E.

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CHAPTER 5

TEMPERATURE, HEAT, AND HUMIDITY SENSORS

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5.1 TEMPERATURE, HEAT, AND HUMIDITY

Temperature sensing and taking into account the effect of temperature on the performance and reliability of automotive components, and therefore the systems that contain these components, is one of the more important aspects of vehicle design. The heat sources that are present on modern automobiles range from the engine itself to catalytic converters, losses in power conversion (e.g. the alternator), and specific heat-generating devices such as heated windshields, seats, and mirrors. Humidity adds to the effect that temperature has on the reliability of components and also impacts vehicle performance and passenger comfort.

5.1.1 Temperature—the Effect of Heat

The temperature of a body or substance is (1) its potential of heat flow, (2) a measure of the mean kinetic energy of its molecules, and (3) its thermal state with reference to its ability to transfer heat to other bodies or substances.

Temperature affects every aspect of automobiles, from the performance of the engine and various vehicle systems to the comfort of the driver and passengers. The wide range of worldwide vehicle operating temperatures (from –60° to +57 °C) and the subsequent localized electronic module temperature ambients underhood (from –40 to +125 °C) and in the passenger compartments (from –40 to +85 °C) affect both the performance and reliability of electronic components. The viscosity of lubricating and cooling fluids is also affected by the wide temperature variations that must be tolerated. Even paint, fabric, plastics, rubber, and other organic and inorganic materials must be designed to survive the environmental extremes of temperature and humidity. Sensing the temperature of these components is essential during vehicle development.

5.1.2 Conduction, Convection, and Radiation

Heat energy is transferred with corresponding temperature changes by conduction, convection, and/or radiation. Conduction occurs by diffusion through solid material or in stationary liquids or gases; convection involves the movement of a liquid or gas between two points, and radiation occurs through electromagnetic waves.

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5.1.3 Heat Sources in Vehicles

In addition to the temperature rise that can be generated by sunlight on the metal and glass that form the body of the vehicle, there are several heat-generating devices in a vehicle as shown in Table 5.1. The foremost heat source is the engine in internal combustion engine equipped vehicles. This causes the engine compartment to generally be classified as a +125 °C ambient for electronic components, although considerably higher temperatures are reached within the combustion chamber (≥1000 °C) or on the engine block.

The catalytic converter used to reduce unburnt hydrocarbons and carbon monoxide emissions has a peak catalyst efficiency around 450 °C, minimum operating temperature around 350 °C, and high temperature operation in the area of 1000 °C.

Tire flexure and friction generated between the tires and the road surface are major sources of heat. Moreover, heat is generated by friction between any moving components of a vehicle. Gears and bearings in transmissions, rear axle, and pumps are most notable for generating a significant temperature rise. Brake surfaces also create high temperatures when the brakes are applied.

Even though they do not generate heat, in the process of reducing the temperature of other components, heat exchangers—such as coolant or transmission radiators for the passenger compartment heater and their associated plumbing and electronic heat sinks—have considerably higher than ambient temperatures.

Electric heating elements, including heated back light, windshield, windshield wiper, mirrors, and seats, increase the temperature to improve visibility and driver comfort. Heated windshield wipers can be maintained at 15 °C even when outside temperatures are around −40 °C. In some cases, temperatures in the area of 350 °C are produced by supplemental heating elements for components such as the catalytic converter, the oxygen sensor, and some advanced electric vehicle batteries.

The windings of electric components such as the starter motor, heater motor, alternator, and solenoids are a source of heat and high temperatures, especially in continuously moving, heavily loaded units like the alternator. The resistance in the windings as well as resistance in semiconductor components like alternator rectifiers and power transistors creates a power loss proportional to the square of the current being conducted ($P = I^2R$). In semiconductors, the change in temperature is related to the power dissipated through the thermal resistance.

$$\Delta T = R_\theta P \tag{5.1}$$

where R_θ = thermal resistance in °C/W
ΔT = temperature difference in °C (frequently $T_{junction} - T_{case}$)
P = power in watts

TABLE 5.1 Heat Sources in Vehicles

General category	Example	Max. temperature °C
Engine	Combustion/ignition process	>1000
Catalytic converter	Chemical reaction	>1000
Road/tire friction	Tires	<100
Brakes	Disk/drum	250
Mechanical motion (gears, bearings)	Transmission/rear axle/air pump/power steering pump	200
Heat exchangers	Radiator (coolant, transmission), heater, heatsink	>175
Electric heaters	Windshield, backlight, seats, mirrors	Ta + 25
Electric windings	Motors, alternator, solenoids	<155 (Class F)
Resistors	Ballast resistor	150
Lamps	Headlamps, tail lamps, dash lamps	125
Power transistors	Ignition driver, voltage regulator	Up to 200
Electric vehicle battery	Sodium sulfur	300

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Lamps have a significant inrush current (10 · steady state) and a high steady state value which generate high temperatures as well.

Temperature at various locations in the vehicle are shown in Table 5.2.

TABLE 5.2 Temperature at Various Vehicle Locations

Location	Temperature, °C		Slew Rate	Humidity		Frost
	Low	High		High	Low	
Underhood—Engine						
Exhaust manifold	–40	+649	–7 °C/min	95% at 38 °C	0	Yes
Intake manifold	–40	+121	–7 °C/min	95% at 38 °C	0	Yes
Underhood—Dash Panel						
Normal	–40	+121	Open	95% at 38 °C		
Extreme	–40	+141	Open	80% at 66 °C		
Chassis						
Isolated	–40	+85	NA	98% at 38 °C	0	Yes
Near heat source	–40	+121	NA	80% at 66 °C	0	Yes
At drive train temperature	–40	+177	NA	80% at 66 °C	0	Yes

5.1.4 Effect of Humidity

Humidity affects the comfort of the drivers and the passengers as well as the performance of the engine and impacts the reliability of vehicle components. The primary measurement for humidity is relative humidity RH, the ratio of water partial pressure to saturation pressure. Other measurements include dew point (temperature); specific humidity (mixing ratio); the mass of water per unit mass of dry gas; and volume ratio, the parts of water vapor per million parts of air. The dew point is a direct measure of vapor pressure and absolute humidity. Humidity is the water vapor in gas. Water in a solid or liquid is called moisture. High humidity and low dew point can lead to increased moisture content which can affect the operation of vehicle fluids such as fuel and brake fluid and impact solid surfaces like the windshield or brake linings.

5.1.5 Reliability Implications to Electronic Components

The effect of temperature on electronic components was recognized as "one of the most severe environments generally encountered on the automobile." Warm-up time of engine liquids and local ambient temperatures are as high as several tens of minutes, especially in cold weather. A recommended practice, SAE J1211, was published in November 1978 that still serves as a guideline to developing environmental design goals for electronic equipment, especially in the area of temperature variations within various vehicle locations.

Temperature affects the performance and expected life of electronic components. Mechanical stress created by different coefficients of thermal expansion can cause failures in thermal cycling test (air-to-air) or thermal shock (water-to-water) transitions.

The failure of electronic components also occurs because the mechanical durability, solder strength, or glass transition of plastic mold compound is exceeded. Electrical properties including thermal runaway in bipolar transistors and loss of gate control in MOS-gated (Sec. 5.4.6) devices also directly cause failure due to temperature extremes.

The typical failure rate for a semiconductor component can be expressed by the Arhennius equation:

$$\lambda = A \cdot \exp \frac{\theta}{kT} \tag{5.2}$$

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where λ = failure rate
A = constant
exp = 2.72
θ = activation energy
k = Boltzmann's constant
$8.62 \cdot 10^{-5}$ eV/°K
T = temperature in °K

The failure rate of semiconductor components typically doubles for every 10 to 15 °C increase in operating temperature. However, increased testing and design improvements have minimized the failures due to specific failure mechanisms. Semiconductor components manufactured in the 90s are orders of magnitude more reliable than those first used in vehicles in the 60s. However, their response time is considerably faster than vehicle liquids and local ambients. For example, the transient thermal response, $r(t)$ $R\theta_{JC}$, which is a reduced level of the thermal resistance (Sec. 5.1.4) based on the transistor operating in a switching mode and being off for a period of time, approaches the dc level within a second. Excessive temperatures can be generated quickly and must be detected within milliseconds to prevent failure.

Accelerated life testing is performed at elevated temperatures to determine the reliability of electronic components and obtain the maximum amount of information in the minimum amount of time. The actual failure mechanisms are a result of the component design and environment in which they operate. Life testing seeks to identify areas that are vulnerable in a particular design and provides minimum acceptable criteria for qualification.

The activation energy is directly proportional to the degree of influence that temperature has on the chemical reaction rate. Temperature acceleration factors for a particular failure mechanism can be expressed as the ratio of the failure rates at two different levels of stress:

$$F_a = \exp\left(\frac{\theta}{k}\right) \cdot \frac{1}{T_r - 1/T_t} \tag{5.3}$$

where F_a = acceleration factor
θ = activation energy
k = Boltzmann's constant, $8.62 \cdot 10^{-5}$ eV/°K
T_r = junction temperature in °K at the rated ambient temperature
T_t = junction temperature in °K at the life test ambient temperature

To determine a component's ability to withstand the adverse effects of temperature and humidity extremes to which the vehicle is exposed, a number of reliability stress tests are included in the qualification procedure. These tests include:

- *High-temperature Storage Life* is performed to accelerate failure mechanisms which are thermally activated through extreme temperatures.

  Typical test conditions: T_a = 70 to 200 °C, no bias, time = 24 to 5000 h
- *Temperature Cycling* (air-to-air) evaluates the ability of a device to withstand both exposure to temperature extremes and transition between temperature extremes. This test also exposes excessive thermal mismatch between materials.

  Typical test conditions: T_a = –65 to 200 °C, cycle = 10 to 4000 (1000 most common)
- *Thermal Shock* (liquid-to-liquid) testing evaluates the ability of the device to withstand both exposure to extreme temperature and sudden transitions between temperature extremes. This testing also exposes extreme thermal mismatch between materials.

  Typical test conditions: T_a = 0 to 100 °C, cycle = 20 to 300 (100 most common)
- *H^3TRB* (high-humidity, high-temperature reverse bias) is an environmental test designed to measure the moisture resistance of plastic encapsulated devices. A bias is applied to accelerate corrosive effects on internal components of semiconductors.

  Typical test conditions: T_a = 85 to 95 °C, RH = 85 to 95%, bias = 80 to 100% of max rating, time = 96 to 1750 h

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- *Autoclave* (or pressure cooker) testing is performed to measure device resistance to moisture penetration and resulting galvanic corrosion. This is a highly accelerated and destructive test.
  Typical test conditions: T_a = 121 °C, RH = 100%, p = 1 atmosphere, time = 24 to 96 h
- *Moisture Resistance* testing evaluates the moisture resistance of components under tropical environments.
  Typical test conditions: T_a = –10 to 65 °C, RH = 80 to 98%, time = 24 h/cycle, cycle = 10

In addition, a number of high-temperature tests under different biasing conditions are also performed for semiconductor devices, including high-temperature forward bias, high-temperature reverse bias, and high-temperature gate bias.

5.2 AUTOMOTIVE TEMPERATURE MEASUREMENTS

Numerous temperature measurements are made during the development of the vehicle to ensure the proper operation of systems and components. Some measurements are included in the control system strategy or as diagnostics for production vehicles. A list of the potential temperature and humidity measurements that can be made and may be incorporated in future systems is shown in Table 5.3. The technique used to measure temperature may vary from development to production mode, from one vehicle manufacturer to another and even from system to system within a given vehicle manufacturer. The choice in technology for production sensors depends upon performance, reliability, and cost. For development vehicles, cost is not a major concern, but availability of test probes, compatibility with readout equipment, and ease of use are additional factors that should be taken into consideration.

Common vehicle temperature measurements will be explained in the remainder of this section.

5.2.1 Measuring Liquid Temperatures

A number of liquid temperatures are measured during vehicle development, especially under high vehicle ambient temperatures and severe driving conditions, such as trailer towing up steep grades and stop-and-go Phoenix traffic during summer months. These include coolant, engine oil, transmission oil, fuel, power steering, brake, and battery electrolyte. Monitoring coolant temperature is common in engine control systems in production vehicles. Engine and transmission oil temperature are being evaluated for future monitoring. Racing vehicles frequently monitor oil and fuel temperature in addition to coolant temperature to achieve peak performance. Sensing fuel temperature may be required to meet future emissions standards. A latent heat cooling system has been developed that uses a temperature sensor to control the engine under various operating conditions. The system employs control valves that control the flow of vaporized coolant based on temperature in a manifold connected to the top of the combustion chamber.

Mounting location, fluid contacting the sensor, and packaging are critical concerns for liquid temperature sensors. Upper temperature limits are typically around 150 to 200 °C and operation down to –40 °C is usually required.

Battery temperature measurements in vehicle development use glass thermometers or glass-shielded thermocouple probes to protect the sensor from the corrosive electrolyte.

5.2.2 Battery Temperature

Maintaining the proper state of charge in the vehicle's battery is essential for obtaining adequate cranking rpm during starting and for ensuring optimum battery life. The charge accep-

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TABLE 5.3 Sensing Requirements versus Vehicle Systems

System	Parameter
Engine control	Air charge (intake air) temperature Engine coolant temperature Intake air humidity Ambient temperature Fuel temperature
HVAC (climate control)	Humidity in passenger compartment (PC) Temperature (PC) Outside air temperature
Electronic transmission (continuously variable transmission)	Transmission oil temperature
Driver information (body computer inputs)	Coolant temperature Ambient air temperature Temperature (PC) Tire surface temperature Rain sensor Windshield moisture Sun sensor Battery temperature
Multiplex/diagnostics Cruise control Idle speed control Memory seat Navigation	Multiple usage of sensors
Antiskid brakes	Brake fluid temperature
Traction control/ABS	Brake moisture sensor
Air bags	
Suspension	
Electronic power steering	Power steering fluid temperature (also electric assisted)
Four-wheel steering Security and keyless entry	

tance curves of lead-acid batteries require that the charging voltage be modified for temperature. A higher voltage is required at lower temperatures. Cold temperatures also place the most difficult requirements on the battery because the viscosity of engine oil is low and the load on the cranking system is very high.

Compensation circuitry in the voltage regulator in the charging system is designed to provide a voltage that is within an acceptable range over the entire vehicle operating temperature range as shown in Fig. 5.1. Semiconductor sensing techniques (Sec. 5.4.6) are used in this approach. The most desirable location for the voltage regulator is close to the battery. However, some systems integrate the regulator inside the alternator and provide a temperature environment that can be considerably different from the battery. The temperature of the battery can also vary by several degrees from cells closest to the engine to those further away from the engine. The overall mass of the battery prevents these temperatures from changing very quickly. However, a failed voltage regulator that applies full voltage to the alternator can easily cause excessive battery temperatures to be generated.

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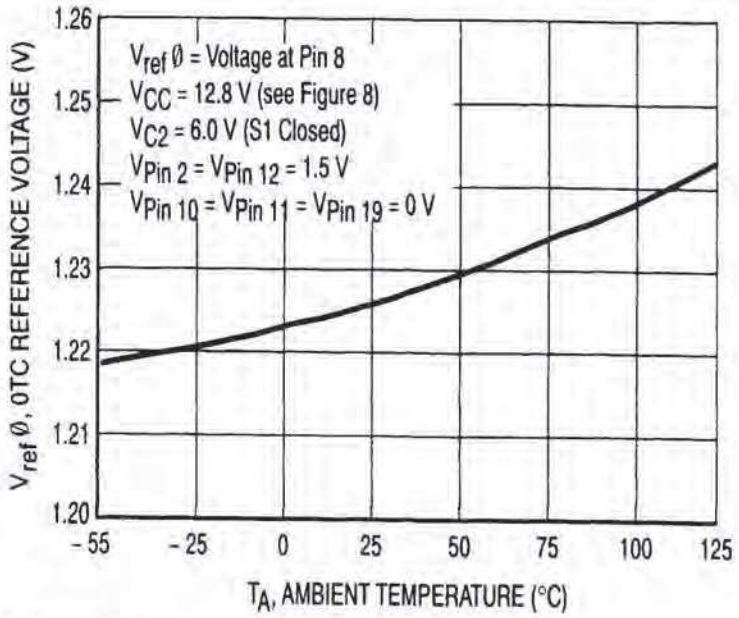

FIGURE 5.1 Temperature compensation in voltage regulator.

Batteries for electric vehicles (EVs) may require maintaining a specified high-temperature operating range. Sodium sulfur cells can store four times the energy of lead acid cells, but the battery's operating temperature must be kept within 300 to 350 °C. Solid oxide fuel cells operate at 1000 °C. If higher-temperature batteries are adopted for use in EV systems, sensing the battery temperature could be part of the diagnostic and fault detection.

5.2.3 Air Temperature Measurements

Air is measured for ambient temperature, passenger compartment temperature, and inlet air on production vehicles. For development purposes, a number of location ambients are always evaluated as potential mounting locations for electronic components. Upper temperature ranges are lower than liquid measurements, with 85 or 125 °C being common upper limits.

5.2.4 Catalyst Temperature

Measuring catalyst temperature during vehicle development has been performed since the earliest implementation of these devices. Concern for excessive temperatures in nearby vehicle locations meant that a number of measurements were made. However, the converter must be at a minimum temperature, usually above 350 °C, to be effective. Tougher exhaust emission standards are spurring manufacturers to utilize the converter sooner after the vehicle is started. Techniques are being pursued that would decrease the warm-up time for the catalyst to increase its effectiveness in controlling emissions. One technique involves heating the catalyst briefly by igniting a measured mixture of fuel and air in an afterburner ahead of the catalyst. Another technique utilizes electric heating to reduce the warm-up time. The power required for this approach would require an excessive power drain from the vehicle's power system. A linear temperature sensor has been developed to measure the temperature across the catalyst. A thermistor (see Sec. 5.4.1) is inserted diagonally inside the converter. A range of resistance has been evaluated and a time constant of about 2 s has been achieved. For fault condition monitoring, the sensor is able to detect a localized hot spot inside the catalyst and may prove to be able to detect misfire as part of future on-board diagnostic equipment required by the California Air Resources Board or the federal Environmental Protection Agency.

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The temperature of exhaust gases increases rapidly under severe operating conditions such as continuous high speed or insufficient octane rating. One company has monitored their efforts at controlling the engine's operating temperature by locating a temperature sensor in the exhaust manifold. If the sensor detects an exhaust gas temperature rise above an established limit, a computer sends a command to inject extra fuel into the combustion chamber to cool the engine. Since exhaust gas temperatures can reach 1000 °C, a specially designed magnesium oxide thermocouple in a metal tube is used to sense the temperature (see Sec. 5.4.2). This approach may also be used in the future to reduce catalyst warm-up time.

5.2.5 Oxygen Sensor

The oxygen sensor used as the feedback element in closed-loop engine control systems generates a signal based on the difference in the oxygen concentration from inside the exhaust gas and ambient. As shown in the Nernst equation:

$$V_S = RT/4F \ln (P_a/P_g) \tag{5.4}$$

where V_S = the generated output voltage
P_a = oxygen partial pressure of the air
P_g = oxygen equilibrium pressure
R = gas constant
F = Faraday's constant
T = absolute temperature of the sensor

In addition to being affected by temperature, the oxygen sensor requires a minimum temperature to operate properly and provide a closed-loop control system. Typically, this minimum temperature is ≥450 °C. To reduce the oxygen sensor's warm-up time, heaters are added. A heated oxygen sensor achieves operating temperature much sooner than an unheated unit and allows closed-loop operation to be initiated. Monitoring temperature during engine and vehicle development is part of control strategy and component development.

5.2.6 Tire Temperature Sensing

Sensing the temperature within the tire is part of the pressure measurement and fault detection provided by tire pressure measuring and automatic adjustment systems. In a system like the one developed by Michelin (Fig. 5.2) that is used on Peugot's experimental sports car, the Proxima, both a pressure and temperature sensor are located on each wheel. A circular antenna and a transceiver allow these signals to be sent to an electronic processing module. An air compressor attempts to maintain desired tire pressure under normal conditions. If the pressure-temperature indications go above 85 °C, the system recommends speeds be held below 240 km/h (148 m/h). For temperatures above 90 °C, the limit is 160 km/h and for 95 °C, the limit is 80 km/h. For temperatures in excess of 100 °C, the system recommends stopping the vehicle.

5.2.7 Fault Detection for Electronic Components

As indicated in Sec. 5.1.6, temperature can cause reliability failures from several mechanisms in electronic systems. Therefore, detecting excessive temperature and designing system strategies to account for excessive temperatures can minimize improper operation and catastrophic failures.

Sensing for fault conditions, like a short circuit, is an integral part of power ICs or smart power transistors. The ability to obtain temperature sensors in mixed Bipolar-CMOS-DMOS semiconductor processes provides protection and diagnostics as part of the features of smart power ICs, like Motorola's SMARTMOS™ products. The primary function of the power IC is to provide a microcontroller-to-load interface for solenoids, lamps, and motors. It is a definite

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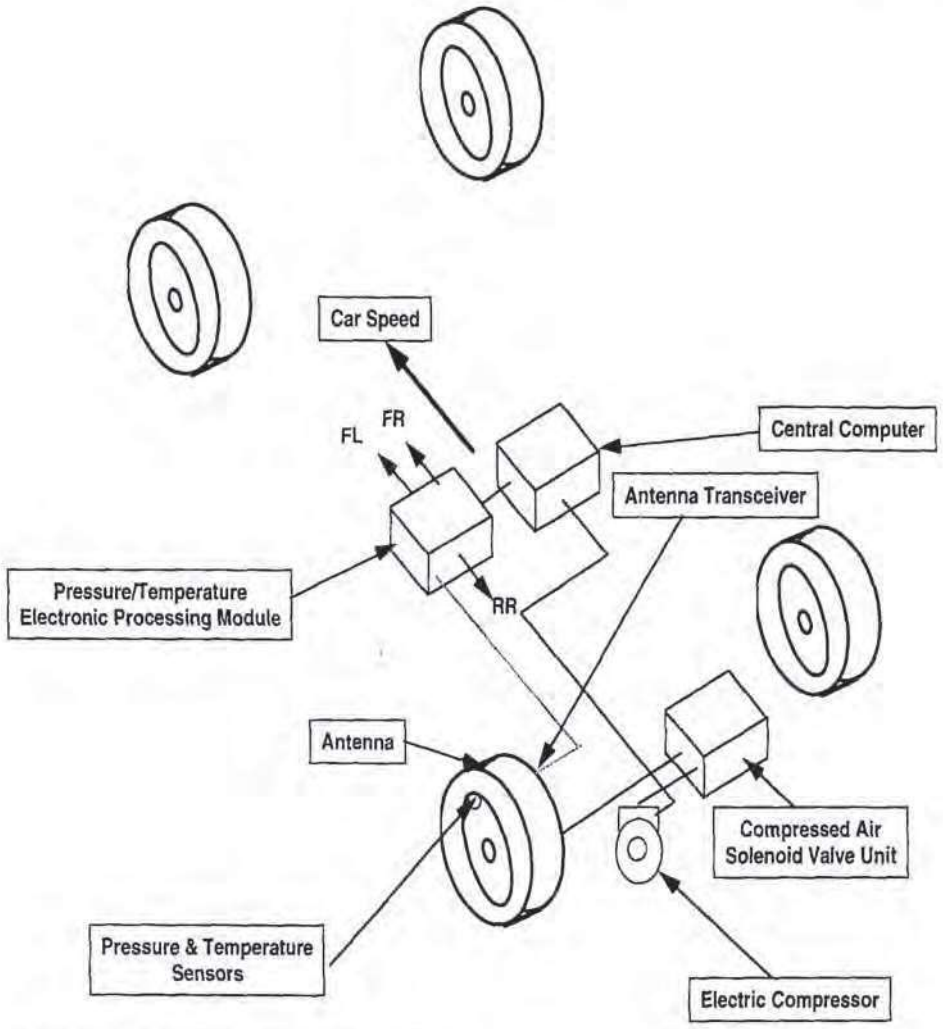

FIGURE 5.2 Temperature sensing in tire pressure control.

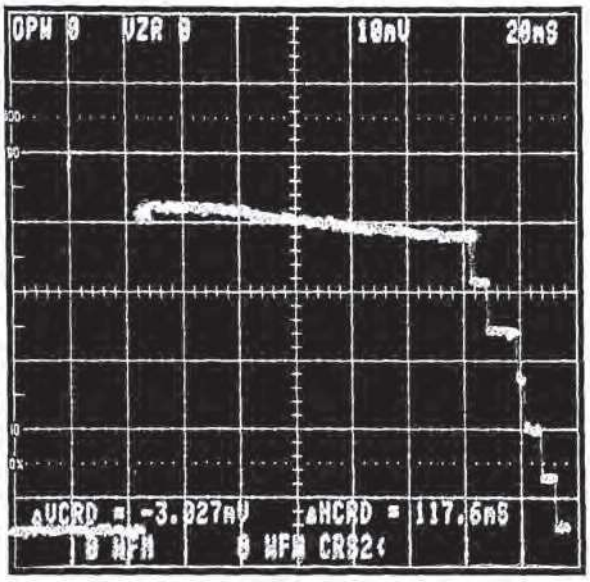

FIGURE 5.3 Thermal shutdown of six outputs of smart power IC.

advantage in multiple-output devices, to sense the junction temperature of each device, provide status input to the microcontroller and, if necessary, shut down a particular unit that has a fault condition. The sequential independent shutdown of six output drivers with a short applied across each unit's load is shown in Fig. 5.3. The action that is taken based on sensing a fault condition can vary depending on the control system. Sensing excessive temperature in a power device may mean that the device can turn itself off to prevent failure in one case and in another situation, a fault signal provides a warning but no action is taken. The remaining portion of the system is allowed to function normally. With the fault conditions supplied to the MCU, an orderly system shutdown can be implemented.

5.2.8 Mass Air Flow Sensor

The generalized model of a transducer is shown in Fig. 5.4. In addition to the desired input, undesired environment effects, like temperature and, to a lesser extent, humidity, are factors that affect the performance and accuracy of the transducer and must be taken into account during the design of the transducer.

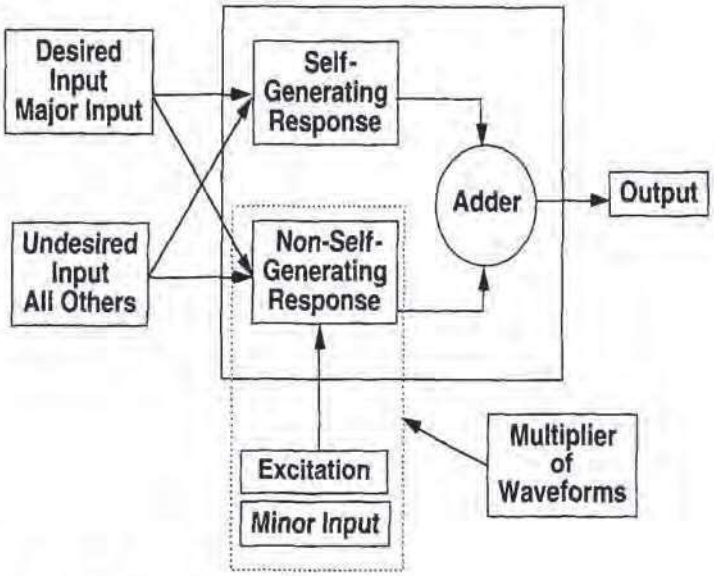

FIGURE 5.4 Generalized model of a transducer.

In the case of mass air flow sensing, temperature effects are used as part of the measurement process. A typical approach for mass air flow involves a hot-wire anemometer with a platinum wire as the sense elements, as shown in Fig. 5.5. The air temperature probe detects the temperature of the air flowing into the combustion process. The hot-wire probe is heated by current supplied from a power transistor. The difference in temperature between the probes is detected as a difference in electrical resistance. The electronic circuitry regulates the heating current to the hot-wire probe to keep the temperature difference constant at any flow rate (Fig. 5.6). The current required is proportional to the air flow rate. One of the main issues in this type of sensor is the response time. Improvements which reduce the response time from 50 to 30 ms have been made in recently developed units.

A microbridge silicon mass air flow sensor has been developed that utilizes temperature-resistive films laminated within a thick film of dielectric material and micromachined cavity as shown in Fig. 5.7. The resistors are suspended over the etched cavity, which also provides thermal isolation for the heater and sensing resistor. Heat is transferred from one resistor to the other as the result of flow. The imbalance in the resistance caused by the heat transfer

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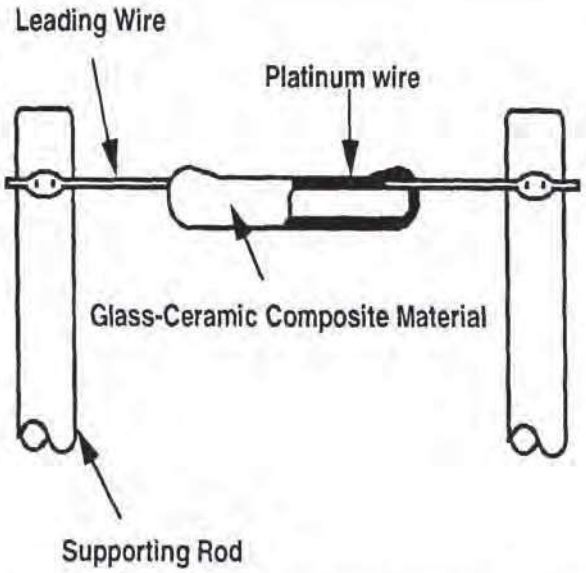

FIGURE 5.5 Probe for hot-wire anemometer mass air flow sensor.

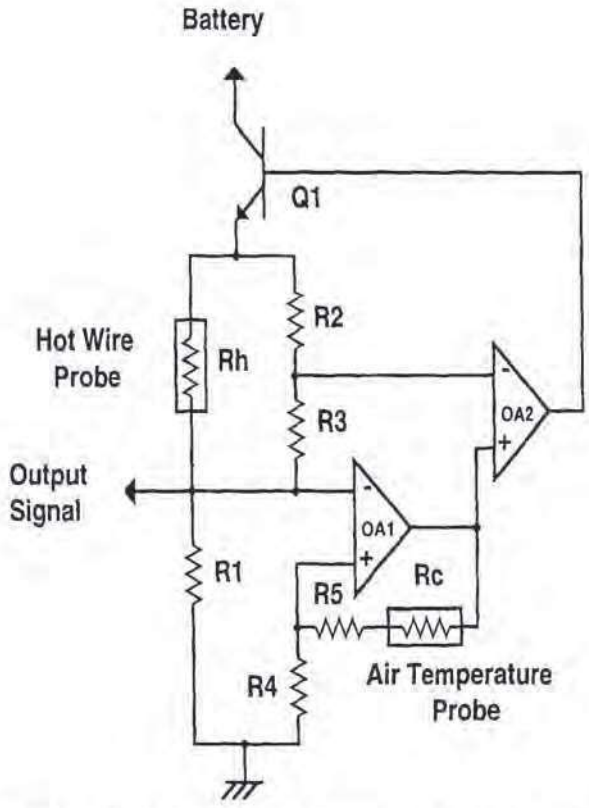

FIGURE 5.6 Circuit for hot-wire anemometer mass air flow sensor.

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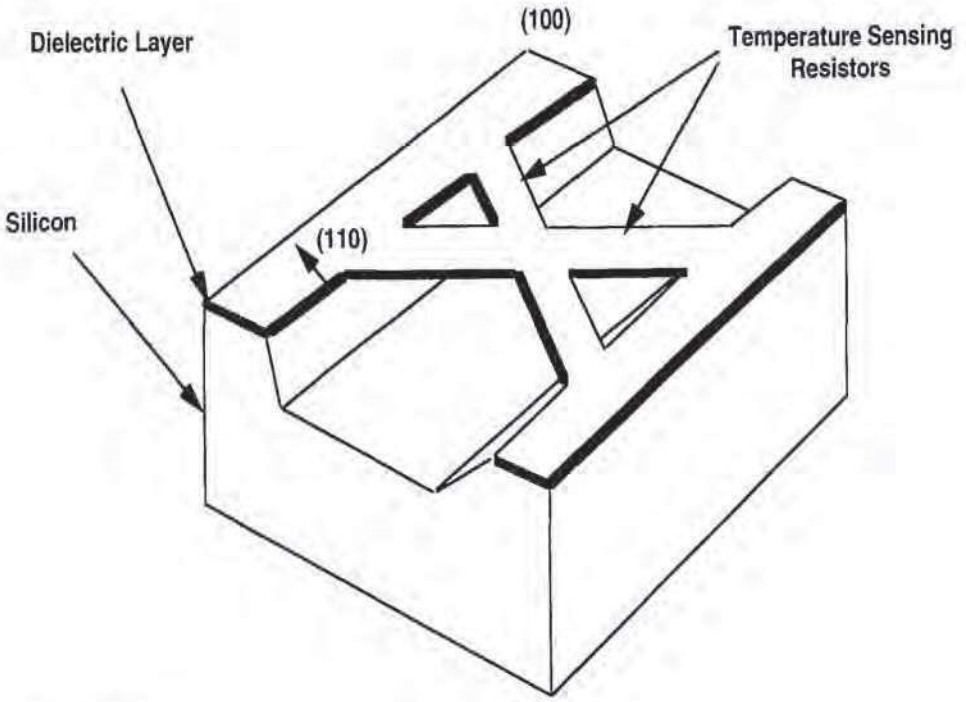

FIGURE 5.7 Temperature sensor in microbridge mass air flow sensor.

is directly proportional to the flow. The small size of the resistors allows fast response time (≤3 ms) and high sensitivity to flow. The device has also been found to be useful as a differential or absolute temperature sensor.

5.2.9 Temperature Measurements in New Systems

As new vehicle systems are developed or existing systems are modified to provide improved performance, or meet legislated or customer demands, new applications for temperature sensors will occur. An example of two systems, air bags and thermo accumulator, is provided.

In inflatable restraint systems, the air bag is inflated based on the ignition of a gas generant. In this system, an igniter receives an electric impulse, passes it through to a heating filament, and actuates a small pyrotechnic charge to ignite the gas generant, which produces nearly pure nitrogen gas to inflate the bag. The initial temperature is high but the nitrogen gas cools rapidly, so a fully deployed bag is only slightly above room temperature. Measuring the temperatures that occur during this event is part of the development activity.

A heat battery, or thermoaccumulator, can store the latent heat from a previously driven vehicle for up to three days at an ambient temperature of –29 °C. The accumulator is made of salt-based crystals which change from solid to liquid form above 78 °C. Heat provided by this device has proven to reduce the emissions which are generated during the first 20 s of the federal emissions test procedure. The unit also has potential application in passenger compartment heating.

5.3 HUMIDITY SENSING AND VEHICLE PERFORMANCE

Correlation of a number of vehicle tests requires that the humidity be monitored. Variations in humidity can explain variations that occur in test results.

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Significant, repeatable, and controllable results may lead to humidity sensing being part of future engine control systems and passenger compartment comfort control systems.

Some sensors, such as rain (and/or windshield moisture) or sun sensors, are already being used on some vehicles to control wiper blade and fan controls.

5.3.1 Engine Performance

Injecting water to cool the intake charge and prevent premature detonation is a technique that has been used in high-compression (≥10:1) engines. The cooling effect from evaporation reduces the operating temperature.

An increase in inlet air humidity has been shown to reduce the nitric oxide emissions. Condensation in the gas tank can add a considerable amount of moisture to the fuel. Measuring the actual amount of humidity or moisture present during development tests is useful to identify all variables that can affect performance.

5.3.2 Passenger Compartment Comfort

A traditional passenger temperature control system shown in Fig. 5.8 uses only temperature as the indication for the system to open or close blend doors in the HVAC (heater, ventilating, and air conditioning) system. Laboratory evaluations monitor the HVAC systems' effectiveness under known and controlled humidity conditions. A fuzzy logic system combining temperature and humidity sensing has been investigated by researchers for home use. In this case, additional humidity is available to speed up the effect of adding heat. In a vehicle application, the blower speed could be adjusted based on the presence of humidity or an alternate strategy could be developed which uses less energy from the vehicle to make the driver and passengers comfortable.

The development of new test techniques frequently involves either the development of new sensors or novel use of existing sensors. A sweat impulse test developed at Volkswagen AG allows researchers to evaluate the ability of a seat to direct sweat away from its surface.

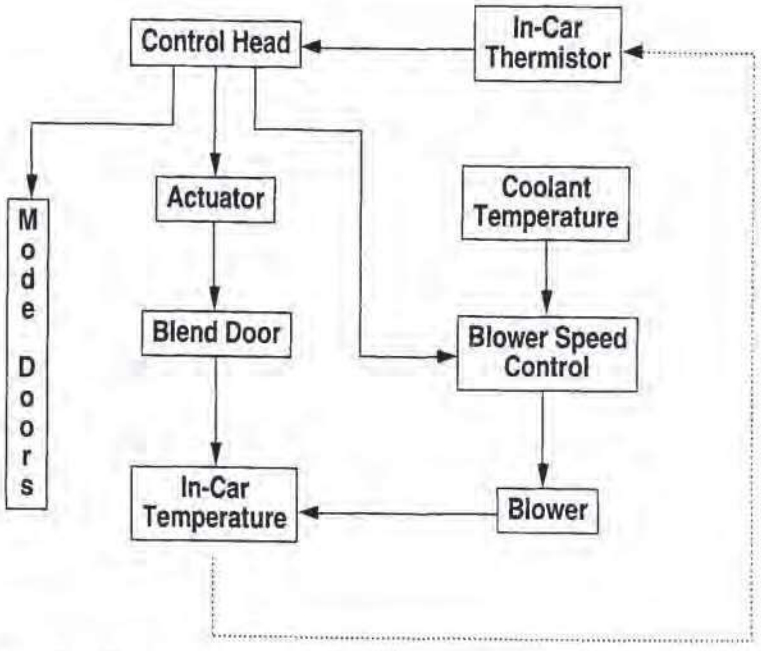

FIGURE 5.8 Automatic temperature control diagram.

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As part of the measurement process, a platinum RTD (Sec. 5.4.5) and a capacitive humidity sensor provide data. In excessive sweating situations, the fabric is unable to absorb sufficient moisture, so it is passed to the surrounding environment as increased humidity.

5.3.3 Brake Moisture Sensing

Brake fluids are hygroscopic and, therefore, absorb moisture. Sufficient moisture lowers the boiling point of the brake fluid, and eventually vaporizes the fluid resulting in loss of stopping power. A meter has been developed that can be inserted into the master cylinder reservoir and measure the boiling point of the brake fluid. A heating element boils a sample of the brake fluid. A microcontroller calculates the actual boiling point by the initial temperature reading, temperature drop, and time between cooling and boiling. This approach may be applicable to other vehicle fluids that can be checked during maintenance procedures.

5.4 SENSORS FOR TEMPERATURE

Several different sensing techniques are used in production vehicles and during vehicle development to provide the temperature measurements. Table 5.4 shows a list of these techniques and the temperature range that is typical for this approach. Characteristics of temperature-sensing devices that allow a designer to determine if the approach will meet development or production requirements are explored in this section. In addition to the operating temperature range, linearity, response time, packaging, reliability, and cost are factors that must be considered. Temperature sensors can be as simple as thermal expansion devices, such as mercury or alcohol thermometers, or as complex as infrared sensors used in night vision systems. Common sensors and some recent additions to temperature sensing are covered in this section. Other sensor techniques, including the temperature-generating characteristics of quartz and temperature-sensing reed switches, are also possible but not covered.

5.4.1 Thermistors

Thermistors have found broad application acceptance in several vehicle systems that require temperature sensing from the coolant system to control the engine. The thermistor is a special

TABLE 5.4 Temperature Sensing Techniques versus Operating Range

Sensing technique	Temperature range, °C	Usage: Production (P) Development (D) Future (F)
Thermistor	0 to 500	P
Thermocouple	−200 to +3000	D
Bimetallic switch	−50 to +400 (650)	P
Potentiometer temperature sensor	−40 to +125	P
Platinum wire resistor (RTD)	−200 to +850 (−40 to +200)	D (P)
Semiconductor (junction)	−40 to +200	P
Thermostat (pressure spring)	−50 to +500	P
Fiber optic temperature sensor	+1800	D/F
Temperature indicator	+40 to +1350	D
Infrared	>Ta	F
Liquid thermometer	−200 to +1000	D

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class of resistance temperature sensor (Sec. 5.4.5) based on semiconductor type materials that exhibit a wide range of temperature coefficients. The resistivity depends upon the material used to form the thermistor. Both negative (NTC) and positive temperature coefficient (PTC) devices can be produced. Commercially available thermistor forms are beads, probes, disks, and rods. The characteristics of thermistor output are shown in Fig. 5.9. The exact relationship between temperature and resistance depends on the material used for the sensor, but the general form of the output can be expressed by the equation

$$R = R_O \cdot e^{\beta}(1/T - 1/T_O) \tag{5.5}$$

where R = resistance at temperature T in ohms
R_O = resistance at temperature T_O in ohms
e = base of natural log
T, T_O = absolute temperature in K
β = indicator of shape of NTC curve

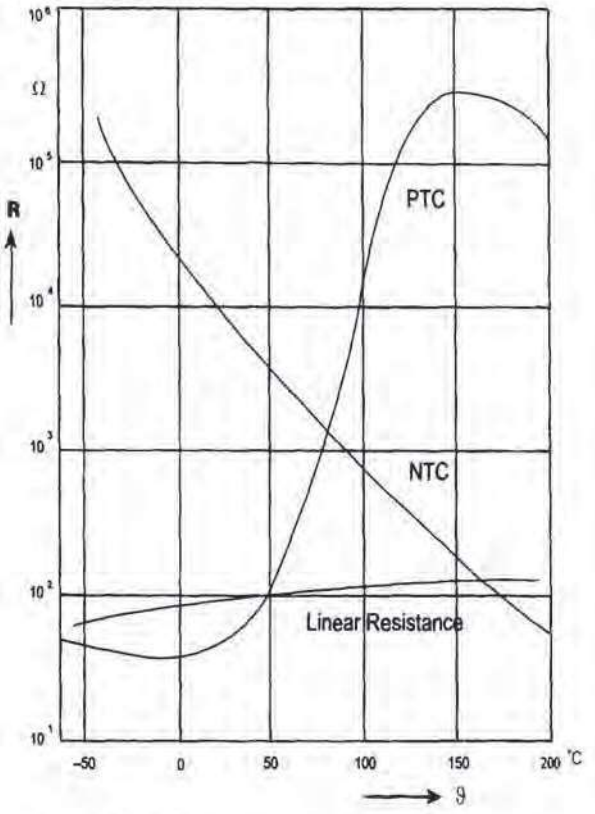

FIGURE 5.9 Thermistor output versus temperature.

This accounts for the high degree of nonlinearity in the output. However, the thermistor's nonlinearity can either be tolerated in many automotive applications, or corrected by an MCU or by circuit techniques. In the case of the water temperature indicator, for example, the thermistor's resistance is matched to a normal operating point on the gage; thus, the nonlinearity during conditions that generate higher temperature is not a problem.

Thermistors have a usable temperature range from –250 to +650 °C. Recent developments in automotive thermistors have focused on techniques to reduce cost and improve the manufacturability and reliability.

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5.4.2 Thermocouples

Thermocouples are used frequently during the development phase of the vehicle because of their low cost, the broad range of temperature measurements that are possible from a single thermocouple such as iron-constantan, ease of extending the range through other materials, ease in obtaining a variety of form factors (especially small shapes), ease in forming the thermocouple, and ease in interfacing to temperature-recording equipment. The thermocouple type, wire size, and construction are factors that allow different units to be used from –250 to +1700 °C.

A thermocouple is formed by a pair of dissimilar conductors connected at one end. A voltage output E, proportional to the difference in temperature T_1 and T_2, is the basis of thermoelectric temperature measurements, also known as the Seebeck effect.

Thermocouple junctions can be formed by welding, soldering, or pressing materials together. Measurements can be made very easily; however, the highest accuracy is obtained by taking into account a number of factors, including reference junction considerations and a number (five) of laws that govern thermocouple behavior. Common types and their operating characteristics are shown in Table 5.5.

TABLE 5.5 Common Thermocouples and Application Factors

ISA code	Conductor		Temperature Range, °C	Standard error Limit, °C	Seebeck Coefficient, μV/°C
	Positive	Negative			
E*	Chromel	Constantan	0 to +316	±2	62
J*	Iron	Constantan	0 to +277	±2	51
T*	Copper	Constantan	–59 to +93	±1	40
K*	Chromel	Alumel	0 to +277	±2	40
N*	Nicrosil	Nisil	0 to +277	±2	38
S*	Platinum†	Platinum	0 to +538	±3	7
R*	Platinum‡	Platinum	0 to +538	±3	7

* Other temperature ranges and error limits are available.
† 10% Rhodium.
‡ 13% Rhodium.

5.4.3 Bimetallic Switch

A bimetallic temperature switch uses two metal strips with different coefficients of linear expansion that are welded together. Increasing temperature causes the strips to warp predictably. A switch point can be established by an initial calibration that indicates that a critical temperature has been reached and provides an input to an electronic control unit or a lamp indication. Switch types can be disk or cantilever construction. The use of switches does not require analog-to-digital conversion in control systems with microcontrollers, but provides limited information (only above or below a desired operating point) about the system. Early engine control systems used a disk switch in the air cleaner to indicate operation below 13 °C and a cantilever design in the engine coolant to indicate temperature above 71 °C.

5.4.4 Potentiometer Temperature Sensor

A bimetallic actuator can be combined with a high-resolution potentiometer to provide a temperature sensor for automotive applications. The linear movement of the bimetallic stack is transmitted by a stainless steel tube and measured as a distance by a conductive plastic film potentiometer providing a linear indication of temperatures up to 650 °C. The time constant for the sensor is approximately 70 s.

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5.4.5 RTDs

A resistive temperature detector, or RTD, made of platinum is the highest inherent accuracy temperature sensor. The RTD has an output that varies with temperature based on the following equation:

$$\text{RTD} = R_O \cdot (1 + A \cdot T + B \cdot T^2) \tag{5.6}$$

where RTD = value of RTD at 0 °C in ohms and is 100 Ω for Pt100 and 200 Ω for Pt200
A = detector constant = $3.908 \cdot 10^{-3}$ ($°C^{-1}$) for Pt100
B = detector constant = $-5.802 \cdot 10^{-7}$ ($°C^{-2}$) for Pt100
T = temperature in °C

A constant current is applied to the RTD to obtain a voltage output over the range from −200 to +850 °C. Linearity can be within 3.6 percent for a range of 0 to 850 °C.

Other metals like nickel, nickel-iron alloy, copper, and aluminum can also be used for the RTDs. In addition to wire-wound RTDs, thin-film techniques also allow an RTD to be applied to a substrate, such as ceramic or silicon.

5.4.6 Semiconductor Techniques

Several semiconductor parameters vary linearly over the operating temperature range. As shown in Fig. 5.10, the gate threshold voltage of a power MOSFET changes from 1.17 to 0.69 times its 25 °C value when the temperature increases from −40 to 150 °C. Also, the breakdown voltage of the power MOSFET varies from 0.9 to 1.18 times its value at 25 °C over the same −40 to 150 °C temperature range (Fig. 5.10). These relationships are frequently used to determine the critical temperature (junction temperature) of semiconductor components in actual circuit operation. External package-level temperature measurements can be several degrees different than the junction temperature, especially during rapid, high-energy switching events. The actual junction temperature and the resulting effect on semiconductor parameters must be taken into account for the proper application of semiconductor devices. Semiconductors can be used for sensing temperature within their operating temperature range.

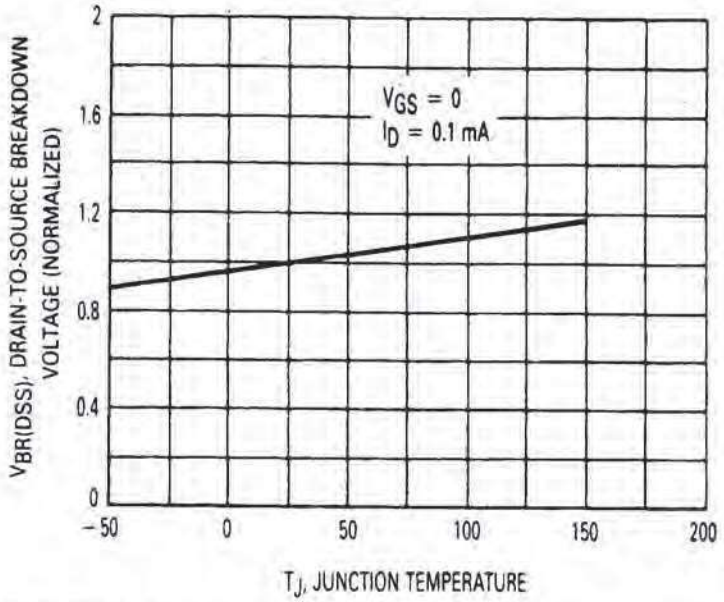

FIGURE 5.10 Breakdown voltage versus temperature.

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The most commonly referenced transistor temperature measurement is the V_{BE} relationship to temperature. A silicon temperature sensor that utilizes this effect has a nominal output of 730 mV at –40 °C and an output of 300 mV at 150 °C. The linearity of this device is shown in Fig. 5.11. The total accuracy is within ±3.0 mV including nonlinearity which is typically within ±1 °C in the range of –40 to 150 °C. The readings are made with a constant (collector) current of 0.1 mA passing through the device to minimize the effect of self-heating of the junction.

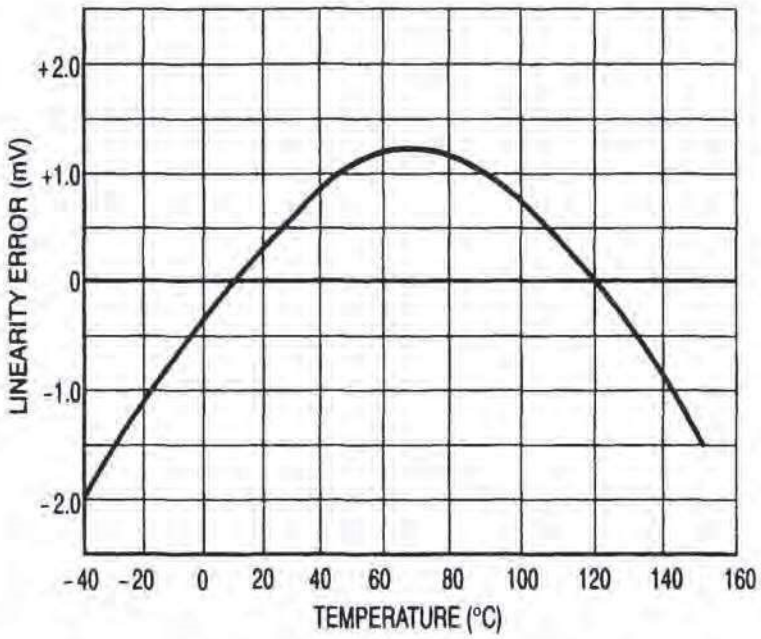

FIGURE 5.11 Linearity of silicon temperature sensor.

The linear relationship of the V_{BE} of a transistor to temperature provides a considerable improvement in accuracy over a thermistor. However, the limited operating range of semiconductor temperature sensors (–40 to 150 °C) has limited their application in vehicles. To be cost-effective in automotive applications, semiconductor sensing is usually incorporated with other sensing or interface devices.

An RTD (Sec. 5.4.5) with an aluminum metal film has been integrated with a semiconductor process to provide a temperature sensor that can directly drive the analog-to-digital input in a microcontroller unit (MCU). The sensor has better than ±2 percent accuracy over a –50 to 150 °C temperature range. On-chip linearization techniques avoid look-up table linearization by the MCU.

Another integrated semiconductor temperature sensor uses the fact that two identical transistors operating at a constant ratio of collector current densities r results in the difference in base-emitter voltages being $(kT) \cdot (\ln r)$. Both Boltzman's constant k and the charge of an electron q are constant, so the resulting voltage is directly proportional to absolute temperature. The voltage is then converted to a current by low-temperature coefficient thin-film resistors.

Polysilicon diodes and resistors can be produced as part of a power MOSFET semiconductor manufacturing process and used as temperature-sensing elements to determine the junction temperature of the device. The thermal sensing that is performed by the polysilicon elements is a significant improvement over power device temperature sensing that is performed by an external temperature-sensing element. An extreme thermal gradient exists between the maximum junction temperature at the top (active area) of the power device and the remote point which is able to be measured by a thermistor or thermocouple. Placing the thermal-sensing element inside the package improves the measurement process considerably.

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