F·U·N·D·A·M·E·N·T·A·L·S O·F
PRESSURE SENSOR TECHNOLOGY

This tutorial addresses the basic physics of pressure, three types of pressure measurement, seven pressure sensor technologies, and three calibration techniques.

Robert E. Bicking, Honeywell Micro Switch

To begin our investigation of pressure sensors, we first must consider the physics on which the technology is based.

Basic Physics of Pressure Sensing

Static Pressure. Pressure, P, is defined as force, F, per unit area, A:

$$P = F/A \qquad (1)$$

The measurement of pressure is generally associated with fluids, either liquids or gases. A container filled with a liquid (see Figure 1) has a pressure (due to the weight of the liquid) at a point in the liquid of:

$$P = \Delta F / \Delta A = hw \qquad (2)$$

where:

h = distance from the surface to the point
w = weight of the liquid (most liquids are nearly incompressible)

The weight per unit volume, V, is given by:

$$w = mg/V \qquad (3)$$

where:

m = mass
g = gravitational acceleration

Note that this relation can be used to determine the height of the column of liquid in a tank by measuring the pressure.
The density, ρ, is given by:

$$\rho = m/V \qquad (4)$$

Thus, the density of a liquid determines

the pressure, P, exerted for a given height. Mercury is 13.6 × denser than water, so would exert a pressure 13.6 × that of water for a column of the same height. It should be noted that the pressure due to the height of a column of liquid is in addition to the atmospheric pressure acting on the surface of the liquid. The height of a column of liquid is:

$$h = P/\rho g \qquad (5)$$

Archimedes' principle states that "A body wholly or partially submerged in a liquid is buoyed up by a force equal to the weight of the liquid displaced." Given a block of material submerged in a container of liquid (see Figure 2) with area A and length L, the downward pressure exerted on the top face is:

$$P_D = h\rho g \qquad (6)$$

and the upward pressure exerted on the bottom face is:

$$P_U = (h + L) \rho g \qquad (7)$$

giving a resultant pressure of:

$$P_U - P_D = L\rho g \qquad (8)$$

and the force is equal to the volume of the block multiplied by the weight of the liquid displaced.
A liquid exhibits nearly no shear stress, which leads to some interesting results. Pressure is transmitted to the inside of a container normal to the surfaces, a fact that can be most easily proved by punching a hole in a container of water and observing
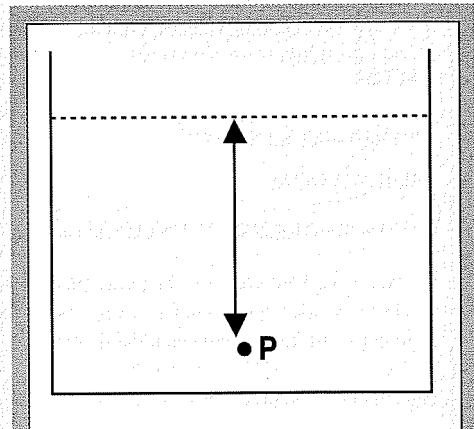

Figure 1. The pressure at any given point in a confined liquid is determined by the weight of the liquid and the distance from the point to the surface.
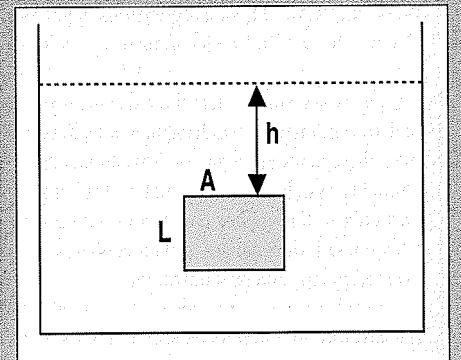

Figure 2. Archimedes' principle states that an object submerged in a confined liquid will be buoyed up by the weight of the liquid it displaces.
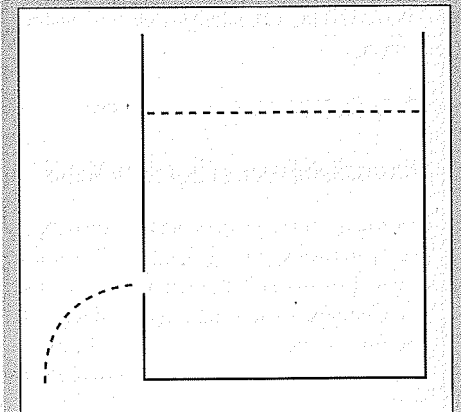

Figure 3. The pressure transmitted to a confined liquid is normal to the liquid's surface, as can be observed by breaching one of the walls of the container.

the stream as it exits the hole (see Figure 3, page 30). This is important in the construction of dams, given that they must resist the force of water. This pressure is called the *static pressure.*

Pascal's law states that an increase in pressure at any point in a liquid results in a like increase at every other point in the liquid. This principle is used in hydraulic systems such as jacks and automobile brakes and is the fluidic equivalent of the principle of the lever, which allows large forces to be generated easily by trading large movement of a small piston for small movement of a large piston (see Figure 4).

Pressure in Moving Fluids. The pressure in a moving fluid exerted parallel to the flow direction is called the *impact pressure,* P_I. This is due to the kinetic energy of the fluid:

$$P_I = \rho V_O^2/2 \tag{9}$$

where:

ρ = fluid density
V_O = fluid velocity

Bernoulli's theorem states that for horizontal flow the following relation holds:

$$P_S = P_O + P_I \tag{10}$$

where:

P_S = stagnation (or total) pressure
P_O = static pressure

This relationship is useful for determining the flow velocity in a variety of applications. Rearranging the equation gives:

$$V_O = \sqrt{2\,(P_S - P_O)/\rho} \tag{11}$$
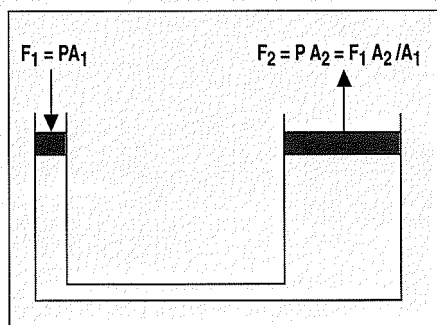
Fluid flow velocity may be measured with

Figure 4. *Pascal's law states that an increase in pressure at any point in a liquid causes a corresponding increase at every other point in the liquid.*

the Pitot tube assembly shown in Figure 5. The tube facing the flow measures total pressure and the tube normal to the flow measures static pressure. This approach is used in HVAC applications and in aircraft to measure flow velocity.

Gases. Gases differ from liquids in two respects: they are very compressible, and they completely fill any closed vessel in which they are placed. The nonlinear air pressure variation with altitude shown in Figure 6 (page 32) is an example of the effect of the compressibility of gases.
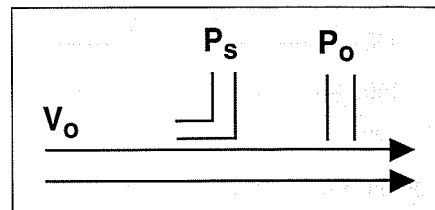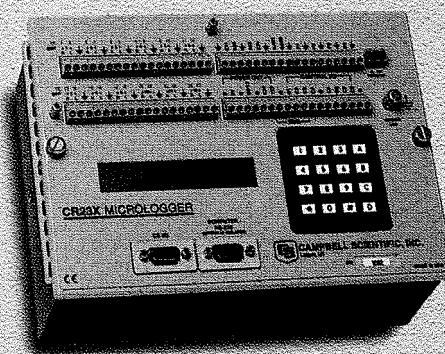
Figure 5. *A Pitot tube assembly can be used to measure the velocity of a moving fluid.*

Dynamic Effects. Static pressure is measured under steady-state or equilibrium conditions, but most real-life applications deal ▶
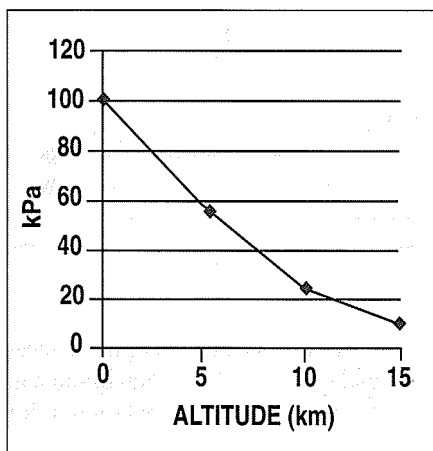
Figure 6. *The compressibility of gases is illustrated by nonlinear atmosphere pressure as a function of altitude.*

with dynamic or changing pressure. For example, the measurement of blood pressure usually gives the two steady-state values of systolic and diastolic pressure. There is much additional information in the shape of the blood pressure signal, however, which is the reason for the monitors used in critical-care situations.

To measure changing pressures, the frequency response of the sensor must be considered. As a rough approximation, the sensor frequency response should be 5–10 × the highest frequency component in the pressure signal. The *frequency response* is defined as the highest frequency that the sensor will measure without distortion or attenuation. Sometimes the *response time* is given instead. For a first-order system, they are related as follows:

$$f_B = 1/2\pi\tau \qquad (12)$$

where:

f_B = frequency where the response is reduced by 50%

τ = time constant where the output rises to 63% of its final value following a step input change

Another issue is the remote measurement of pressure where a liquid coupling medium is used. Care must be taken to purge all air because its compressibility will corrupt the waveform.

Types of Pressure Measurements

Absolute pressure is measured relative to a perfect vacuum. An example is atmospheric pressure. A common unit of measure is pounds per square inch absolute (psia).
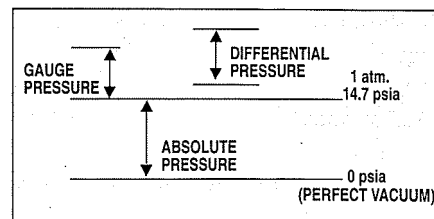

Figure 7. *The same sensor can be used for all three types of pressure measurement; only the references differ.*

Differential pressure is the difference in pressure between two points of measurement. This is commonly measured in units of pounds per square inch differential (psid).

Gauge pressure is measured relative to ambient pressure. Blood pressure is one example. Common measurement units are pressure per square inch gauge (psig). Intake manifold vacuum in an automobile engine is an example of a vacuum gauge measurement (vacuum is negative gauge pressure).

The three types of measurements are shown in Figure 7. Note that the same sensor may be used for all three types; only the reference is different. Differential pressures may be measured anywhere in the range— above, below, and around atmospheric pressure.
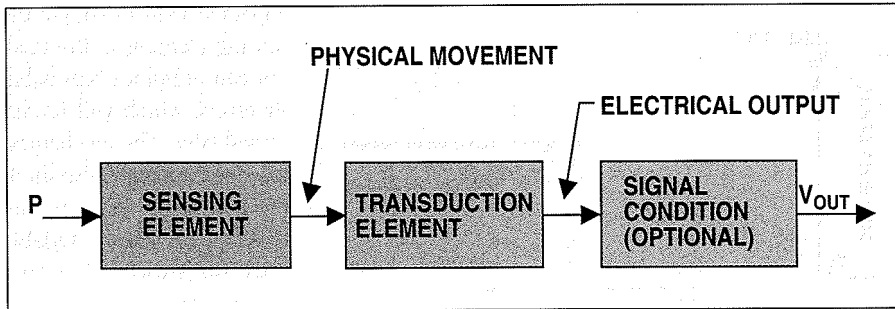
Circle 107 on *Sensors* RS Card

Figure 8. *The typical pressure sensor has three functional blocks.*

Pressure Units

As previously noted, pressure is force per unit area and historically a great variety of units have been used, depending on their suitability for the application. For example, blood pressure is usually measured in mmHg because mercury manometers were used originally. Atmospheric pressure is usually expressed in in.Hg for the same reason. Other units used for atmospheric pressure are bar and atm. The following conversion factors should help in dealing with the various units:

$$
\begin{aligned}
1 \text{ psi} \ &= 51.714 \text{ mmHg} \\
&= 2.0359 \text{ in.Hg} \\
&= 27.680 \text{ in.H}_2\text{O} \\
&= 6.8946 \text{ kPa} \\
1 \text{ bar} &= 14.504 \text{ psi} \\
1 \text{ atm.} &= 14.696 \text{ psi}
\end{aligned}
$$

Example: Convert 200 mmHg to psi:

$$
\begin{aligned}
200 \text{ mmHg} \bullet 1 \text{ psi}/51.714 \text{ mmHg} \\
= 3.867 \text{ psi}
\end{aligned}
$$

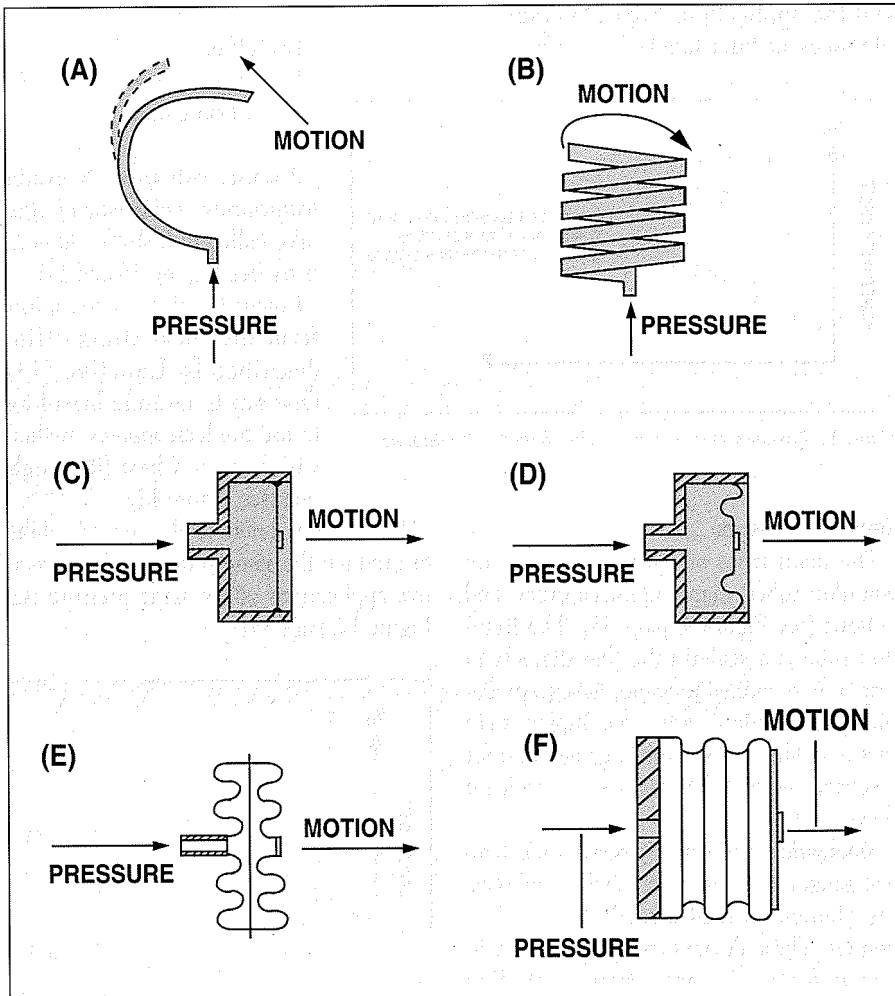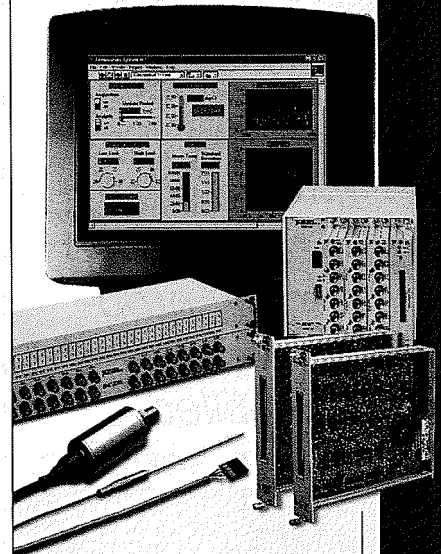A check that the answer is correct is to ▶

Figure 9. *The basic pressure sensing element can be configured as a C-shaped Bourdon tube (A); a helical Bourdon tube (B); flat diaphragm (C); a convoluted diaphragm (D); a capsule (E); or a set of bellows (F).*
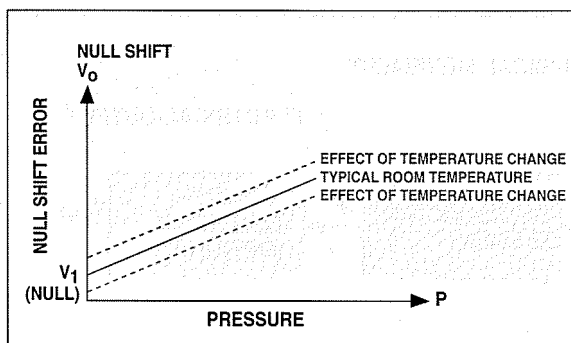
Figure 10. *Temperature has an effect on the offset of a pressure sensor.*

verify that it is in the desired units and that mmHg cancels.

Pressure Sensing

Pressure is sensed by mechanical elements such as plates, shells, and tubes that are designed and constructed to deflect when pressure is applied. This is the basic mechanism converting pressure to physical movement. Next, this movement must be transduced to obtain an electrical or other output. Finally, signal conditioning may be needed, depending on the type of sensor and the application. Figure 8 (page 33) illustrates the three functional blocks.
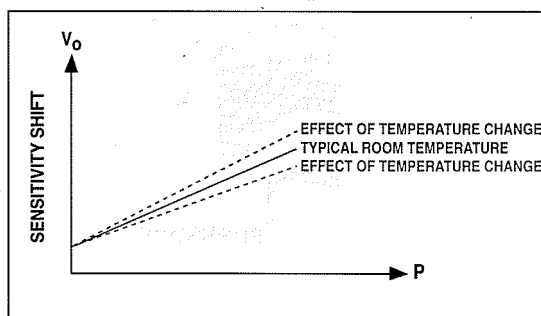

Figure 11. *Pressure sensor sensitivity is also affected by temperature.*

Sensing Elements

The main types of sensing elements are Bourdon tubes, diaphragms, capsules, and bellows (see Figure 9, page 33). The Bourdon tube is a sealed tube that deflects in response to applied pressure. All except diaphragms provide a fairly large displacement that is useful in mechanical gauges and for electrical sensors that require a significant movement.

Mechanical Pressure Gauges. In mechanical gauges, the motion created by the sensing element is read directly by a dial or pointer. These devices are typically seen in low-performance applications, including blood pressure measurement and automotive pressure gauges. The mechanical

approach used to couple the sensing element to the readout can introduce repeatability errors, which will be discussed later. The mechanical mass of the gauges also limits the frequency response and makes these sensors suitable only for slowly changing measurements.

Electromechanical Pressure Sensors. Electromechanical pressure sensors convert the applied pressure to an electrical signal. A wide variety of materials and technologies has been used in these devices, resulting in performance vs. cost tradeoffs and suitability for applications. The electrical output signal also provides a variety of choices for various applications.

Sensor Effects. A pressure sensor may be modeled as:

$$V_{OUT} = k_O + k_1 P \qquad (13)$$

where:

k_O = offset
k_1 = pressure sensitivity in V/ pressure unit

A sensor will typically exhibit *temperature coefficients of offset* (also called null shift) *and sensitivity* (see Figures 10 and 11).

Linearity refers to deviations from the ideal straight line described by Equation (13). One way to measure linearity is to use the least squares method, which gives a best fit straight line (see Figure 12).

Repeatability refers to the sensor's ability to produce the same output with consecutive applications of the same pressure (see Figure 13, page 35).
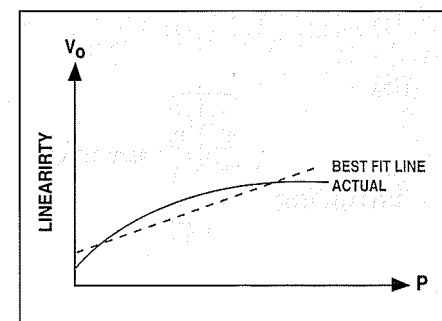

Figure 12. *The least squares method can be used to measure a pressure sensor's linearity.*
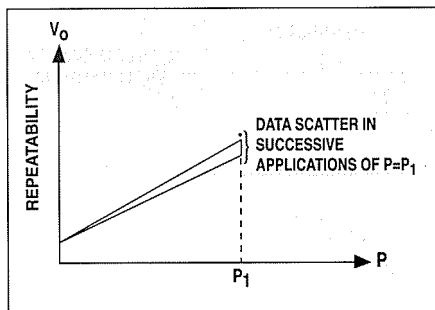
Figure 13. *Repeatability refers to the ability of a pressure sensor to provide the same output with successive applications of the same pressure.*
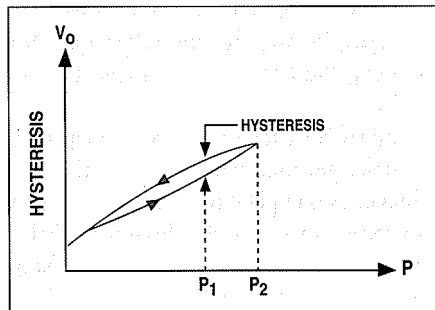

Figure 14. *Hysteresis is a sensor's ability to give the same output at a given temperature before and after a temperature cycle.*
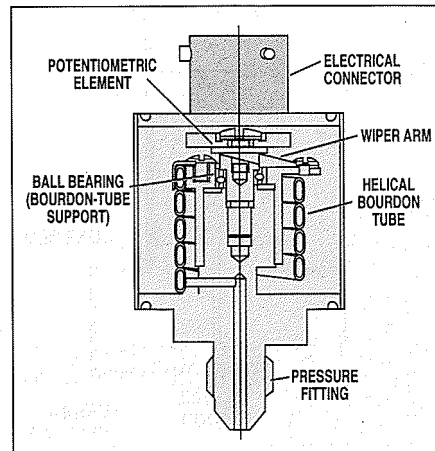

Figure 15. *Potentiometric pressure sensors use a Bourdon tube, capsule, or bellows to drive a wiper arm on a resistive element. Such sensors tend to be inexpensive, but subject to repeatability and hysteresis errors.*

Hysteresis refers to the ability of the sensor to give the same output when the same increasing and then decreasing pressures are applied consecutively (see Figure 14).

Temperature hysteresis refers to the ability of the sensor to give the same output at a given temperature before and after a temperature cycle. Repeatability and hysteresis effects are not easily compensated and are indicators of the basic stability of the device.

Gauge factor is a measure of the sensitivity of a sensor. It is defined as the ratio of the change in an electrical transduction parameter over the full range of pressure to the value of that parameter at zero pressure.

Thus, the gauge factor of a resistive sensor is:

$$\Delta R/R \qquad (14)$$

where:

R = base resistance
ΔR = resistance change with full-scale pressure, for example

Pressure Sensor Technologies

Potentiometric Pressure Sensors. Potentiometric pressure sensors use a Bourdon tube, capsule, or bellows to drive a wiper arm on a resistive element. For reliable operation the wiper must bear on the element with some force, which leads to repeatability and hysteresis errors. These devices are very low cost, however, and are used in low-performance applications such as dashboard oil pressure gauges. An example is shown in Figure 15.

Inductive Pressure Sensors. Several configurations based on varying inductance or ▶

Getting Sensor Data Off Rotating Equipment

Designers and users of rotating machinery can now collect data from rotor-mounted sensors the easy way with innovative new telemetry systems that:

■ offer noise-free digital accuracy
■ eliminate wear-prone slip-ring contacts
■ require no shaft modifications.

The new AT-4000, AT-5000 and AT-7000 wireless rotor telemetry systems collect data from strain gages, thermocouples or almost any other sensor type, digitize the signal, and transmit the data across an air gap at radio frequencies. By converting data on the rotor to 12-bit digital code before transmission, these telemetry systems provide data accuracy that's ten times higher than analog FM systems. The AT-4000 single-channel system and

AT-7000 multi-channel system have rotating collars that clamp directly to any existing shaft, avoiding machine modifications or in-line transducers. The AT-5000 is a miniaturized system that can be used even where space is extremely tight. Each system is non-contact, thereby eliminating the installation and maintenance headaches of conventional slip-rings.

For complete information about Accumetrics state-of-the art wireless telemetry solutions, contact:

Accumetrics Associates, Inc.,
409 Front Street, Schenectady, NY 12305
Tel: 518-393-2200 Fax: 518-393-3622
e-mail: accumterics@global2000.net
Web: www.accumetrix.com
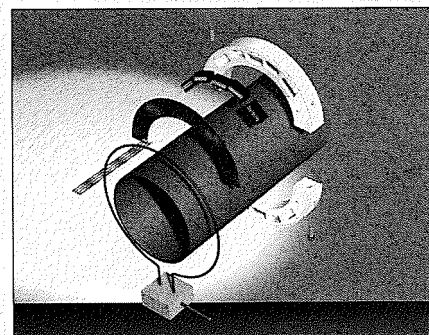
The AT-7000 Multi-Channel System clamps on and offers modular expandability up to 64 sensor channels. The AT-4000 Wireless Torque Transducer also clamps on for easy application.
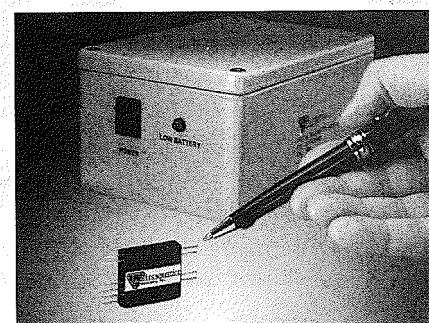
The AT-5000 Telemetry System has been miniaturized for instant application on almost any rotating shaft.
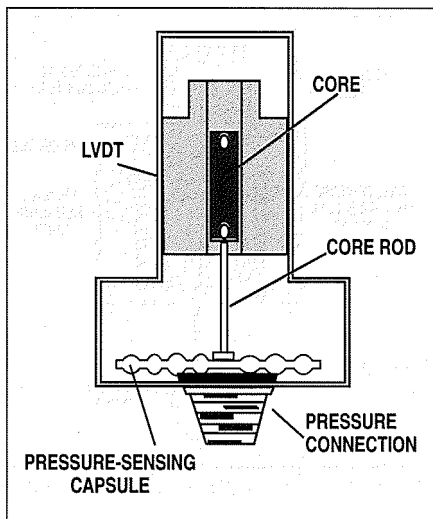
Accumetrics Associates, Inc.

Figure 16. *An LVDT pressure sensor, one configuration of inductive devices, drives a moving core that varies the inductive coupling between the transformer primary and secondary.*

inductive coupling are used in pressure sensors. They all require AC excitation of the coil(s) and, if a DC output is desired, subsequent demodulation and filtering. The linear variable differential transformer (LVDT) types have a fairly low frequency response due to the necessity of driving the moving core of the differential transformer

(see Figure 16). The LVDT uses the moving core to vary the inductive coupling between the transformer primary and secondary.

Capacitive Pressure Sensors. Capacitive pressure sensors typically use a thin diaphragm as one plate of a capacitor. Applied pressure causes the diaphragm to deflect and the capacitance to change. This change may or may not be linear and is typically on the order of several picofarads out of a total capacitance of 50–100 pF. The change in capacitance may be used to control the frequency of an oscillator or to vary the coupling of an AC signal through a network. The electronics for signal conditioning should be located close to the sensing element to prevent errors due to stray capacitance.

The capacitance of two parallel plates is given by:

$$C = \mu A/d \qquad (15)$$

where:

μ = dielectric constant of the material between the plates
A = area of the plates
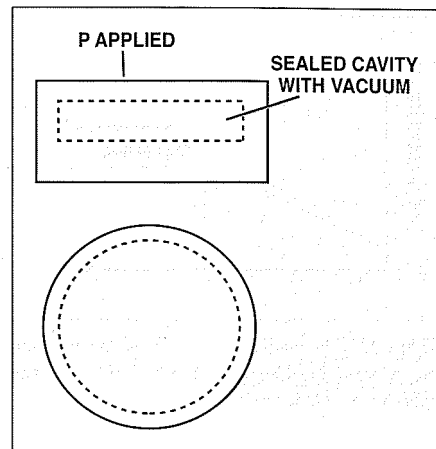
Figure 17. *The basic capacitive pressure sensor consists of two plates with a vacuum between them.*

d = spacing between the plates

If the dielectric constant of the material between the plates isn't kept constant, errors may result. Capacitive absolute pressure sensors with a vacuum between the plates are ideal in this respect. Because the capacitance of this sensor depends only on physical parameters, sensors with good performance can be constructed using materials with low coefficients of thermal expan-
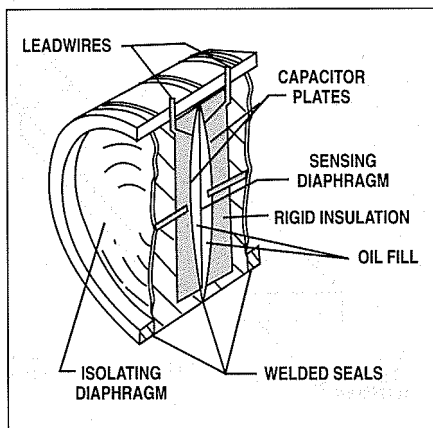
Figure 18. *A more complex capacitive pressure sensor can be built to detect differential pressure.*

sion. Since the device has to be fairly large to obtain a usable signal, frequency response may be a problem in some applications. Also, low-pressure capacitive sensors exhibit acceleration and vibration sensitivity due to the necessity for a large, thin diaphragm. A basic capacitive sensor is shown in Figure 17 (page 36) and a more complex differential pressure capsule is shown in Figure 18.

Piezoelectric Pressure Sensors. Piezoelectric elements are bi-directional transducers capable of converting stress into an electric potential and vice versa. They consist of metallized quartz or ceramic materials. One important factor to remember is that this is a dynamic effect, providing an output only when the input is changing. This means that these sensors can be used only for varying pressures. The piezoelectric element has a high-impedance output and care must be taken to avoid loading the output by the interface electronics. Some
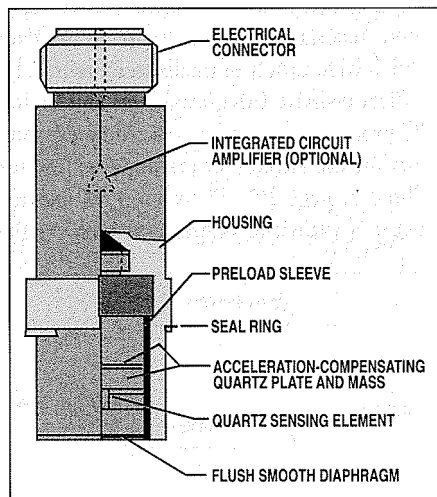
Figure 19. *Piezoelectric sensors convert stress into an electric potential and vice versa. Sensors based on this technology are used to measure varying pressures.*

piezoelectric pressure sensors include an internal amplifier to provide an easy electrical interface (see Figure 19).

Strain Gauge Pressure Sensors. Strain gauge sensors originally used a metal diaphragm with strain gauges bonded to it. A strain gauge measures the strain in a material subjected to applied stress. Consider a strip of metallic material (see Figure 20, page 38) with electrical resistance given by:

$$R_O = \rho L/WT \qquad (16)$$

where:
ρ = resistivity
L, W, T = length, width, thickness

Metallic strain gauges depend only on dimensional changes to produce a change in resistance. A stress applied to the strip causes it to become slightly longer, narrower, and thinner, resulting in a resistance of:

$$R = \rho(L + \Delta L) / (W - \Delta W)(T - \Delta T), \text{ or}$$
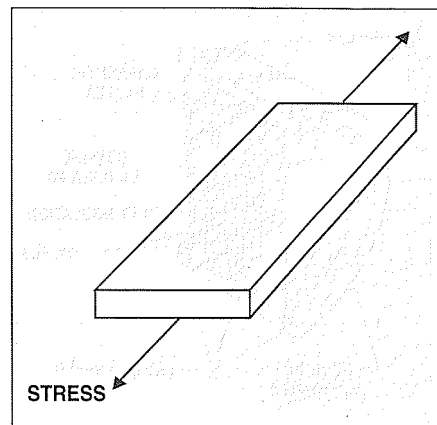$$R \cong R_O(1 + 3\Delta) \qquad (17) \blacktriangleright$$

Figure 20. *Strain gauge pressure sensors measure the strain in a material that is subjected to applied stress.*

As might be expected, the signal due to deformation of the material is small, on the order of 0.1% of the base resistance.

Semiconductor strain gauges are widely used, both bonded and integrated into a silicon diaphragm, because the response to applied stress is an order of magnitude larger than for a metallic strain gauge. When the crystal lattice structure of silicon is deformed by applied stress, the resistance changes. This is called the piezoresistive effect. Following are some of the types of strain gauges used in pressure sensors.

Deposited strain gauge. Metallic strain gauges can be formed on a diaphragm by means of thin film deposition. This construction minimizes the effects of repeatability and hysteresis that bonded strain gauges exhibit. These sensors exhibit the relatively low output of metallic strain gauges.

Bonded semiconductor strain gauge. A silicon bar may be bonded to a diaphragm to form a sensor with relatively high output. Making the diaphragm from a chemically inert material allows this sensor to interface with a wide variety of media (see Figure 21).

Piezoresistive Integrated Semiconductor. IC processing is used to form the piezoresistors on the surface of a silicon wafer (see Photo 1, page 39). There are four piezoresistors within the diaphragm area on the
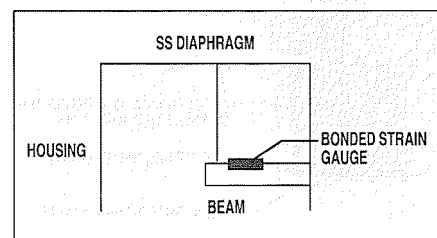

Figure 21. *A silicon bar can be bonded to a diaphragm to yield a strain gauge sensor with a relatively high output.*

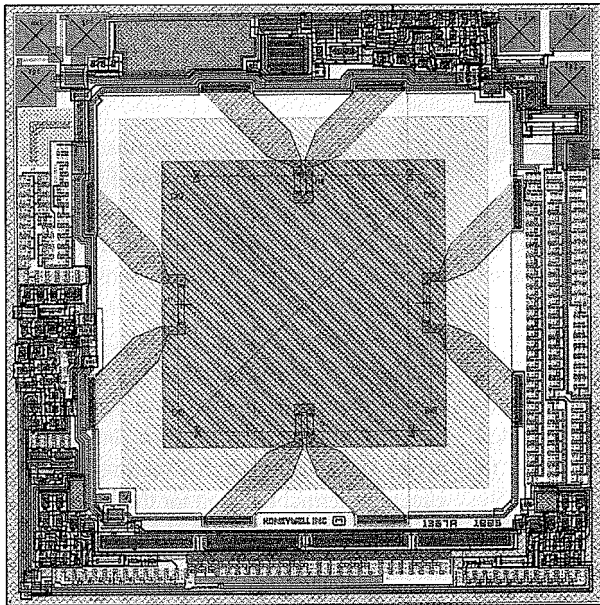**Circle 81 on *Sensors* RS Card**

Photo 1. *IC processing is used to form the piezoresistors on the surface of a silicon wafer to fabricate an integrated piezoresistive pressure sensor.*

sensor. Two are subjected to tangential stress and two to radial stress when the diaphragm is deflected. They are connected in a four-element bridge configuration (see Figure 22) and provide the following output:

$$V_{OUT} / V_{CC} = \Delta R / R \qquad (18)$$

where:

V_{CC} = supply voltage
R   = base resistance of the piezoresistor
ΔR = change with applied pressure and is typically ~2.5% of the full R

Etching of the back of the wafer is used to form the diaphragm (see Figure 23). The high output of the bonded strain gauge is combined with the low hysteresis of the

deposited strain gauge in this design, due to the integrated construction and the nearly perfect elasticity of single-crystal silicon. The cost of the sensing element is low since a large number of devices fit on a silicon wafer. Typical die size is 0.1 in. square with a 50 mil square diaphragm. The circuitry needed for amplification, temperature compensation, and calibration may also be included on the same IC. Various pressure ranges are accommodated by varying the diaphragm thickness and, for very low pressures, by varying the diaphragm diameter. This device can be used to construct absolute, differential, and gauge pressure sensors, depending on the reference (see Figure 24).

Because the sensing element is so small (see Photo 2, page 40), the package can have a great deal of mounting and port interface flexibility. Also, the small size
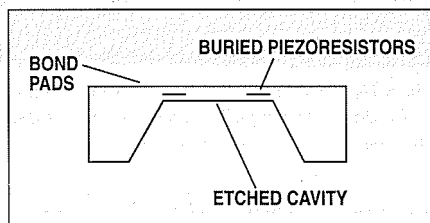

Figure 23. *The back of a wafer is etched out to form the diaphragm of a piezoresistive pressure sensor.*

Figure 24. *Piezoresistive pressure sensors can be configured to provide absolute, differential, or gauge pressure readings, depending on the reference. The diaphragm is shown here as it deflects under applied differential pressures.*
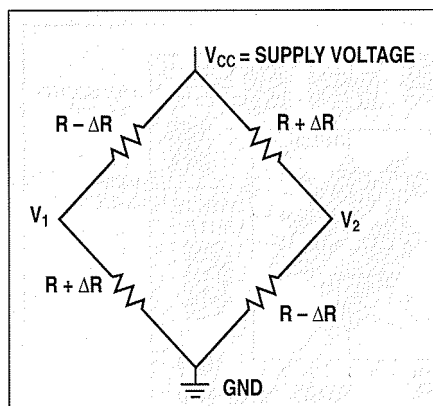

Figure 22. *Piezoresistive integrated semiconductor pressure sensors incorporate four piezoresistors in the diaphragm. When the diaphragm is deflected, two resistors are subjected to tangential stress and two to radial stress. The four are connected to a four-element bridge.*
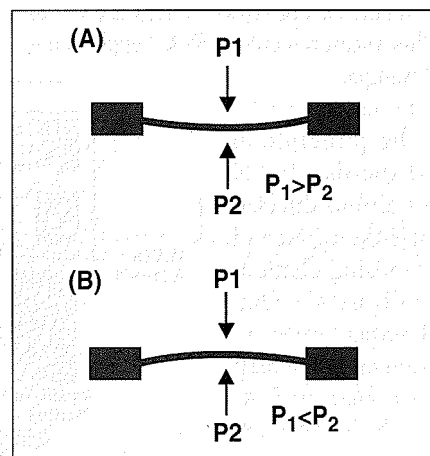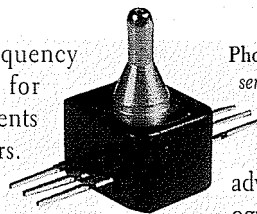
means that it has a wide frequency response and may be used for dynamic pressure measurements without concern about errors. Mechanical vibration and acceleration have a negligible effect.

Using a Flow Sensor to Measure Pressure. A recently developed micromachined flow sensor (see Photo 3) represents a new approach to low-pressure measurement in applications where a small flow across the sensing element may be tolerated. The sensor consists of a thin film thermally isolated bridge structure suspended over a cavity in the silicon IC.

Because of its small size and excellent thermal resistance, only a few milliwatts of power
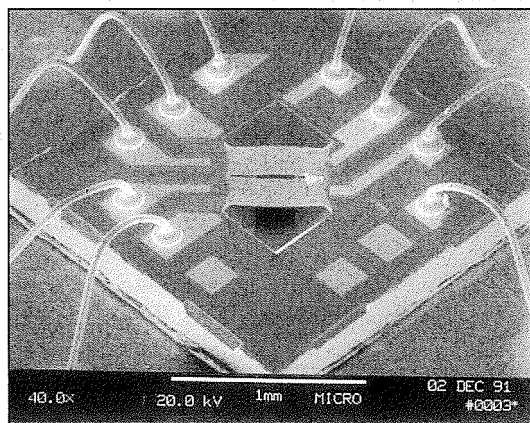

Photo 3. *The recently developed microbridge mass airflow sensor consists of a thin thermally isolated bridge structure suspended over a cavity in the silicon IC. The chip is 67 mil square.*

are required to achieve high air flow sensitivity. By calibrating the device with a flow restriction for a specified pressure drop, a sensor capable of measuring pressures of a few inches of water results. This is ideal for airflow measurement in HVAC applications, for example.

The sensor operates on the principle of heat transfer due to mass airflow directed across the surface of the sensing element (see Figure 25). Output voltage varies in proportion to the mass air (or other gas flow) through the inlet and outlet ports of the package (see Photo 4, page 41). The sensor has a unique silicon chip based on recent

Photo 2. *This totally integrated silicon pressure sensor measures 0.52 in. long by 0.44 in. wide by 0.75 in. high, including the port.*

advances in microstructure technology. It consists of a thin film, thermally isolated, bridge structure containing a heater and temperature-sensing elements. The bridge structure provides a sensitive and fast response to the flow of air over the chip. Dual sensing elements flanking a central heating element indicate direction as well as rate of flow. A specially designed housing precisely directs and controls the airflow across the sensing microstructure. Highly effective thermal isolation for the heater and sensing resistors is attained by the etched cavity air space beneath the flow sensor bridge. The small size and thermal isolation of the microbridge mass airflow sensor are responsible for the remarkably fast response and high sensitivity to flows.

Pressure Switches. Pressure switches, combining a diaphragm or other pressure measuring means with a precision snap switch, can provide precise single-point pressure sensing. Alternatively, simple electronic switches may be combined with electrical sensors to construct a pressure switch with an adjustable set point and hysteresis.

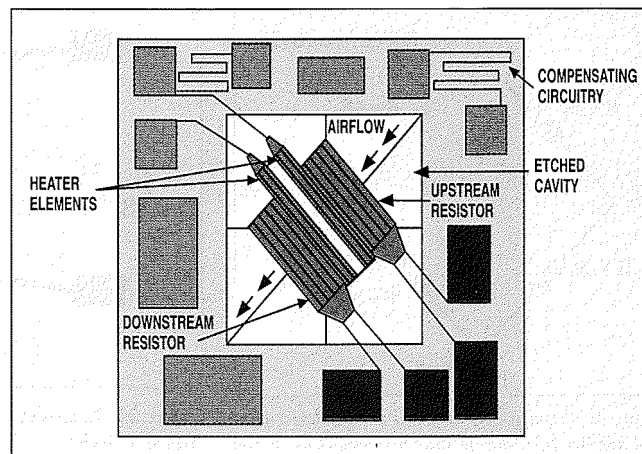**Electrical Interfacing.** Care must be taken with the output from a pressure sensor to avoid corrupting the signal by noise or 60 Hz AC pickup. If the signal must be run some distance to the interface circuitry, twisted and/or shielded wire should be considered. A decoupling capacitor located at the sensor and connected from the supply to ground

Figure 25. *A silicon bar can be bonded to a diaphragm to yield a strain gauge sensor with a relatively high output.*
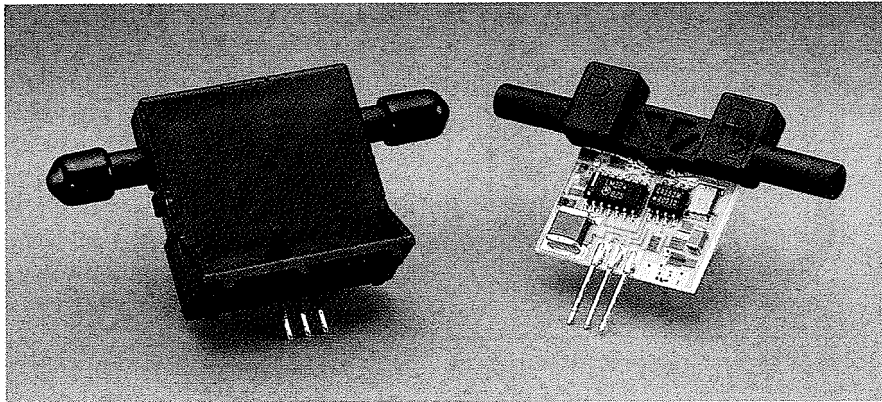
Photo 4. *The output voltage of the microbridge mass air flow sensor varies in proportion to the mass flow of air or other gas through the inlet and outlet ports of the package. The packaged sensor is 1.20 in. wide by 1.24 in. long by 0.61 in. high.*
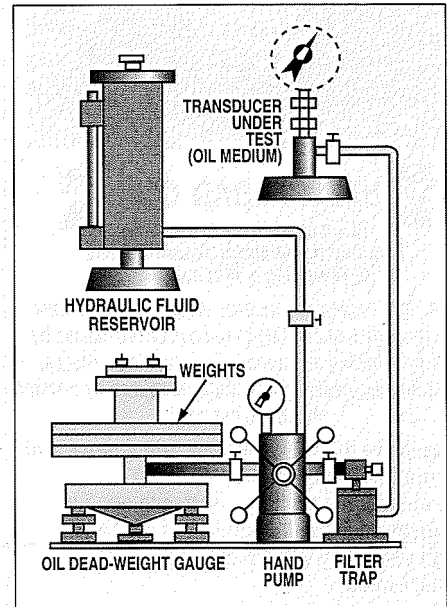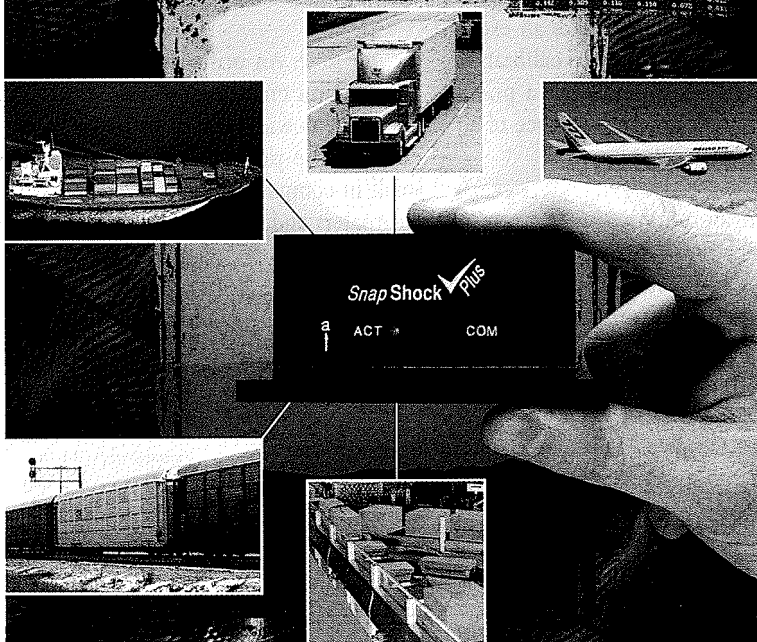

Figure 26. *Dead-weight testers, used to calibrate pressure sensors, incorporate calibrated weights that exert force on a piston which in turn acts on a fluid to produce a test pressure. Oil-type testers like the one shown here are commonly used for high pressures; pneumatic air bearing devices are the usual choice for lower pressures.*
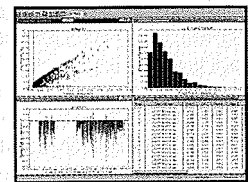
will also filter noise, as will a capacitor from output to ground.

For long runs, a current output sensor should be considered. These devices have a 2-wire interface and modulate the supply current in response to applied pressure. Obviously, wire resistance has no effect and noise must change the loop current, not simply impress a voltage on the signal. The industry standard interface is:

$$P_L = 4 \text{ mA} \tag{19}$$

$$P_H = 20 \text{ mA} \tag{20}$$

where:
P_L = low pressure range limit
P_H = high pressure range limit

With this approach, runs of 1000 ft or more are possible.

Calibration
Manufacturers of pressure sensors have elaborate calibration facilities to verify the accuracy of their production test equipment. These include dead weight testers and temperature-controlled servo-rebalance ▶
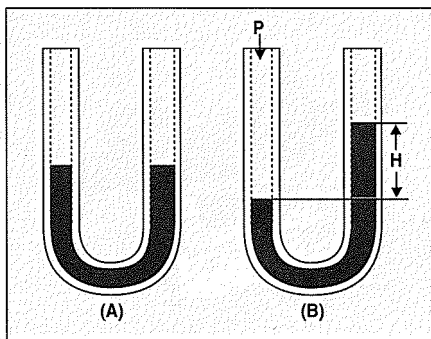
Figure 27. *The mercury manometer, another calibration option for pressure sensors, can be used on gauge, differential, and absolute sensors with a suitable reference. The difference between column heights gives the pressure reading. Manometers are used mainly to calibrate sensors designed to measure in the lower pressure ranges.*

testers using Bourdon tubes made from high-stability quartz.

Dead-Weight Tester. A dead-weight tester uses calibrated weights that exert force on a piston which then acts on a fluid to produce a test pressure. For high pressures (>500 psi), oil is typically used (see Figure 26, page 41); for lower pressures, pneumatic air bearing testers are available and are much more convenient as well as less messy to use.

Manometer. A mercury manometer is a simple pressure standard and may be used for gauge, differential, and absolute measurements with a suitable reference. It is useful mainly for lower pressure work because the height of the column of mercury will otherwise become unwieldy. The difference in column heights gives the pressure reading (see Figure 27).

Low-Cost Calibration. Many of the higher performance commercially available pressure sensors are furnished with individual test data. A sensor with excellent repeatability and hysteresis makes an excellent low-cost in-house pressure calibration reference when combined with a pneumatic pressure regulator and a source of air pressure (see Figure 28).

Selection Considerations

Selection of a pressure sensor involves consideration of the medium for compatibility with the materials used in the sensor, the type (gauge, absolute, differential) of measurement, the range, the type of electrical output, and the accuracy required. Manufacturer's specifications usually

apply to a particular temperature range. If the range of operation in a given application is smaller, for example, the errors should ratio down. Total error can be computed by adding the individual errors (worst-case) or by computing the geometric sum or root sum of the squares (RSS). The latter is more realistic since it treats them as independent errors that typically vary randomly. Following is a comparison of the two methods.

Given the following error terms:
- Linearity = 1% F.S.
- Null calibration = 1% F.S.
- Sensitivity calibration = 1% F.S. Temperature errors are sometimes given as coefficients per °C referenced to 25°C. Simply multiply the coefficient by the temperature range of the application to obtain the total error.
- Temperature error = 0.5% F.S.
- Repeatability and hysteresis = 0.1% F.S.

$$RSS = \sqrt{(1^2 + 1^2 + 1^2 + 0.5^2 + 0.1^2)}$$
$$= 1.8\% \tag{21}$$

Worst case error is equal to the sum of all the maximum errors:

$$Worst\ case\ error = 1 + 1 + 1 + 0.5 + 0.1$$
$$= 3.6\% \tag{22}$$

Applications

Industrial. *Fluid level in a tank*: A gauge pressure sensor located to measure the pressure at the bottom of a tank can be used for a remote indication of fluid level using the relation:

$$h = P/\rho g \tag{23}$$

Fluid flow: An orifice plate placed in a pipe section creates a pressure drop. This approach is widely used to measure flow because the pressure drop may be kept small in comparison to some other types of flowmeters and because it is impervious to
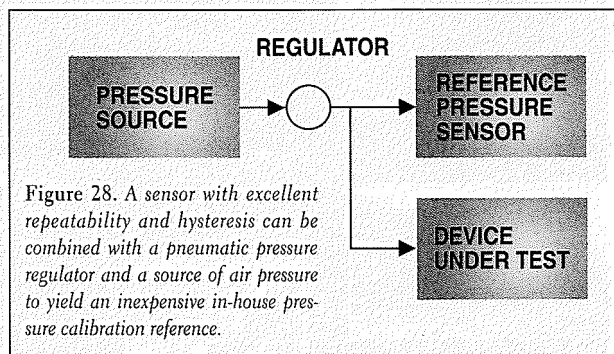

Figure 28. *A sensor with excellent repeatability and hysteresis can be combined with a pneumatic pressure regulator and a source of air pressure to yield an inexpensive in-house pressure calibration reference.*

clogging, which may otherwise be a problem when measuring flow of a viscous medium or one containing particulate matter. The relation is:

$$V_O = \sqrt{2\,(P_S - P_O)} / \rho \qquad (24)$$

In some cases, differential pressures of only a few inches of water are measured in the presence of common-mode pressures of thousands of pounds per square inch. These pressure sensors are built with elaborate mechanisms to prevent damage due to the high common-mode pressures and also frequently have remotely controllable pressure ranging.

Automotive. A wide variety of pressure applications exist in the modern electronically controlled auto. Among the most important are:

Manifold absolute pressure (MAP). Many engine control systems use the speed-density approach to intake air mass flow rate measurement. The mass flow rate must be known so that the optimum amount of fuel can be injected. MAP is used in conjunction with intake air temperature to compute the air density. This requires a 15 psia range or higher (for supercharged or turbocharged engines). It is also desirable to include an altitude correction in the control system, and this requires measurement of barometric absolute pressure (BAP). Some systems use a separate sensor, but it is more common for the MAP sensor to do double duty since it reads atmospheric pressure for two conditions. One, before the engine begins cranking and two, whenever the throttle is wide open.

Engine oil pressure. Engine lubrication requires pressures of 10–15 psig. The oil pump is sized to achieve this pressure at idle and the pressure increases with engine speed. A potentiometric gauge or pressure switch is used for this function since precision isn't required.

Evaporative purge system leak detection. To reduce emissions, modern fuel systems are not vented to the atmosphere. This means that fumes resulting from temperature-induced pressure changes in the fuel tank are captured in a carbon canister and later recycled through the engine. Government regulations require that leaks in this system be detected by the onboard diagnostics system. One approach is to pressurize the system and measure pressure decay over a fixed time interval. A 1 psig sensor is used for this function.

Tire pressure. Recent development of the "run-flat" tire has prompted development of a remote tire pressure measurement system. The reason is that a flat tire of this type is difficult to detect visually and the distance over which it can be used without any pressure is limited. ■

Robert E. Bicking is a Senior Engineering Fellow, Honeywell Micro Switch, 11 W. Spring St., Freeport, IL 61032-4353; 815-235-5547, fax 815-235-5670.

Reader Feedback

To rate this article, circle the appropriate number on the Reader Service Card.

3	13	23
Excellent	Good	Fair