J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

PRESSURE SENSORS

Each physical quantity A can be measured by use of primary methods of measurement or by secondary methods, that is, by measurement of some other quantities W_i in physical relation with quantity A. Quantity A must be measured or must be controlled (regulated), but it is desirable to measure quantities W_i because of their advantages. There are many physical and technical possibilities for designing a specific device giving the relation between A and W_i. Such a device is called a transducer (measurement transducer, because the meaning of the word *transducer* is very wide and can mean any change-processing devices). A transducer is a device that provides a usable output signal in response to a specific measurand (a measurand is the physical quantity being measured). Transducers have their own internal structure. In the simplest case we can imagine some elementary transducers connected in linear order. Based on the physical background we can find a specific physical phenomenon, in our case, pressure that has a known, well-defined, influence on some quantities that characterize a specific body: volume, dimensions (linear and angular displacements, strain), resistance, sound velocity, density, dielectric constant, or other quantities whose variations allow determination of pressure. Let us call that body a *pressure-sensing element,* or *primary pressure transducer.* From a transformation theory point of view, it receives and transforms information by itself. A *pressure sensor* device, see Fig. 1, consists of the pressure-sensing element and at least one basic (secondary) transducer. This transducer converts a sensing-element signal into another quantity, one of the quantities W_i chosen as the most convenient, not only an electrical quantity. In this article only sensing elements (primary transducers) and basic (secondary) transducer systems are considered. Within the group of secondary transducers, capacitive, inductive, reluctive, strain gauge, resistive, potentiometric, and piezoelectric transductions are used for information processing in modern pressure sensors. Pressure sensors can have digital or analog output. In analog sensors output signals are voltage amplitude, voltage ratio, current, frequency, capacitance, and inductance.

Fundamental Definitions

Pressure is one of the fundamental physical quantities that describes the thermodynamic state of a body. Pressure is an intensive type of quantity, that is, defined at points, it is a scalar parameter describing the “force side” of the body. Pressure characterizes the intensity of the internal effective repelling forces tending to increase the volume of a body. The intensity of this force in every case is demonstrated as a continuously distributed force acting on a unit area. By this we mean the surface area of a vessel enclosing a defined body (for example, gas) or any virtual surface inside the body (gas). Pressure is not a basic physical quantity and therefore it is defined by other basic quantities resulting from the defining equation, that is, newton/m^2 (N/m^2) or pascal (*Pa*). Let us interpret the pressure using the stress tensor σ_{ij} defined at each point in the volume of a concrete body. In the ideal gas no tangential component of the stress tensor exists. Normal and negative components are equal to each other so we can write $\sigma_{ij} = -p\delta_{ij}$, where δ_{ij} is a Kronnecker delta and p is a parameter of state called pressure. In this case pressure can be expressed by the classical formula $p = 2n\langle E\rangle/3 = \rho\langle v^2\rangle/3$, where n is the number of particles in a unit volume, $\langle E\rangle$ is the mean kinetic energy of the particles,

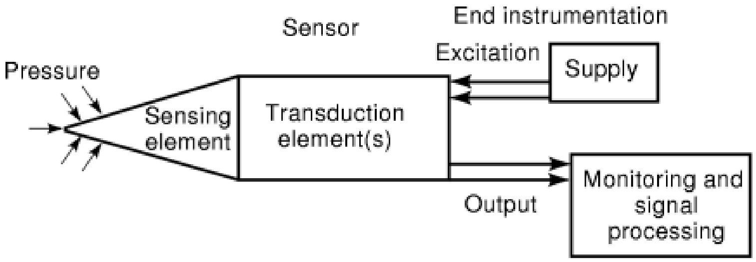

Fig. 1. Schematic of a pressure sensor.

ρ is the density of gas, and $\langle v^2 \rangle$ is the mean value of the square velocity of particles. Pressure in an ideal gas is associated only with the thermal motion of particles and therefore can be considered as fully "hot." In the case of real gas the hot pressure is partially reduced by the so-called *internal pressure* caused by the some intermolecular attractive bond interactions. In the case of liquids the internal pressure makes the hot pressure practically "frozen." "Cold pressure" can be produced in liquids by mass or in a closed volume by surface forces. In real liquids (e.g., natural water) in thermodynamic equilibrium at some place close to the Earth's surface, the forces acting inside the liquid on a directed surface element dA are given by the formula $\boldsymbol{dF} = -\mathbf{n}p dA$, where $\boldsymbol{n}$ is a vector of element dA and $p = \rho g h$, where g is the Earth's acceleration, ρ is the density of a given liquid, and h is the distance between the free surface of the liquid and a specific point. This formula was given by Pascal, who defined p as the hydrostatic pressure. In the case of solids the correct interpretation of pressure and its effects is more difficult. The stress tensor σ_{ij} can be formally separated into two components: the axial stress tensor $A_{ij,i=j}$, with identical values of diagonal elements equal to (Tr σ_{ij})/3, and the deviatoric stress tensor D_{ij}, whose elements can be expressed as $D_{ij} = \sigma_{ij} - \delta_{ij} A_{ij}$. If all modules of deviatoric elements are small relative to the modules of negative-sign axiatoric elements, we define such a stress state as a quasihydrostatic pressure, which is the real situation. When the deviatoric stress tensor disappears and axiatoric elements are negative, hydrostatic pressure is acting in the solid. In the field of pressure measurement one should become familiar with the following definitions: *Absolute pressure* is pressure measured relative to zero pressure (MPa abs). *Zero pressure* is a state of vacuum. *Vacuum* is a state of space (a closed volume) in which pressure is reduced to a minimum that can be attained through practical means. *Perfect vacuum* is zero absolute pressure, resulting in the complete absence of any particles of matter. *Standard pressure* is the pressure of one normal atmosphere. *Gauge pressure* is the pressure measured relative to ambient pressure, usually relative to actual atmospheric pressure (MPa gag). *Differential pressure* is the difference (usually small) between pressures acting in two specific volumes (points) measured using one sensing element (MPa dif). *Stationary pressure* is pressure that is held constant long enough relative to the longest relaxation time of specific processes that take place in the liquids or solids under study. *Dynamic pressure* is a pressure generated by an impact wave causing a "jump" in the density (also internal energy) on a front of the impact wave. This phenomenon is fully nonreversible. We can speak also about *quick variable pressures,* which are generated continuously but the length of the pressure wave exceeds the dimensions of the container or the pressure sensor. With a pressure medium flowing in tubes, there is *static pressure* of the flowing fluid (the fluid is a liquid or gaseous substance), which can be measured normal to the direction of flow at the inner surface of a tube. *Impact pressure* is the pressure that can be generated in a moving fluid due to flow velocity. The *stagnation pressure* is the sum of the static pressure and impact pressure. *Partial pressure* is a pressure exerted by one constituent of a mixture of gases.

Primary Pressure Measurements

There are two primary methods for generation and measurement of pressure: using liquid manometers (1), which are the most accurate and range from a few pascals to about 0.5 MPa, and using gas or liquid-operated dead-weight manometers (pressure balances or piston gauges) (2). For the first type of manometer the difference of pressure Δp between two levels h_2 and h_1 is given by

$$\Delta p = \int_{h_1}^{h_2} \rho(h, T) g(h)\, dh \qquad (1)$$

where ρ is density of liquid (mercury in the most cases), known most accurately through the primary measurements of mass and length with temperature and pressure corrections and $g(h)$ is a local Earth acceleration known also on the basis of the most accurate primary measurements of time and length. In the second method, based on metrological properties of a quasisealed piston–cylinder system, the generated pressure is given by

$$p = Q_{\text{eff}}/A_{\text{eff}} \qquad (2)$$

where p is a pressure generated just under the bottom surface of the piston and Q_{eff} is the effective weight of a standard mass used as a force generator. The acceleration of the Earth must be known at the specific location of the experiment with highest accuracy; air buoyancy, the surface tension effect, and other corrections should also be taken into consideration. The quantity A_{eff} is the effective area of the piston–cylinder system. At first approximation for low pressures it is equal to the mean values of the piston area and the inner-hole area of the cylinder. A_{eff} depends slightly on temperature and more strongly on pressure, and therefore its pressure dependence is a fundamental problem for designers of this type of pressure etalon (3). There are three fundamental types of piston–cylinder systems: simple-piston, reentrant-cylinder, and controlled-clearance systems. The last one is schematically shown in Fig. 2. The first and third systems have found wide applications in practice; the first for pressures below 1 GPa and the third for pressures up to 1.4 GPa are commercially available. The accuracy of pressure balance depends on its pressure range and is illustrated in Fig. 3 (2).

General Characteristics of Pressure Sensors

A pressure sensor is normally designed to sense (measure) a specific measurand, pressure, and to respond only to this measurand according to the theoretical formula or to the pressure scale. The pressure scale is given by several pressure values well established from primary methods of pressure measurements. Real metrological properties of sensors are described by the following characteristics [see, e.g., Ref. 4]:

(1) Measurand characteristics
(2) Electrical design characteristics
(3) Mechanical design characteristics
(4) Static performance characteristics
(5) Dynamic performance characteristics
(6) Environmental characteristics
(7) Installation (reinstallation) effects and mounting errors

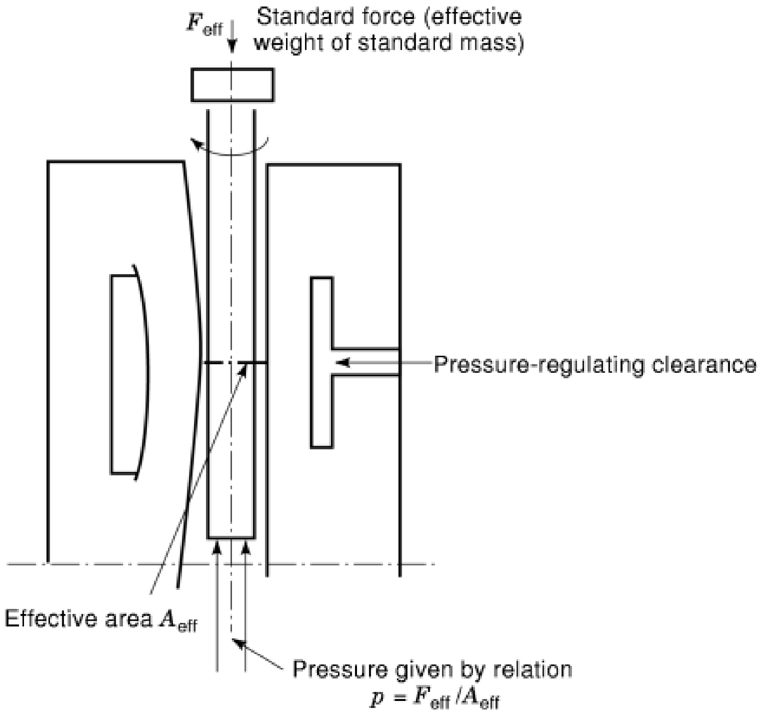

Fig. 2. Schematic of a piston gauge (pressure balance) with a clearance-controlled piston–cylinder system. On the right an initial clearance and on the left a reduced clearance at the measurement moment are shown.

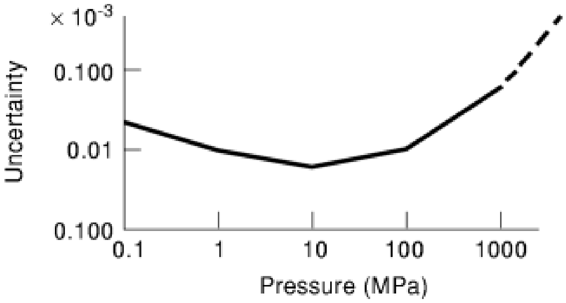

Fig. 3. Accuracy of pressure balances as a function of the maximum pressure range (2).

(8) Reliability characteristics (overload, life, and the number of operating cycles)

Measurand characteristics for pressure sensors is the *character* of pressure, which can be static, dynamic, or variable (quick-variable), and *range* of pressure defined by lower and upper limits. The range of pressure sensors is in principle unidirectional (e.g., from 0 MPa abs to 10 MPa abs) and asymmetrically bidirectional in the case of gauge pressures when the reference pressure is atmospheric pressure (e.g., from −0.1 MPa gag to 1.0 MPa gag) or expanded and suppressed-zero scale (e.g., from 0.3 MPa abs to 0.5 MPa abs). The algebraic differences between the limits of the range in the span of the sensor (for the preceding examples) are equal to 10 MPa, 1.1 MPa, and 0.2 MPa. Some electrical design characteristics are as follows:

(1) *An excitation,* usually stated in terms of dc or ac voltage or of a current applied to the sensor (only piezoelectric pressure-sensing elements do not require external electrical excitation for operation)

(2) *Output,* an electrical quantity produced by the sensor as a function of the measured pressure, in analog form as a continuous function of current or voltage magnitudes and also a continuous variation of capacitance, inductance, frequency. In the case of digital output, the system gives information in the form of discrete quantities coded in the specific notation, preserving the accuracy of the sensor throughout the measuring system.

(3) *End points,* which are the output values at the lower and upper limits of the sensor range.

(4) *Impedances* across the output terminals and across the excitation terminals, and load impedance presented to the sensor output by the associated external circuitry and transmission line (mismatching of output impedances can cause loading error.

(5) *Demodulator and amplifier* characteristics and also *grounding,* which can be isolated or common for input and output, or floating when two or more portions of sensor are electrically isolated.

The main static performance characteristics of a sensor is usually determined by the test during which known values of pressure are applied to the sensor in an ascending mode and descending mode (a calibrating cycle), and corresponding output readings are recorded and correlated. The output of the actual sensor is affected by its real behavior, which causes the indicated pressure value to deviate from the ideal characteristic (true values). The algebraic difference between the indicated value and true value is a sensor error or sensor uncertainty (usually expressed as a percentage of full-scale output). The ratio of the error to the full-scale output is defined as the relative uncertainty or accuracy class. Pressure sensor errors can be considered in terms of maximum deviation over the range from known reference lines, but interpretation of individual errors such as nonrepeatibility, hysteresis, zero and sensitivity drift, possible friction errors, and nonlinearity (when linear functions of output pressure can be accepted) are required. For high-pressure sensors hysteresis induced by sensing elements is the main source of measurement errors. Dynamic performance characteristics are characterized by a *frequency response,* that is, frequency dependence of the output to pressure amplitude ratio when the pressure varies sinusoidally. We can speak of $\nu_{\max}$ below which the response is correct within some percent of error and $\nu_{\min}$ above which the sensor response is correct, in the cases when a sensor is designed for quick variable pressure measurements. Another useful dynamic parameter is the *response time,* when a stepped change of pressure is applied to the sensor and its output reaches some arbitrary fixed level, say 90% of the final value. In most cases, when $p_{\text{step}} > 0$, the pressure change satisfactorily describes the relation $p_{\text{read}} = p_{\text{step}}\,(1 - e^{-t/\tau})$ where τ is the time constant of the sensor. After that time the response of the sensor reaches about 63% of its final value or decreases by 63% of the p_{step} value when it has a negative sign. The upper limit of the frequency response and response time characteristics of the sensor are controlled by its energy-dissipating properties, that is, damping processes. Each oscillation process can be underdamped, critically damped, and overdamped. In an underdamped state of the sensor, an oscillation of the output is observed. In overdamped and critically damped states, the steady value is reaching monotonically with different values of τ. In the last situation (at critical damping) the time constant is smallest. The specific external conditions (temperature, shock, vibration, and humidity) to which a pressure sensor may be exposed during storage and operation constitute *environmental conditions.* The influence of temperature in the *operating temperature range* should be defined within specific error limits—a temperature error or temperature error band. The effect of temperature causes a thermal zero drift, thermal sensitivity shift, and temperature gradient error (a transient error). For the pressure sensors the knowledge of the influence of temperature on the sensor properties is very important because any change of pressure is connected with a change in temperature, especially for dynamic pressure. There are many scientific and industrial demands related to the pressure measurement at elevated or high temperatures (or cryogenic low temperature). For such demands a specific pressure sensor has been developed (5,6). Acceleration effects may be especially large when mechanical pressure-sensing elements are used. The

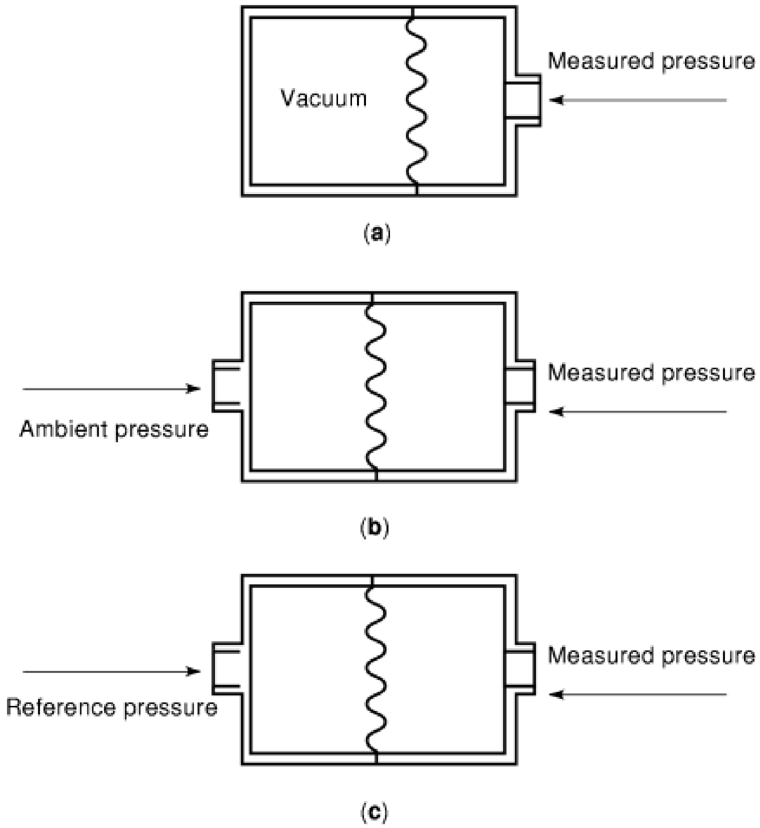

Fig. 4. Reference pressures: vacuum (for absolute pressure measurements), ambient pressure or normal pressure (for gauge pressure measurements), and basic, variable pressure (for differential pressure measurements).

error connected with this effect is usually more severe along one axis of the sensor than along the other axis, which depends on the sensing element's construction. Too large an acceleration (10*g* or higher) may lead to the failure of the sensor. For rocket technology, special pressure sensors are constructed. In some pressure-sensing elements such as the resistance pressure gauges, the sensitivity to acceleration is negligible. Vibration effects (vibratory acceleration) can affect pressure sensors in the same manner as constant acceleration does. The vibration effects may reduce static error connected with friction error and may induce resonance effects at some characteristic frequencies, with the largest effect connected with the main resonance.

Let us define *low pressures* as pressures for which the standard pressure is not negligible. Practically, we can accept it as 100 MPa, which makes the standard pressure 10^{-3} of the maximum value of the low-pressure value. For this range of pressure the differences among *absolute, gauge,* and *differential* pressures are essential. In Fig. 4 there are shown reference configurations adequate to low-pressure using diaphragms as pressure-sensing elements. The most commonly used classical, in principle mechanical, elastic sensing elements and the nature of their deflections are illustrated in Figs. 5 and 6.

Diaphragm Pressure-Sensing Elements

Flat diaphragms are essentially circular, rectangular, or square-edge-clamped elastic thin plates (noncircular plates play an important role in silicon pressure sensors). Let us consider here the simplest situation, that is, a deformation state of a thin circular plate loaded on one side by measured pressure, which is a classical problem

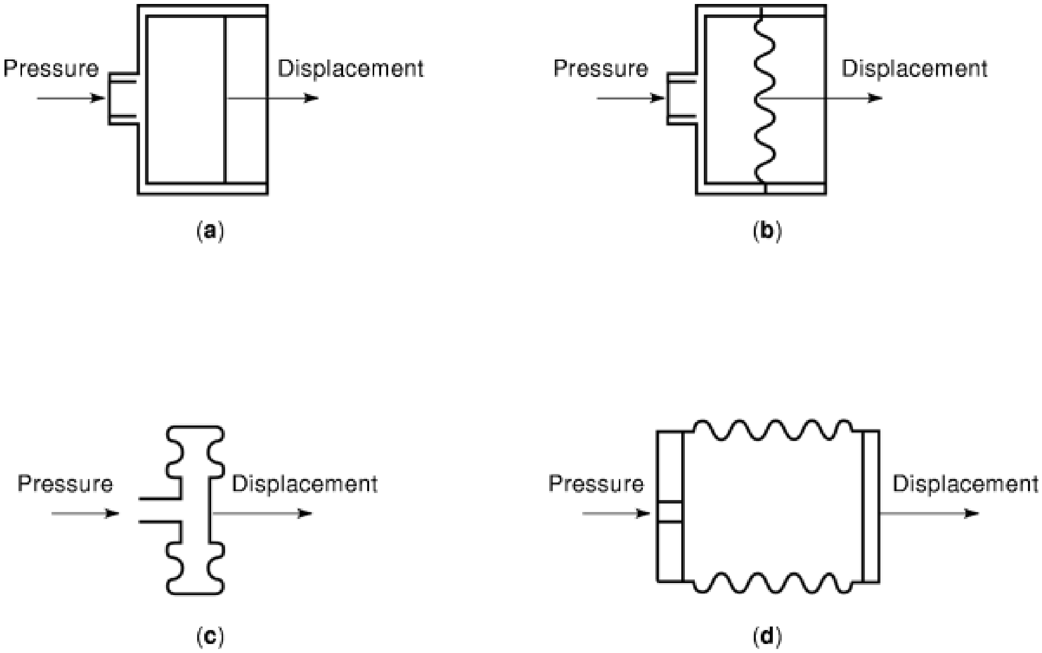

Fig. 5. Elastic pressure-sensing elements: (a) flat diaphragms, (b) corrugated diaphragms, (c) capsules, and (d) bellows.

in the elastic theory of plates (7). Figure 7, in enlarged scale, shows a plate deformed by pressure. The radial ε_r and tangential strains ε_τ of the bottom free surface are given by

$$\begin{aligned}\epsilon_r &= 3(1-\nu^2)(a^2-3r^2)p/8Eh^2\\ \epsilon_\tau &= 3(1-\nu^2)(a^2-r^2)p/8Eh^2\end{aligned} \qquad (3)$$

where a is the radius of the diaphragm, h a thickness, ν Poisson's ratio, E Young's modulus of the plate material and r the local (optional) radius. At the center of diaphragm, that is, for $r = 0$, we have

$$\epsilon_r = \epsilon_\tau = 3(1-\nu^2)a^2p/8Eh^2 \quad \text{(tensile, positive strain)} \qquad (4)$$

and deflection

$$f = 3(1-\nu^2)a^4p/16Eh^3 \qquad (5)$$

On the edge of diaphragm, assuming perfect clamping, for $r = a$, we have

$$\begin{aligned}\epsilon_r &= 3(1-\nu^2)a^2p/4Eh^2 \quad \text{(compressive, negative strain)}\\ \epsilon_\tau &= 0\end{aligned} \qquad (6)$$

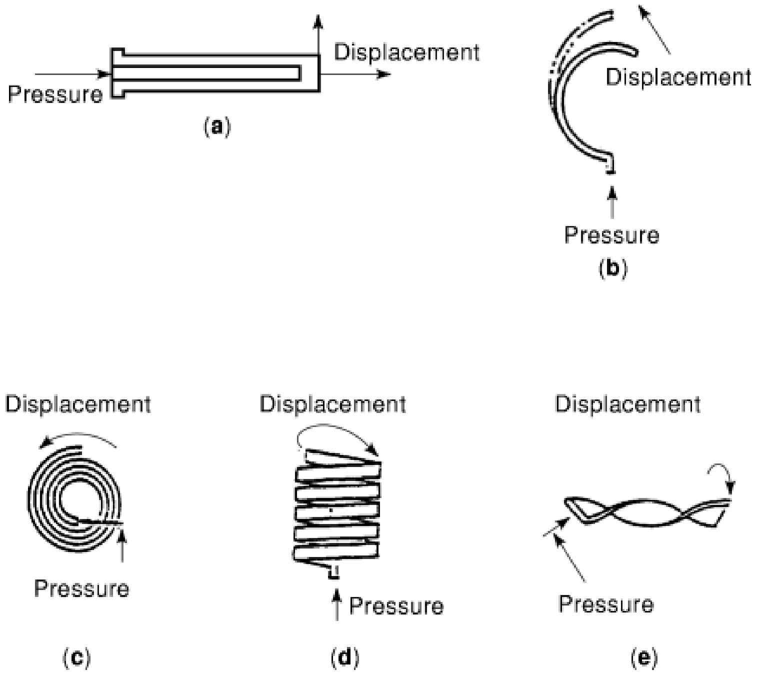

Fig. 6. Elastic pressure-sensing elements: (a) straight tube, (b) curvilinear (Bourdon tube) basic type, (c) spiral type, (d) helical type, and (e) twisted type.

A good approximation of the fundamental resonant frequency of the diaphragm is given by

$$f_R = 0.47hE^{0.5}/a^2\rho^{0.5}(1-\nu^2)^{0.5} \qquad (7)$$

So, one can see that the deflection at the center is proportional to the applied pressure (differential pressure across the diaphragm) and varies with the fourth power of its diameter. The preceding expressions are valid for small deflections only. With increasing pressure in the deformed diaphragm, tension stress starts to play an increasingly important role. The characteristic pressure or deflection for large deflections is therefore strongly nonlinear. The deflection at the center of a diaphragm for $f < 4h$ can be to a good approximation calculated from following expression (8):

$$pa^4/Eh^4 = 16f/3(1-\nu^2)h + 6f^3/7h \qquad (8)$$

For the higher deflections, but not higher than $10h$, the following, simpler, formula can be used:

$$pa^4/Eh^4 = 3.45(f/h)^3 \qquad (9)$$

Flat diaphragm pressure-sensing elements as primary transducers of the pressure-to-displacement or pressure-to-strain type are widely used in practice within the pressure range from some kilopascals to about 100 MPa and in special designs up to 1 GPa (high-pressure performance). Their typical accuracy varies from 0.5% up to 2%. *Corrugated diaphragms* contain a number of concentric corrugations of different shapes and dimensions.

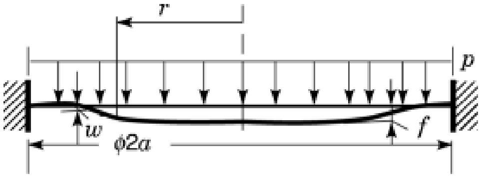

Fig. 7. Pressure-loaded edge-clamped thin elastic plate (illustration of deformation in enlarged scale).

These increase the stiffness as well as the effective area of the diaphragm, the measurement of which is very important in the case of the pressure-to-force transducer. The useful deflection is therefore larger than that of the flat diaphragms. The deflection can be a linear function of applied pressure with proper selection of corrugation and thickness of diaphragms. The coefficient of proportionality between pressure and deflection depends on the shape, location, and number of corrugations. In Fig. 8 examples are given illustrating this problem (8). Corrugated diaphragm sensing elements are typical pressure-displacement primary transducers, having a typical accuracy of 1.5% to 2.5%, and they can measure the pressure from some kilopascals up to some megapascals. Diaphragms made of very thin metal or nonmetallic materials (soft diaphragms) are called *membranes*. Membranes used as pressure-sensing elements are backed by a spring that provides necessary elastic properties. Typically membranes are used to isolate the pressure-sensing element from the pressurized chemically active liquid. As a pressure-transmitting medium a silicone oil with optimal properties from a metrological point of view is used. Pressure-sensing elements called *capsules* can have open or closed form [see Figs. 9(a) and 9(b)]. The closed-form element with vacuum as a reference pressure is frequently referred as an *aneroid* and is used in atmospheric pressure manometers. It consists of two corrugated metal diaphragms formed into shells of opposite curvature and fastened together with hermetically sealed joints around their peripheries, by (most preferred) inert-gas or electron-beam welding. Factors influencing the deflection of capsules are the same as those that apply to corrugated diaphragms. The use of two corrugated diaphragms in one capsule nearly doubles the deflection obtained from each diaphragm. Capsules are often joined in double or triple systems [see Fig. 9(c)]. The *bellows* sensing element is usually made of a thin-walled tube formed in a large number of deep convolutions sealed at one end, which can translate axially when pressure is applied to a port in its opposite anchored end. Due to large numbers of their convolutions, bellows are frequently used when a large stroke is required. The number of convolutions vary from five to over twenty depending on pressure and displacement requirements and on outside diameter. Bellows are sensing elements that can work as a pressure-to-displacement transducer or pressure-to-force transducer. In pressure-to-force transducing the determination of the effective area of the bellows is very important. The effective area of the bellows is the effective area of the piston gauge in equilibrium with the force resulting from the pressure acting inside the bellows, which is equal to the pressure in the piston gauge. The effective area of the bellows is constant to a high degree. The pressure range covered by bellow sensors is typically from 0.1 MPa up to 1.0 MPa and the accuracy is about 1%. In the case of bellows, a large hysteresis up to 2% can be observed. Diaphragm and bellow sensing elements are made of high-elastic metal alloys such as brass, bronze, phosphor bronze, beryllium copper alloy, stainless steel, and alloys called Monel, Inconel, and NI-Span C. An important consideration in the selection of diaphragm materials is the chemical nature of the fluids that will come in contact with the diaphragm. Proper manufacturing methods include heat-treating and pressure-cycling to reduce elastic aftereffects like drift, creeping, and hysteresis in the diaphragms.

Bourdon-Tube Sensing Elements

The Bourdon tube is named after the French inventor, Eugenie Bourdon, who patented it in June 1849, and has found very wide applications. The Bourdon tube is a curved or twisted tube, typically oval or elliptical in cross section, which is sealed on one end (tip) and rigidly mounted on the other. When pressure is applied internally

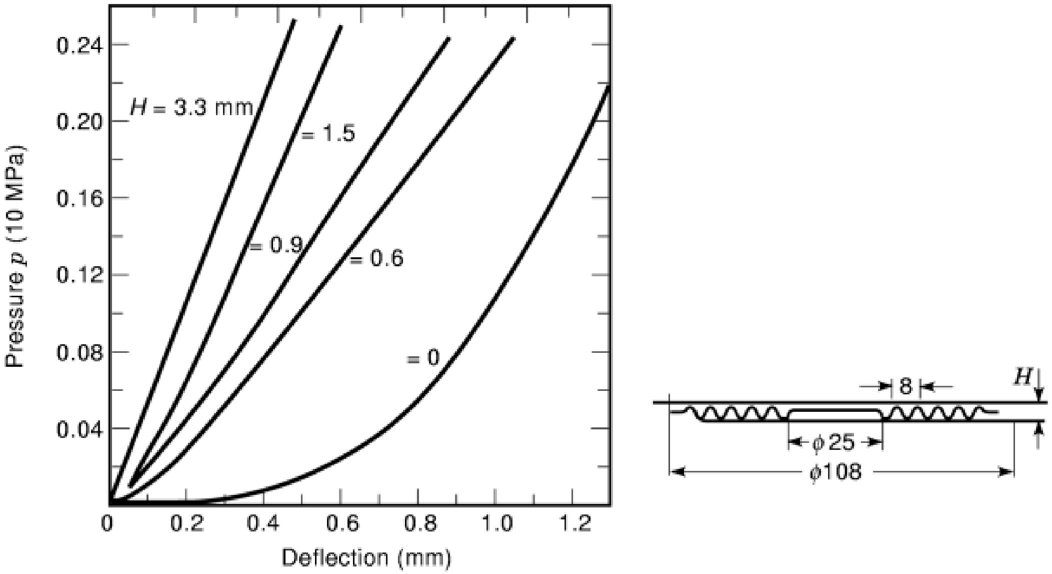

Fig. 8. Illustration of the problem of obtaining of the linear dependence of deflection for corrugated diaphragm under pressure (8).

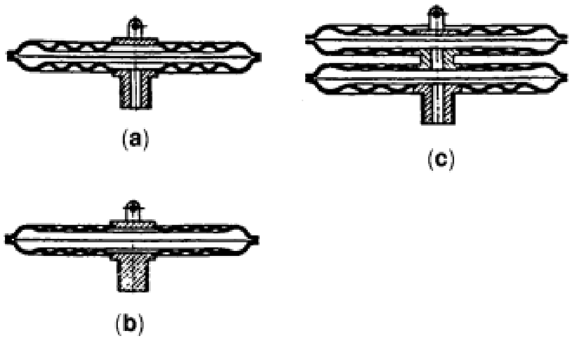

Fig. 9. Different type of the capsule systems: (a) open forms for gauge pressure measurements, (b) closed form (aneroid) for measurements with a given reference pressure, if vacuum is used for absolute pressure measurements (typically for atmospheric pressure, and (c) double system of capsules.

to the tube, the tube tends to straighten. This phenomena can be easily but quantitatively explained as follows. When the Bourdon tube is subjected to an internal pressure, the cross section approaches a circle and the length of the tube increases slightly with pressure; hence the effect is to increase the radius of the tube. This results in a curvilinear tip deflection (tip travel) in curved tubes and an angular tip deflection in twisted tubes. The principle of action of this simple device is very difficult to describe in terms of elastic theory. For *C-shaped Bourdon* tubes (see Fig. 10), the initial total angle of curvature ψ_0 (typically of 180° to 270°) decreases by $\Delta\psi$ up to ψas a result of the effective pressure (the difference between internal and ambient pressures). In the case of low pressure (thin-walled Bourdon tube, i.e., when the ratio of the thickness g of the tube to the minor dimension of its cross section b is smaller then 0.6) we have the following approximate expression defining the main characteristic of a Bourdon tube (8):

$$\Delta\psi/\psi = p(1-\nu^2)R^2(1-b^2/a^2)\alpha/Ebg(\beta + R^2g^2/\alpha^4) \quad (10)$$

where R is the mean curvature radius of the tube and α and β are parameters depending on the shape of the tube cross section the values of which are given in the Table 1. In the case of a high-pressure Bourdon tube (thick-walled tubes, $g/b > 0.7$) we can use following expression:

$$\Delta\psi/\psi = p(1-\nu^2)R^2(1-X)/Ebg(g^2/12b^2 + X) \qquad (11)$$

where $X = (\sinh^2 c + \sin^2 c)/c(\cosh c \sinh c + \cos c \sin c)$ and constant $c = (3^{0.5}\alpha^2/\mathrm{Rg})^{0.5}$. The tip travel $\boldsymbol{w}$ can be described by two components, radial, w_{r}, and tangential, w_τ as follows:

$$w_{\mathrm{r}} = \Delta\psi R(1-\cos\psi_0)/\psi_0, \qquad w_\tau = \Delta\psi R(1-\sin\psi_0)/\psi_0 \quad (12)$$

In practice the deflection of the free end of the tube is a linear function of the pressure. From Eqs. (10) and (11) we can see that the wall thickness, the *a*/*b* ratio Young's modulus, the radius of curvature and other parameters in the case of more complicated cross sections of the Bourdon tube determine the sensitivity of the tube to pressure changes. For laboratory use, the precision of about 0.1% of full scale is attainable for pressures as high as 1 GPa. For pressures up to 2 GPa, the Bourdon tubes have been developed with an accuracy on the order of 1% to 2%. In many commercially available versions of Bourdon manometers the servo systems have been incorporated into the gauge mechanism, enabling automatic recording and regulation. Typical pressure ranges for this type of Bourdon manometers are from 0.01 MPa up to 0.6 MPa with typical accuracy of 0.2% to 2%. As an important extension of the simple Bourdon gauge, pressure-sensing elements in the form of spirally and helically wound tubes have been developed and also widely used. *The spiral Bourdon* tube amplifies tip travel due to its multiturns (usually 3 to 6 turns). Of course, its curvature radius increases with each turn from port to tip but the tube centerline is in one plane. In the case of the *helical Bourdon tube,* since it is coiled into multiturns, the total angle of curvature is typically between 1800° and 3600°. Its tip travel is proportionally greater than that of the tube with less than 360° curvature. For low-pressure applications (up to about 5 MPa) the pressure-sensing element is manufactured from quartz, and for higher pressures only high-strength elastic metallic materials are used. The *twisted Bourdon tube* is a strong flattened tube, twisted along its length. The total number of twists is usually between 2 and 6, but it can be less than one full turn. The twist rate (twists per unit of length) also varies within wide limits. The centerline of the tube is straight throughout its length under normal and pressurized states. The metrological deflection is an angle created by the rotating free end of tube in relation to its anchored second end (pressure port). In special cases prestressed twisted tube gauges do not show any deflection until a pressure close to the definite lower limit of it measuring range is reached. Then deflection occurs only over the narrow part of the pressure range, so zero suppression can be obtained for that kind of transducer. The deflection of this kind of Bourdon tube varies also with the ratio of its major to minor cross-sectional axes, the difference between internal and external pressure, the total tube length, and the rate of twist of the twisted tube. It also strongly depends on the wall thickness of the tube and the modulus of elasticity of the tube material. Materials used for fabrication of Bourdon tubes are practically the same as for diaphragm fabrication. More complicated is the process of its fabrication. The tubing can be machined from one bar stock or can be drawn. Tube fabrication begins with a regular shape and then flattening and forming into the desired configuration takes place. Machined tubes can have one or two ends integrally machined from the same bar stock. Drawn tubes are welded or brazed to the fittings or to the machined base port section of the transducer. Then the tip is sealed, welded, or brazed with great care to ensure leak-proof joints. After these operations the pressure and temperature cycling is performed.

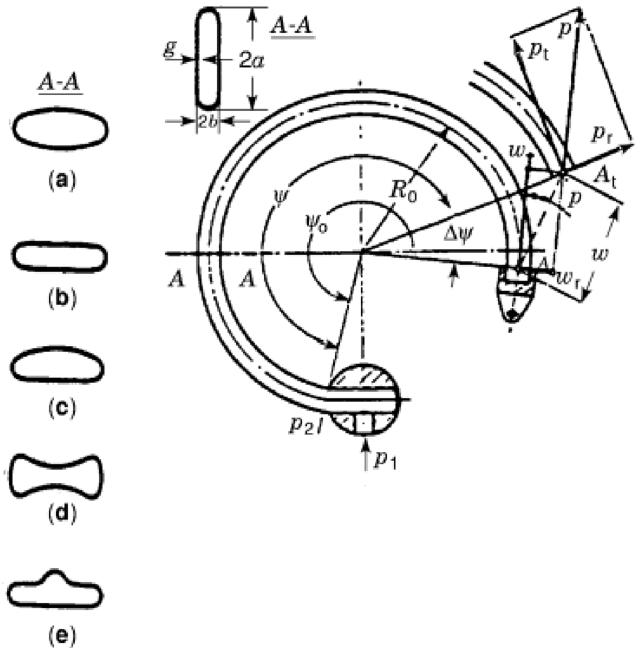

Fig. 10. *C*-shaped Bourdon tube main dimensions; various cross sections of tubes for low-pressure measurements (8).

Table 1. Data for Deformation Calculation of C-Shaped Bourdon Tube Expressions (10-11)

Cross Section of the Tube		a/b										
		1	1.5	2	3	4	5	6	7	8	9	10
(a)	α	0.750	0.636	0.566	0.493	0.452	0.430	0.416	0.406	0.400	0.395	0.390
	β	0.083	0.062	0.053	0.045	0.044	0.043	0.042	0.042	0.042	0.042	0.042
(b)	α	0.637	0.549	0.548	0.480	0.437	0.408	0.388	0.372	0.360	0.350	0.348
	β	0.096	0.110	0.115	0.121	0.121	0.121	0.121	0.120	0.119	0.119	0.118

Straight-Tube Sensing Elements

Straight-tube sensing elements are used in an increasing number of pressure sensors. Based on the Bourdon idea it was suggested (9) to design a straight tube with an eccentric bore. When pressurized with liquid the tube will bend because there is a net force due to pressure in the bore acting on one side of the neutral axis of the tube (on the hole axis side). The resultant deflection can be recorded by means of any displacement transducer, for example a dial micron gauge. Not too high an accuracy from 1% up to 2% of this transducer has been reported. The design is rather easily to fabricate and is well suited to high-pressure applications. The second type of straight-tube element widely used in practice has a circular cross section. A differential pressure acting across its wall causes a very slight expansion or change of the tube diameter and length. These changes of tube dimensions can be easily detected by means of the proper displacement transducer or can be calculated based on knowledge of the longitudinal and circumferential strains of the open surfaces of the tubes. These tube elements being short tubes or cylinders, are devided into two groups: thin-walled cylinders and thick-walled cylinders. Each group can have closed-end or free-tube versions; see Fig. 11. Thin-walled cylinders are sensing elements for small pressures, and thick-walled cylinders are sensing elements for high-pressure measurements. With a strain gauge transduction system $\varepsilon \rightarrow \Delta V$ many commercial types of low and high-pressure sensors were developed. In the case of thin-walled cylinders one obtains the longitudinal strains ε_l and circumferential strains ε_τ from Laplace sheet theory (7) taking into account also the existing longitudinal stress due to the pressure acting on the closed end:

$$\epsilon_\tau = pD(2-\nu)/4gE, \qquad \epsilon_1 = pD(1-2\nu)/4gE \tag{13}$$

where D is the inside diameter of a cylinder, g the thickness of a cylinder, E Young's modulus and ν Poisson's ratio of cylinder material. The classical tube sensing elements have some disadvantages: the influence of a closed end and the mounting stress in the open end of the tube on strains where the strain gauges are bonded, so in any case such pressure sensors must be tested. In the case of the free cylinder pressure-sensing element (10), that is, with a tube having two free ends, the longitudinal stress does not exist. In this case, for a thin-walled cylinder, from Laplace sheet theory, one can obtain

$$\epsilon_\tau = pD/2gE, \qquad \epsilon_1 = -\nu pD/2gE \tag{14}$$

The longitudinal strains are negative here and the results from Poisson's ratio contrast the classical case, where they are positive. This fact enables us to increase the bridge sensitivity by thermostating the strain gauge bonded along the cylinder. Further advantages of this solution are an exact expression for strains and the lack of an influence of the mounting stress, except the small friction force due to o-ring sealing applied in this design. For high pressures the thick-walled cylinder must be used. Thus the calculations of circumferential and longitudinal strains can be based on Lame's theory (7), which gives following expressions: For closed-end tubes

$$\epsilon_\tau = p(2-\nu)/(W^2-1), \qquad \epsilon_1 = p(1-2\nu)/E(W^2-1) \tag{15}$$

and for free tubes

$$\epsilon_\tau = 2p/E(W^2-1), \qquad \epsilon_1 = -2\nu p/E(W^2-1) \tag{16}$$

where W is the wall ratio (the ratio of the outer to inner diameter of cylinder). When pressure is applied not only inside the tube but also on the end surfaces (10) one can obtain the following expressions:

$$\epsilon_\tau = p[2/E(W^2-1)+\nu/E], \qquad \epsilon_1 = -p[2\nu/E(W^2-1)+1/E] \tag{17}$$

when $W \rightarrow \propto$, that is, a cylinder system with pressure acting on the open ends also becomes a free-rod system. When the pressure is applied to the outside of the measuring cylinder that system is called a bulk-modulus pressure sensor (11), and the circumferential and longitudinal strains measured on the inside diameter of the cylinder are

$$\begin{aligned} \epsilon_\tau &= -p[W^2(2-\nu)/E(W^2-11)] \\ \epsilon_1 &= -p[W^2(1-2\nu)/E(W^2-1)] \end{aligned} \tag{18}$$

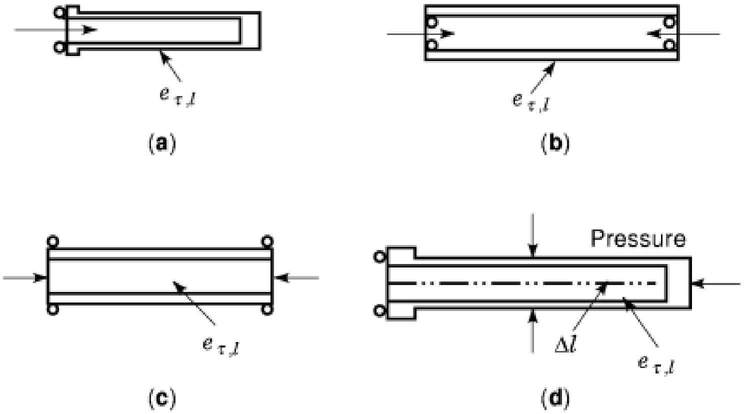

Fig. 11. Elastic pressure-sensing elements, short-tube types: (a) closed end, (b) open ends, (c) loaded open ends, and (d) short-tube type bulk modulus.

The change of the length of this type of cylinder is a measure of pressure,

$$\Delta l = -p[l(1-2\nu)W^2/E(W^2-1)] \qquad (19)$$

where l is the length of the straight measuring tube. From the data presented in Ref. 11, $l = 100$ mm ± 0.05 mm, $\nu = 0.296 \pm 0.002$, $E = 186$ GPa ± 2 GPa, $W = 2 \pm 0.005$, we obtain the following formula: $\Delta l = p(0.294 \pm 0.007)$ μm·MPa^{-1}. For the strain-gauge free active element pressure sensors the pressure characteristics can be calculated based on its dimensions and material data. With this estimate we obtain an accuracy of 2% to 4%, which is high enough for many industrial purposes.

Strain-Gauge Pressure Sensors

The conversion of pressure-induced strains in definitive elastic pressure-sensing elements (usually flat diaphragms or straight-tube elements) into changes of resistance using a different type of strain gauge has been used in commercial pressure sensors for many years. Two or more commonly used sensors with four active arms of a Wheatstone bridge with ac and dc excitations in special form that gauge ε (or $\Delta R/R$), appropriate for pressure measurements, have been developed. For straight-tube sensing elements described previously, using four active element arms of a Wheatstone bridge we have the following expressions for different types of *strain-gauge dilating cylinder* pressure sensors:

Thin-walled closed end cylinder	$\Delta V/V \cong kpD(1+\nu)/2gE$
Thin-walled free cylinder	$\Delta V/V = kpD(1+\nu)/gE$
Thick-walled closed-end cylinder	$\Delta V/V \cong kp(1+\nu)/2E(W^2-1)$
Thick-walled free cylinder	$\Delta V/V = kp(1+\nu)/E(W^2-1)$
Thick-walled open-end free cylinder	$\Delta V/V = kp(1+\nu)[2/(W^2-1)+1]/2E$
Free-rod approximation	$\Delta V/V = kp(1+\nu)/2E$,
Thick-walled bulk-modulus type	$\Delta V/V = kpW^2(1+\nu)/E(W^2-1)$

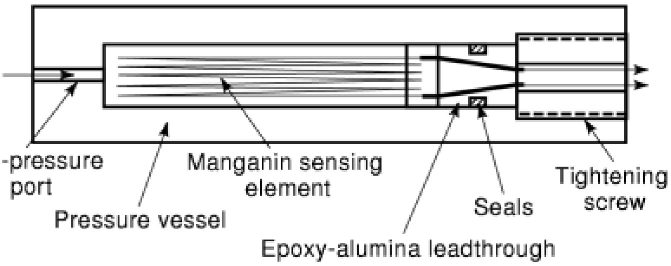

Fig. 12. Resistance pressure sensor with a manganin hairpin form sensing element.

where ΔV is a output voltage signal, V the excitation voltage of the bridge, and $k = \Delta R/R\varepsilon$ the constant of the strain gauge equal to about 2 for metallic gauges and even more than 50 for semiconductor gauges. In the case of a clamped diaphragm, the opposite-sign strains in the center of diaphragm and on its periphery (on the same side) are induced by pressure. For the four active arms of a Wheatstone bridge the following expression for output voltage can be easily derived: $\Delta V/V = \frac{9}{8}$. This expression is only an approximation of the real characteristic of the sensor because strain gauges cannot be fixed exactly in the center nor at the periphery of the diaphragm due to its finite dimensions.

Resistance Pressure Sensors

Resistance pressure sensors utilizing the change of the electrical resistance of a metallic wire (12) a semiconductor element (13) with applied pressure are widely used especially in scientifice and industrial laboratories for elevated and high-pressure measurements. Pressure-sensing elements, usually in the form of small-coil, double helical coil, or hairpin elements, should be strain-free mounted in a pressure chamber having direct contact with a pressure-transmitting medium, or they can be separated from the chamber using soft bellow, diaphragm, or membrane systems. The pressure-sensing element located inside the high-pressure chamber is connected with the measurement system by a special leadthrough in order to isolate it from the body of the pressure chamber (see Fig. 12). In most cases, manganin wire is used. The relative change of resistance of the manganin sensing element with pressure (typical resistance of 100 Ω) is almost linear up to 1 GPa and can be characterized by the pressure coefficient $\Delta R/R_p$ equal to (2.2 to 2.5) × 10^{-5} MPa^{-1}. Specialized resistance bridges, modern multimeters, and strain-gauge amplifiers are successfully used. A resistance change corresponding to pressure changes of about 50 kPa can be attained. The heavily doped bulk n-type InSb single crystal as a semiconductor pressure-sensing element is widely used too (14). This type of gauge is characterized by high (but slightly nonlinear) sensitivity to pressure and low sensitivity to temperature and to the nonhydrostatic state of the pressure-transmitting medium. Typically the resistance of the gauge is below 0.2 Ω, thus it is necessary to use a four-probe measurement system for its precise determination. The mean pressure coefficient of the relative resistance of this gauge is equal to about 0.7 × 10^{-3} MPa^{-1}. Carbon resistors could be also used effectively as pressure sensors at pressures below 1 GPa (15). The variation of resistance is nonlinear, but thermal properties are sufficiently appropriate. Also, thin- and thick-film resistors can be successfully applied in some cases (15). The accuracy of this type of pressure sensor is typically 0.1% to 0.2%. In general, resistance pressure sensors have a number of advantages such as small volume, long-term stability, ease of manufacture, low cost, and need for conventional methods of measurements.

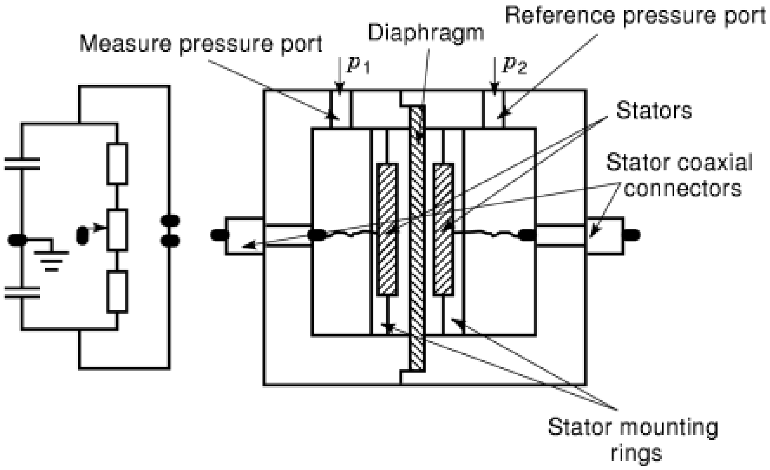

Fig. 13. Dual-stator capacitive pressure sensor.

Capacitive Pressure Sensor

Classical capacitive pressure sensors (nonsilicon devices) can be divided into two groups. In the first group, for low-pressure measurements, the elastic diaphragm pressure-sensing elements and the capacitive method of transduction with standard methods of capacitance measurement are used. In the second group, for high-pressure measurements, pressure-sensing elements are the measuring capacitors with substances whose permittivity strongly depends on pressure and weakly on temperature. Here the sensing element is an axial capacitor, filled with a specific liquid dielectric under measured pressure, or has the form of a small, parallel-plate capacitor mounted directly in the high-pressure chamber using a special low-capacitance high-pressure leadthrough. In the first group there are two possibilities. In the first, applied pressure to the diaphragm deforms its center, which moves to and from a stationary electrode and changes the capacitance of the system; or a measured pressure and a reference pressure are applied to a diaphragm mounted between two stationary electrodes and results in changes in the capacitances of two capacitors connected in series in different directions. In the second possibility (see Fig. 13), dual stationary electrodes and a diaphragm create two arms of a four-arm ac bridge circuit. The pressure-sensing element in most cases is used as a separate element. It is prestressed and clamped during the mounting of the sensor housing. The tension obtained in this way increases the diaphragms resonant frequency and reduces the vibration error of the transducer, which is important for vehicle applications. Prestressing also tends to shorten the transducer's time constant and lower its hysteresis. In the second group of sensors a pressure-measuring liquid polar dielectric or solid dielectric (16) can be used. There are some promising materials for wider application in pressure measurements using differential methods of measurement: First, using a combination of As_2O_3 and $Bi_{12}GeO_{20}$ sensing elements with pressure coefficients 110.6×10^{-6} MPa^{-1} and -102.8×10^{-6} MPa^{-1} and temperature coefficients 76.7×10^{-6} K^{-1} and 73.7×10^{-6} K^{-1}, or using a second combination of $CaCO_{3\perp}$ and $CaCO_{3\parallel}$ with pressure coefficients equal to 213.4×10^{-6} MPa^{-1} and 59.0×10^{-6} MPa^{-1} and temperature coefficients 3.6×10^{-6} K^{-1} and 3.6×10^{-6} K^{-1}. The first combination gives a quite good temperature compensation effect and pressure sensitivity of 21.3×10^{-5} MPa^{-1}, about 10 times higher than those of the manganin pressure sensor.

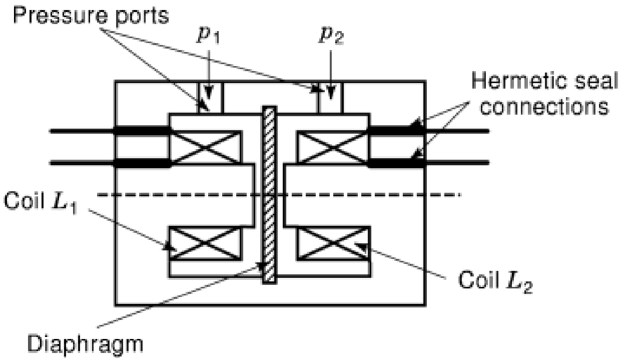

Fig. 14. Reluctive differential pressure sensor with a diaphragm as the pressure-sensing element.

Inductive Pressure Sensors

In inductive pressure sensors the self-inductance of a single coil is varied by pressure-induced displacement of a ferromagnetic diaphragm located close to the coil. So the motion of the diaphragm with respect to the iron core coil changes its inductance. In another solution of the inductive pressure sensor the inductance changes are produced by the large displacement of the ferromagnetic core within a long coil caused by the motion of bellows or the displacement of a Bourdon tube. In this type of sensor there are big difficulties in compensating for the environmental effects, especially the temperature effect. Therefore the reluctive pressure sensors are used much more frequently than the inductive types.

Reluctive Pressure Sensors

The reluctance changes in the magnetic circuit necessary to produce our output voltage signal in reluctant sensors are in most cases obtained by one of the following: (1) Utilize the pressure-induced deflection of a ferromagnetic diaphragm located between two ferromagnetic-core coils, connected as a two-arm inductance bridge. Then, the diaphragm displacement decreases the gap in the magnetic flux path of one coil while simultaneously increasing the gap in the second coil flux path (see Fig. 14). The output voltage is proportional to the ratio of the two inductances and is almost a linear function of pressure. (2) Use a twisted Bourdon tube with a ferromagnetic plate fastened to its end. The plate together with a two-coil magnetic E-shaped core element creates a magnetic circuit with two small gaps (see Fig. 15). The rotating plate decreases the flux gap of the one coil and decreases the gap of the other coil. Coil connection and production of output voltage signal are the same as those for the solution presented in item (1). (3) Use a differential transformer system with a ferromagnetic core whose displacement depends on pressure and is generated by pressure-sensing elements such as capsules, bellows, corrugated diaphragms, Bourdon tubes, or straight-tube bulk-modulus elements (4). Utilize the changes in permeability due to a change in stress of a specially designed straight-tube sensing element to be a fixed core in the differential transformer circuit. The circuit operation is similar to that described previously but the decreases (or increases) in reluctance path occur in the fixed core proportional to the strain deformations due to the pressure. This method is used for elevated pressure measurements.

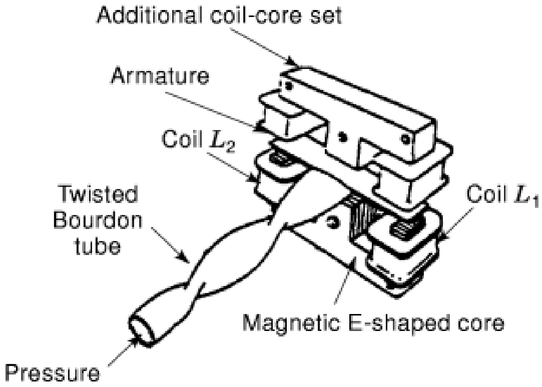

Fig. 15. Reluctive pressure sensor with E-shaped core and a Bourdon twisted tube as the pressure-sensing element (4).

Piezoelectric Pressure Sensors

Piezoelectric pressure sensors employing natural or synthetic quartz as a piezoelectrically active material have been used since 1900. The mechanical and electrical design has now been successfully developed such that they are capable of measuring pressures as small as acoustic pressure and as high as 1 GPa. The response time of a typical sensor is on the order of a few microseconds and resonant frequencies up to about 1 MHz. Piezoelectric sensors are extremely useful in dynamic and quickly-variable pressure measurements. Quartz is very stable, with a high mechanical strength (above 2 GPa) and high modulus of elasticity. The damping is very small and shows practically no hysteresis effect. Its piezoelectric and deformation response up to 2.5 GPa in the uniaxial compressive stress state is linear and can be used at temperatures up to 500°C. The quartz sensing element is a single plate, cut from a quartz crystal in the X-cut plane. Pressure is transmitted directly to the piezoelectric element by a flat diaphragm, producing in the crystal in the x direction a strain that gives rise to polarization of the crystal with the surface charge density proportional to the strain. The total charge on the surface is $Q = d_{11}Ap$, where d_{11} is the appropriate piezoelectric coefficient of quartz equal to 2.25×10^{-12} C/N and A the area of the crystal plate surface (17). For a plate of diameter 5 mm, the charge generated by a pressure of 10 MPa is equal to 0.44×10^{-9} C. For a typical value of thickness, $h = 1$ mm, the capacitance of the crystal capacitor is about 25 pF. Connecting the leads in the form of a coaxial cable would increase this value additionally by 75 pF, so the voltage generated by this pressure would be equal to 0.44 V. As a piezoelectric sensor is designed for dynamic pressure measurement, its frequency characteristics play an important role. The resonant frequency ν_{res} of a thin vibrating plate is given by the expression $\nu_{\mathrm{res}} = c_l/2h$, where $c_l = (E/\rho)^{0.5}$ is the velocity of longitudinal waves in the plate and ρ the density. So for typical values of h, for $c_l = 5.5 \times 10^3$ m/s and $\rho = 2.655$ g/cm^3 the resonant frequency is approximately 2.8 MHz. The matched diaphragm and quartz crystal form a single mass–spring system. This fact and the bonding will reduce this value to less than one half. While the lower-frequency response of the quartz sensor is governed by electrical characteristics, the upper-frequency response is the result of its mechanical characteristics. The best commercially available sensors cover a wide frequency range, from about 1 Hz up to about 1 MHz. Two types of specialized amplifiers for this kind of sensor are used: the voltage amplifier and the charge amplifier (voltage-mode and charge-mode operated sensor). The construction of the sensing element makes quartz sensors sensitive to acceleration. If a sensor is mounted on an accelerating surface (this is a real situation) additional, unwanted electric signals will be generated. This can be compensated for by using within the same sensor housing an acceleration-sensitive crystal, whose signal reduces the unwanted signal generated in the pressure-sensing element (see Fig. 16). Other piezoelectric materials are used such as tourmaline (for low pressure because of its low mechanical properties), piezoelectric

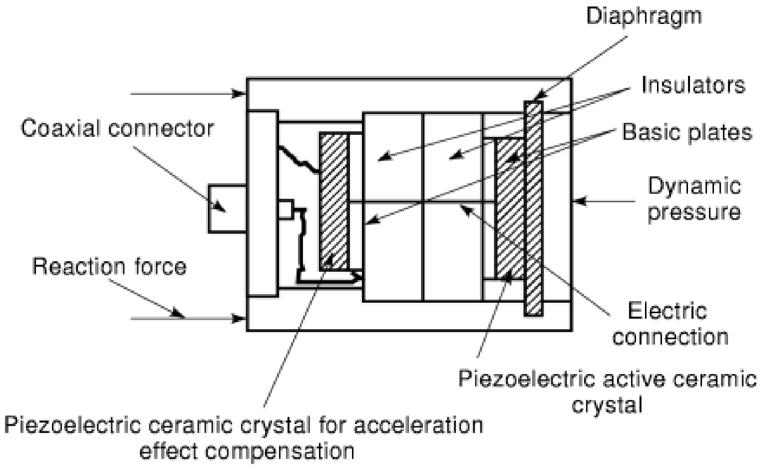

Fig. 16. Acceleration-compensated quartz dynamic pressure sensor.

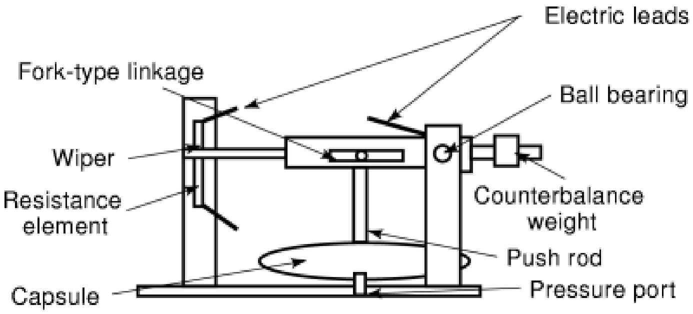

Fig. 17. Potentiometric low-pressure sensor with a capsule sensing element and lever system.

ceramics [barium titanate ($BaTiO_3$)] and ferroelectric ceramics [$(Pb)(Zr)(Ti)O_3$, known commercially as *PZT*]. These materials have piezoelectric coefficient 100 times as great as quartz but a much smaller maximal working temperature, which is determined by Curie points (300°C for PZT and 200°C for $BaTiO_3$).

Potentiometric Pressure Sensors

Pressure sensors with potentiometric transduction elements are widely used in industry because of their simple operation principle, high-level output voltage signal, low cost, availability, and sufficient accuracy. A large number of designs and configurations by many producers have been developed for different measurement requirements. The most commonly used sensing elements are corrugated diaphragms, capsules (single or multiple), and all types of Bourdon tubes. A wide pressure range is covered by these sensors, for low pressure with capsules (see Fig. 17) and for high pressure with *C*-shaped Bourdon tubes.

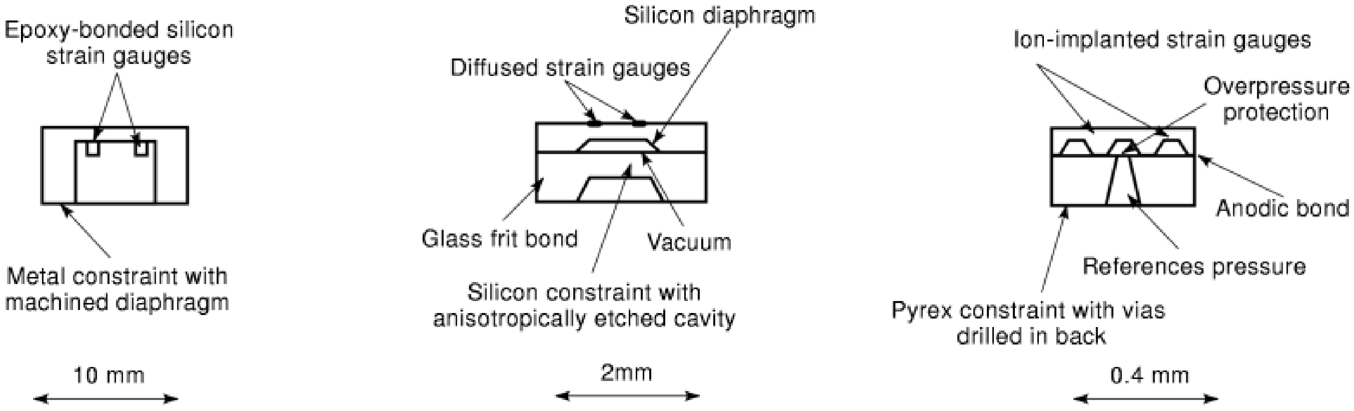

Fig. 18. Illustration of the evolution of silicon pressure sensors. On the left a preprototype of sensor is shown.

Semiconductor Devices as Silicon Pressure Gauges

Silicon pressure gauges based on silicon chips etched to form a thin (2 μm to 5 μm for low pressure) or thick (20 μm to 50 μm for elevated pressure) diaphragms with a diffused, ion-implanted piezoresistor or with a capacitor or other diaphragm deformation detectors are widely used in a large number of applications such a altimeters, blood-pressure gauges, tire-leak detectors, pneumatics, hydraulics, and oceanography investigations (18). The main features of silicon pressure sensors are that they can be mass-produced in a variety of ranges, which lowers the cost. They could be smart sensors, are very small, and have good linearity (1% or better), stability, and sensitivity. The sensitivity can be varied from 10 mV/kPa to 1 μV/kPa for high pressures. Moreover, their interfacing is convenient for signal processing. It is expected that in the next decade silicon pressure sensors within the pressure range up to 200 MPa will continuously replace conventional pressure-measurement devices and within the pressure range up to 1 GPa their industrial application will be much wider. In Fig. 18 a short presentation of the development of this kind of sensor is given. Figure 18(a) shows a schematic of the preprototype of a silicon sensor, with a metal constraint and diaphragm but with a silicon strain gauge. Its overall dimensions of about 10 mm are macroscopic. Figures 18(b) and 18(c) present the initial state of silicon sensor technology with a diffused and ion-implanted strain gauge having typical overall dimensions of about 2 mm. The typical absolute pressure sensor with a silicon diaphragm sensing element for low pressure with ion-implanted strain gauges and overpressure protection is shown in Fig. 18(c). In Fig. 19 is shown the dependence of output voltage of the transducer versus pressure, with the upper limit of measuring pressure well represented and good linearity. In the case of the output voltage graphed against elevated pressure, a large nonlinearity can be observed. The large nonlinearity and much smaller sensitivity are disadvantages of this type of sensor for high-pressure measurements. Currently produced silicon sensors have sophisticated silicon technology and can have overall dimensions of about 1 mm. Different types of deflection diaphragm detection methods are used, such as the widely used capacitive method (19) or field-effect transistor method (20), the advantage of which is the direct displacement to voltage (or current) transduction (see Fig. 20), (21). In the case of capacitance pressure sensors we have to note that stray capacitances are of the same order as the sensor capacitance. In all silicon pressure sensors, temperature compensation devices must be added to circuits.

Silicon.

Absolute Pressure Sensors. When the reference pressure in silicon sensors is a vacuum pressure [see Fig. 18(b)] a specific sensing element will be under the influence of absolute pressure, but the operation principle of the sensing element does not change. Sensors can easily measure absolute pressures and are widely applied in the vacuum technology industry and space investigations. There are well-established technological

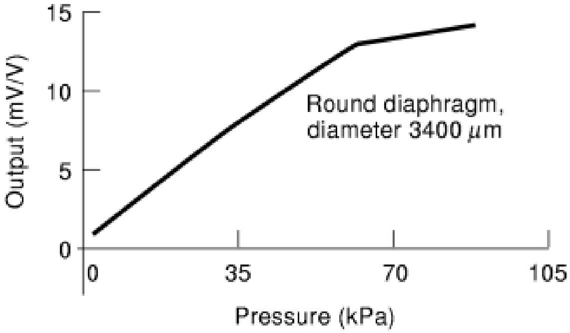

Fig. 19. Low-pressure response of a pressure silicon sensor with overpressure protection (22).

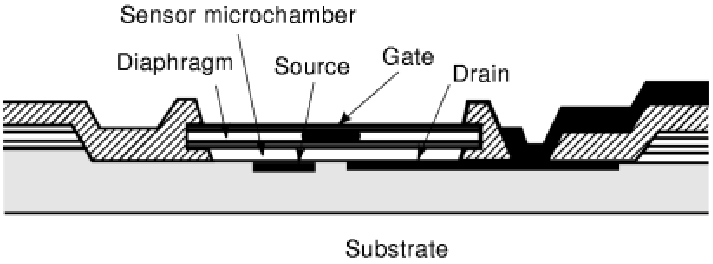

Fig. 20. Schematic cross section of a pressure-sensitive field-effect transistor sensor (21).

procedures for fabrication of such sensors (22). For absolute pressure measurements, it is important to join a silicon diaphragm perfectly for a sufficiently long time to the sensor constrained under high vacuum with no leakage through the bonding surface.

Differential Pressure Sensors. The measurement of differential pressure plays a very important role for flow-parameter measurement, that is, the mass-rate or volume-rate measurement. It is especially important in the case of natural gas transportation, for example, in the case of intercontinental and international ventures. When the pressure difference between two pressurized volumes is small and the maximum pressure does not exceed some megabars the silicon sensor pressure is applied. Differential pressure sensors have the same configuration as gauge sensors, that is, sensors for which the reference pressure is an ambient pressure at the moment the reference cavity is hermetically sealed. In differential sensors the reference cavity is connected with a volume of smaller pressures. Zero deflection of a diaphragm is achieved at equal input pressures (from both sides of the diaphragm) but equilibrium of the measurement system may occur at a some value of differential pressure. In such cases the pressure sensor output is proportional not only to a differential pressure, but to a certain degree to a static pressure as well. This last effect is the static pressure sensitivity of the sensor, which depends on the design of the sensor and material used. The shape of diaphragms, especially their deflection, can be determined using conventional methods of calculation because of the small influence of static pressure on the elastic properties of silicon. The larger influence of pressure on a differential pressure sensor is connected with the pressure effect on the electronic properties of strain-sensing elements (for example, for the diffused strain gauge on the diaphragm surface). When the pressure is large and attains some hundreds of megapascals the effect of static pressure can be so large that differential pressure is more accurately measured as the difference between two absolute or gauge pressures.

Table 2. Commercially Available Pressure Sensors

Sensing Element and First Transduction Element	Pressure Range[a]	Calibration Accuracy	Producer
Diaphragm, strain resistance gauge	0–50 MPa (G,D)	0.5%–1.0% FS	Dimisco,West Wood, MN
Silicon, stainless steel diaphragms	0–50 MPa (G)	2.0% FS	Entran Sensors & Electronics, NJ
Diaphragm, thin resistancefilm	0–50 MPa (A,G,D)	0.5% FS	Statham, CT
Resistance, semiconductorn-type InSb single crystal	0–1 GPa (G)	0.5%–2.0% FS	
Resistance, manganin wire	0–2.5 GPa (G)	0.5–2.0% FS	High Pressure Research Center, Warsaw, Poland
Metal foil, semiconductorstrain gauge	0–10 MPa (A,D,G)	0.5%–2.0% FS	Sensotec, Inc., OH
Bourdon tube	0–100 MPa (G)	0.1%–1.5% FS	Cole-Parmer Instrument Co.
Diaphragm	0–50 MPa (A,D,G)	0.1%–1.5% FS	Illinois
Bourdon tube, diaphragm	0–100 MPa (D,G)	0.5%–2.0%	Dwyer Instrum. Inc., Chicago, IL
Bourdon tube	0–0.4 GPa (G)	0.5%–1.0% FS	Nova Swiss, Nova Werke AG, Effreticon
Straight short tube, strain gauge	0–1.4 GPa (G)	0.5%–1.5% FS	Switzerland
Straight short tube bulk-modulus potentiometric	0–1.5 GPa (G)	1.0% FS	Harwood Engineering, MA

[a] A, absolute pressure; G, gauge pressure; D, differential pressure; % FS, % of full scale.

Actual Market Information

The designing and technological processes of modern pressure sensors are now in a strong development stage. Table 3 gives actual pressure-sensor producers, types, and main metrological properties of commercially available pressure sensors.

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ROLAND WIOENIEWSKI
Warsaw University of Technology