CHAPTER 8.2
TRANSDUCERS FOR MECHANICAL QUANTITIES

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TRANSDUCERS FOR SOLID-MECHANICAL QUANTITIES

Transducers for solid-mechanical quantities sense and/or react to acceleration, velocity, vibration, shock, attitude, displacement, and position of a solid element. Transducers can also measure force, torque, weight or mass, and strain (deformation resulting from stress).

Acceleration, Vibration, and Shock

Acceleration, a vector quantity, is the time rate of change of velocity with respect to a reference system. When the term acceleration is used alone, it usually refers to *linear acceleration a*, which is then related to linear (translational) velocity υ, and time t by $a = d\upsilon/dt$. *Angular acceleration* α is related to angular (rotational) velocity ω and time t by $\alpha = d\omega/dt$. Mechanical *vibration* is an oscillation wherein the quantity, varying in magnitude with time so that this variation is characterized by a number of reversals of direction, is mechanical in nature. This quantity can be stress, force, displacement, or acceleration; however, in measurement technology the term vibration is usually applied to *vibratory acceleration* and sometimes to *vibratory velocity.* Mechanical *shock* is a sudden nonperiodic or transient excitation of a mechanical system.

Acceleration Transducers (Accelerometers). Acceleration transducers (accelerometers) are used to measure acceleration as well as shock and vibration. Their sensing element is the *seismic mass,* restrained by a spring. The motion of the seismic mass in this acceleration-sensing arrangement is usually damped (see Fig. 8.2.1*a*). Acceleration applied to the transducer case causes motion of the mass relative to the case. When the acceleration stops, the mass is returned to its original position by the spring (see Fig. 8.2.1*b*). This displacement of the mass is then converted into an electrical output by various types of transduction elements in *steady-state acceleration transducers* whose frequency response extends down to essentially 0 Hz. In piezoelectric accelerometers the mass is restrained from motion by the crystal transduction element, which is thereby mechanically stressed when acceleration is applied to the transducer. Such *dynamic acceleration transducers* do not respond appreciably to acceleration fluctuating at a rate of less than 5 Hz. They are normally used for vibration and shock measurements.

Capacitive and photoelectric accelerometers have been produced at various times, and vibrating-element accelerometers (in which the mass, as it tends to move, applies tension to a wire or ribbon, thereby changing the frequency at which the wire can oscillate) have been used in some aerospace programs. However, the most commonly used steady-state acceleration transducers are the potentiometric, reluctive, strain-gage,

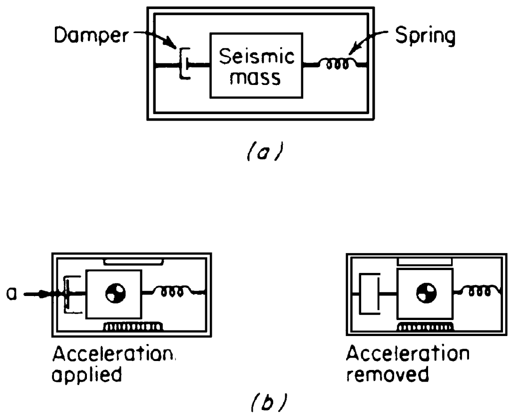

FIGURE 8.2.1 Basic operating principle of an acceleration transducer: (*a*) spring-mass system; (*b*) displacement of seismic mass. (*From Ref. 1 by permission*)

and servo types. For vibration and shock measurement the piezoelectric accelerometers are most frequently used because of their inherently high frequency-response capability; some miniature semiconductor-strain-gage accelerometers are also used for these measurements since they can respond to fairly high acceleration frequencies.

Potentiometric Accelerometers. Potentiometric accelerometers usually employ a mechanical linkage to amplify the motion of the seismic mass so as to produce the necessary extent of wiper-arm travel over the resistance element. The mass is supported by flexural springs or a cantilever spring in some models. In others it slides on a central coaxial shaft, restrained by calibrated coil springs. Magnetic, viscous, or gas damping is normally used in potentiometric accelerometers, primarily to reduce output noise due to wiper-arm whipping and transient wiper-contact resistance changes. Over-load stops keep the wiper arm from moving beyond the resistance-element ends in the presence of acceleration beyond the range of the accelerometer.

Reluctive Accelerometers. Reluctive accelerometers require ac excitation power having a frequency greater than the upper limit of the transducer's frequency response. When moderately high frequency response is needed, the inductance-bridge version has been found most suitable. In a typical design the seismic mass is attached to a spring-restrained ferromagnetic armature plate, pivoted at its middle and placed above two coils so that the small seesaw motion of the plate, due to acceleration action on the mass, causes a decrease of inductance in one coil and an increase of inductance in the other. Since the coils are in opposite bridge arms, these inductance changes are additive and produce a bridge output voltage double that obtainable from having only one coil change its inductance. When a relatively low frequency response is needed, a differential-transformer, synchro or microsyn transduction circuit can be used to convert the seismic-mass displacement into the required electrical output.

Strain-Gage Accelerometers. Strain-gage accelerometers are very popular and exist in several design versions. Some use unbonded metal wire stretched between the seismic mass and a stationary frame or between posts on a cross-shaped spring to whose center the seismic mass is attached and whose four tips are attached to a stationary frame. Other designs use bonded-metal wire, metal foil, or semiconductor gages bonded to one or two elastic members deflected by the displacement of the seismic mass. The recently developed micromachined accelerometers also employ strain-gage transductions.

Servo Accelerometers. Servo accelerometers are closed-loop force-balance, torque-balance, or null-balance transducers. The displacement of the seismic mass is detected by a position-sensing element, usually reluctive

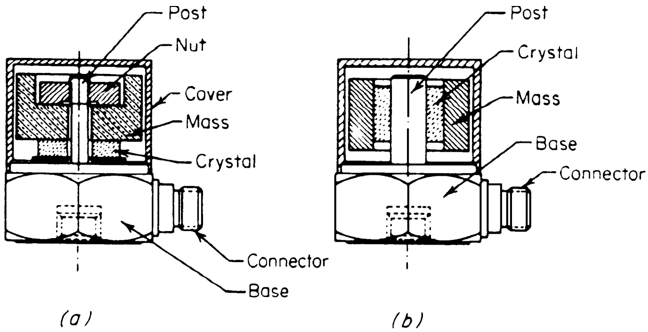

FIGURE 8.2.2 Piezoelectric acceleration transducers: (*a*) single-ended compression type; (*b*) shear type. (*Endevco, Dynamic Instrument Division*)

or capacitive, whose output is the error signal in the servo system. This signal is amplified and fed back to a torquer or restoring coil so that the restoring force is equal and opposite to the acceleration-induced force. The coil or torquer is attached to the seismic mass and returns the mass to its original position, when the feedback current is sufficient, so that the position error signal is reduced to zero. The current, which is proportional to acceleration, passes through a resistor. The *IR* drop across the resistor is the accelerometer output voltage, proportional to the acceleration.

Piezoelectric Accelerometers. Piezoelectric accelerometers exist in several design versions, two of which are illustrated in Fig. 8.2.2. Both contain a seismic mass that applies a force, due to acceleration, to a piezoelectric crystal. With acceleration acting perpendicular to the base, an output is generated by the crystal due to compression force in one design and to shear force in the other. Crystal materials include quartz and several ceramic mixtures such as titanates, niobates, and zirconates.

Ceramic crystals are used more frequently than natural crystals. They gain their piezoelectric characteristics by exposure to an orienting electric field during cooling after they are fired at a high temperature. If they are subsequently heated, as during transducer operation at elevated temperature, they can lose their piezoelectric qualities if that temperature is above the *Curie point*, which varies between about 100 and 600°C, depending on the materials used in the crystal. Piezoelectric accelerometers almost invariably require some signal-conditioning circuitry to provide a usable output since they have a relatively low output amplitude and a very high output impedance. In many designs, the necessary conditioning circuitry is included in the transducer. For other accelerometers, a separate charge or voltage amplifier is needed, connected to the transducer by a thin shielded coaxial cable of special low-noise construction to avoid noise pickup from within the cable itself.

Criteria for Selection. Criteria for selection of an acceleration transducer are primarily the required acceleration range and frequency response. They are mutually dependent; e.g., a typical ±2*g* potentiometric accelerometer design will have an upper frequency limit for flat response of about 12 Hz, whereas a ±20*g* accelerometer of the same design can have an upper frequency-response limit of about 40 Hz. As frequency-response requirements increase, the reluctive, servo, metal-strain-gage, semiconductor-strain-gage, and piezoelectric transducers successively become candidates for selection. The best accuracy characteristics are provided by servo accelerometers, which are also most suitable for low-range (±0.2*g* or lower) applications.

Attitude and Attitude-Rate Transducers

Attitude is the relative orientation of a vehicle or an object represented by its angles of inclination to three orthogonal reference axes. Attitude rate is the time rate of change of attitude.

The sensing methods employed by attitude transducers are best categorized by the kind of reference system to which the orientation to be measured is related. The *inertial* reference system is provided by a *gyroscope (gyro)* in which a rotating member will continue turning about a fixed axis as long as no forces are exerted on the member and the member is not accelerated. *Gravity* reference is used to establish a vertical reference axis. This principle is applied in *pendulum-type transducers*, in which a weight is attached to a wiper arm and a potentiometric or reluctive element is attached to the case, so that an output change is obtained when the object, to which the case is mounted, deflects from a vertical position.

A *magnetic reference axis* can be established by the poles of a magnetic field which remains fixed in position. This reference system is employed by certain navigational transducers related to the compass. *Flow-stream reference* refers to the direction of fluid flow past an object moving within that fluid, a reference system employed in *angle-of-attack* transducers mounted well forward of the nose of high-speed aircraft and rockets, so that the flow stream used is not altered in direction by the vehicle itself.

Optical reference systems are used by electrooptical transducers mounted (in a known attitude) so as to sense a remote light source or a light-dark interface whose position is known. This establishes a reference axis between the object on which the transducer is mounted and the target sensed by the transducer. *Optically referenced* transducers include such aerospace (primarily spacecraft) devices as the sun sensor, star tracker, and horizon sensor, as well as military target-locating equipment.

Gyros. Gyros are the most widely used attitude and attitude-rate transducers. The operating principle of the gyro is illustrated in Fig. 8.2.3. A fast-revolving rotor turns about the *spin axis* of the gyro. This axis, which remains fixed in space as long as the rotor revolves, establishes the inertial reference axis. The rotor shaft ends are supported by a *gimbal* frame which is free to pivot about the gimbal axis. The pivot points are part of the gyro housing structure, which is attached to the object whose changes in attitude about the gimbal axis are to be measured. An angular-displacement transduction element (pick-off) is then used to provide an output proportional to attitude. A simple example of such an element is a wiper arm, attached to the gimbal frame at the pivot point, wiping over a ring-shaped potentiometric resistance element attached to the inside of the case. Potentiometric transduction as well as reluctive (especially synchro) and, occasionally, capacitive and photoconductive transduction are used in most gyros.

Gyro attitude transducers (free gyros) are often designed as two-degree-of-freedom gyros, i.e., those providing an output for each of two of a vehicle's three attitude planes (pitch, yaw, and roll, or x, y, and z axes). The design illustrated in Fig. 8.2.4 provides an inner gimbal for one axis and an outer gimbal for the other axis, with a separate pick-off for each axis. The caging mechanism (symbolized by the hand) is used to lock the inner gimbal to a reference position until the spin axis is to start serving as inertial reference axis. At this point the gyro is uncaged (after the rotor has come up to speed). AC or dc motors are commonly used to turn the rotor. Some gyros use a clock spring, wound before each use, or a pyrotechnic charge which, when activated, forces a stream of combustion gases into a small turbine.

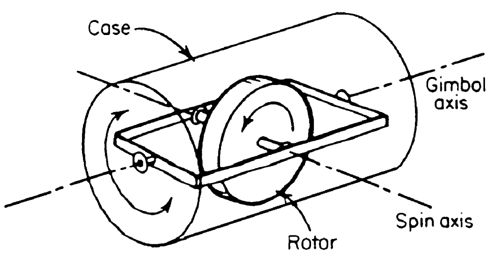

FIGURE 8.2.3 Basic single-degree-of-freedom gyro. (*From Ref. 1 by permission*)

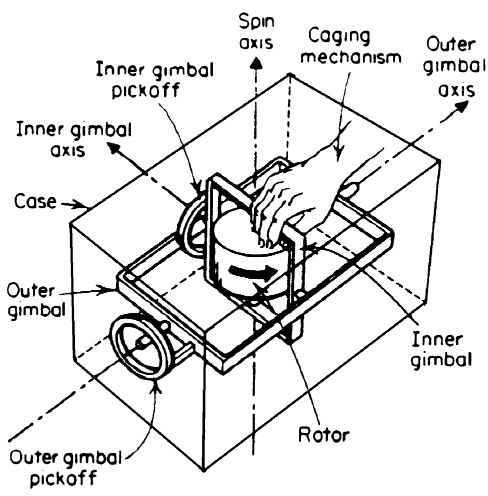

FIGURE 8.2.4 Two-degree-of-freedom gyro. (*Conrac Corp.*)

Rate gyros are attitude-rate transducers. They provide an output proportional to angular velocity (time rate of change of attitude). The operating principle of the rate gyro (see Fig. 8.2.5) is similar to that of the single-degree-of-freedom free gyro, except that the gimbal is elastically restrained and its motion is damped. The output is representative of gimbal deflection about the output axis in response to attitude-rate changes about the input axis. The deflection of the gimbal (precession) is caused by the torque *T* applied to it. The applied torque is the product of the instantaneous attitude rate about the input axis and the angular momentum of the gyro.

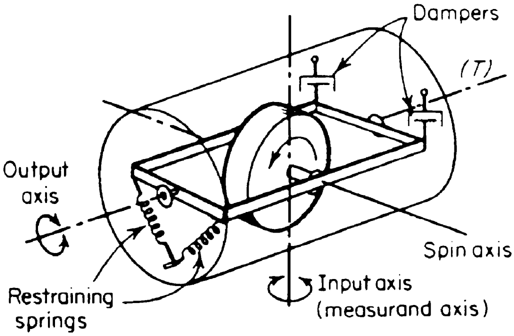

FIGURE 8.2.5 Basic-rate gyro. (*From Ref. 1 by permission*)

The more recently developed *ring laser gyro (RLG)* and *fiber-optic gyro* contain essentially no moving parts; the rotor is replaced by two laser beams traveling in opposite directions many times around a triangular or circular path; attitude rate changes then cause a frequency or phase difference at the optical path terminations.

When selecting a gyro, attention must be paid not only to the usual characteristics (weight, size, range, linearity, repeatability, threshold, and so on, and dynamic characteristics for rate gyros) but also to *drift,* the amount of precession, per hour, of the spin axis from its intended position because of internal unwanted torques or other instabilities, and the time period (after spin-motor runup or after uncaging) during which measurements must be obtained continuously.

Displacement and Position Transducers

Position is the spatial location of a body or point with respect to a reference point. *Displacement* is the vector representing a change in position of a body or point with respect to a reference point. Displacement transducers are used to measure linear and angular displacements, as well as to establish position from a displacement measurement.

The sensing element of most displacement transducers is the *sensing shaft* with its coupling device, which must be of a design suitable to make the motion of the sensing shaft truly representative of the motion of the measured point (driving point). A spring-loaded sensing shaft (without coupling device) is used for some applications. A number of *noncontacting* transducer designs are also in use. These require no coupling or sensing shaft. Various transduction principles are employed in displacement transducers.

Capacitive Displacement Transducers. In these devices a linear or angular motion of the sensing shaft causes a change in capacitance either by relative motion between one or more moving (*rotor*) electrodes and one or more stationary (*stator*) electrodes or by moving a sleeve of insulting material, having a dielectric constant different from that of air, between two stationary electrodes.

Inductive Displacement Transducers. Inductive displacement transducers can be of the coupled or the noncontacting types. Coupled designs contain a coil whose self-inductance is varied as a nonmagnetic sensing shaft moves a magnetically permeable core gradually into or out of the central hollow portion of the coil. Some designs incorporate an additional coil (balancing coil) having a fixed inductance value equal to the inductance of the transduction coil at a predetermined "zero" position of the sensing shaft. The two coils are connected as two arms of an inductance bridge. This two-coil principle is used in some noncontacting displacement transducers in which the transduction coil has a stationary core but changes its inductance with the distance between itself and a moving ferromagnetic object.

Photoconductive Displacement Transduction. Photoconductive displacement transduction is employed in several nonconducting displacement measuring systems. Pulsed or continuous-wave lasers or light-emitting diodes are typically used as light sources. Noncontacting photoconductive sensors usually require an optical reflector mounted to the measured object. Various optical configurations are used to obtain an output from the photoconductive element as the intensity, the phase, or the position of the reflected light beam changes. The *laser interferometer* is included in this group of displacement-sensing devices.

Potentiometric Displacement Transducers. Potentiometric displacement transducers are widely used because of their relative simplicity of construction and their ability to provide a high-level output. All these designs use a sensing shaft. The wiper arm is either attached directly to the shaft (but insulated from it) or mechanically connected to it through an amplification linkage. Straight potentiometric resistance elements are used in linear displacement transducers, circular or arc-shaped elements in angular displacement transducers. The elements are usually wire-wound, but conductive plastic, carbon film, metal film, or ceramic-metal mixtures (cermets) are also used. Some transducers have two or more wiper-element combinations moved by the same sensing shaft. A good sliding seal is needed at the point where the sensing shaft enters the transducer case, to protect the internally exposed resistance elements from atmospheric contaminants and moisture.

Reluctive displacement transducers are as commonly used as the potentiometric types. The reluctive transduction circuits employed in linear- and angular-displacement transducers are illustrated in Fig. 8.2.6. Only the linear-variable transformer (LVDT) and the inductance-bridge circuits are used for linear-displacement measurements. Many winding configurations exist for the LVDT transducers; one manufacturer offers 12 different "off-the-shelf" configurations, including several with two separate secondary windings. Alternating current excitation is required for all reluctive transducers. However, some designs are available with integral ac/dc output conversion and, in some cases, also integral dc/ac excitation conversion. Synchro-type transducers are often connected to a synchro-type receiver, which indicates the measured angle directly, e.g., on a dial.

A few strain-gage displacement transducers have been designed for the measurement of small linear and angular displacement. The gages are usually attached to the top and bottom surfaces of a cantilevered or end-supported beam which is deflected by the displacement.

Digital-Output Displacement Transducers (Encoders). Digital-output displacement transducers (encoders) are frequently referred to as *linear encoders* and *angular* or *shaft-angle encoders*, respectively. These consist essentially of a strip (for linear displacements) or a disk (for angular displacements), coded so as to provide a digital readout for discrete (sometimes very small) displacement increments and a reading head. Two types of encoders are in common use:

1. Photoelectric encoders, in which the reading head consists of a light-source assembly on one side of the disk or strip and a corresponding light-sensor assembly facing it on the other side of the disk or strip; the coded pattern is partly translucent, partly opaque.
2. Magnetic encoders, with a magnetic reading head and a partly magnetized, partly nonmagnetized coded pattern.

Incremental encoders have a simple, alternately ON and OFF coded pattern. They provide an output in the form of number of *counts* between the start and end of the displacement. Hence the start position must be known if the end position is to be determined in absolute terms. *Absolute encoders* have a code pattern such that a unique digital word is formed for each discrete displacement increment. Various codes are used for this purpose, such as the binary, binary-coded-decimal (BCD), and the Gray code.

Among displacement-transducer *selection criteria*, the most critical are range, resolution, starting force, overtravel, and type and magnitude of full-scale output. Accuracy and dynamic characteristics, type of available excitation supply, and freedom from contamination by the ambient atmosphere or other fluids need to be considered as well, for all transducer applications.

Force, Torque, Mass and Weight Transducers

Force is the vector quantity necessary to cause a change in momentum. *Mass* is the inertial property of a body, a measure of the quantity of matter in the body and of its resistance to change in its motion. *Weight* is the gravitational force of attraction; where gravity exists, it is equal to mass times acceleration due to gravity. *Torque* is the moment of force, the product of force, and the perpendicular distance from the line of action of the force to the axis of rotation (lever arm).

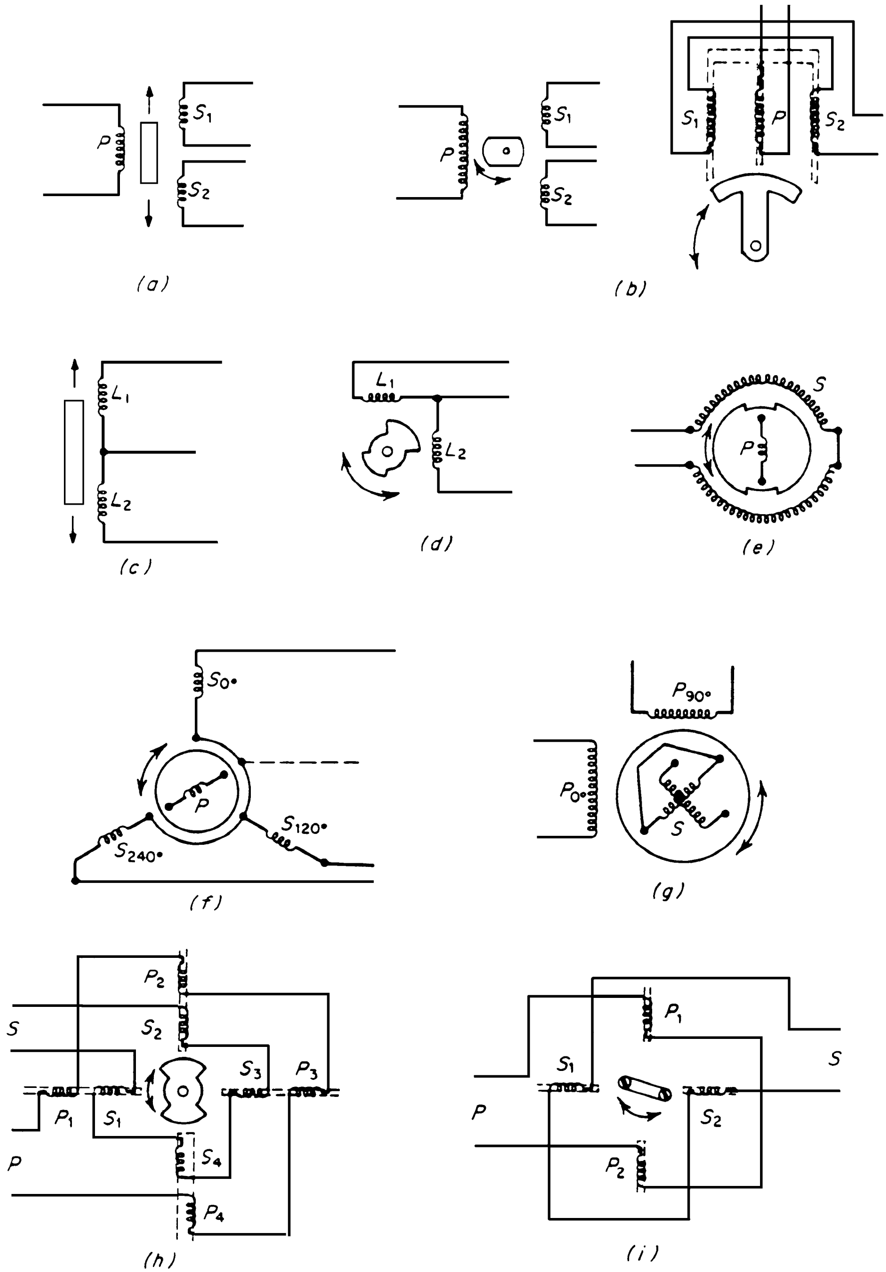

FIGURE 8.2.6 Transduction circuits of reluctive displacement transducers: (*a*) linear differential transformer; (*b*) angular differential transformer; (*c*) linear inductance bridge; (*d*) angular inductance bridge; (*e*) induction potentiometer; (*f*) synchro; (*g*) resolver; (*h*) microsyn; (*i*) shorted-turn signal generator. (*From Ref. 1 by permission*)

Force Transducers (Load Cells). Force transducers (load cells) are used for force measurements (compression, tension, or both) as well as for weight determinations in any locality where gravity exists and the gravitational acceleration g is known. The standard g (on earth) is 9.80665 m/s^2. Mass can be determined from weight, which is expressed in force units. A mass of 1 kg, for example, "weighs" 2.205 lb (pounds force) on earth. Torque is measured by *torque transducers.*

The sensing elements of force and torque transducers usually convert the measured into a mechanical deformation of an elastic element. This deformation, in terms of either local strains or gross deflection, is then converted into a usable output by a suitable transduction element. Bending beams (cantilever, end-supported, or end-restrained), solid rings or frames (*proving rings*), and solid or hollow rectangular or cylindrical columns are the most commonly used force-sensing elements. Special solid or notched shafts are used as torque-sensing elements.

Piezoelectric Force Transducers. Piezoelectric force transducers are used for dynamic compression-force measurements. A typical design has the shape of a thick washer. The annular piezoelectric crystal segments are sandwiched between two hollow cylindrical columns. Bidirectional force measurements can be obtained by preloading this *force washer.* An amplifier is used to boost the low-level output signals.

Reluctive Force Transducers. Reluctive force transducers use proving-ring sensing elements in most design versions. The deflection of the proving ring is converted into an ac output by an inductance-bridge or differential-transformer transduction element. An entirely different design uses the permeability changes because of stresses in a laminated column to vary the voltage induced by a primary winding in a secondary winding.

Strain-Gage Force Transducers. Strain-gage force transducers are the most widely used type. Bonded-metal foil and metal wire gages predominate, but unbonded wire gages and bonded semiconductor gages are used in some designs. Columns and proving rings are the usual sensing elements. The shear-web sensing element of the force transducer shown in Fig. 8.2.7 is related to the column, but is reported to offer greater transduction efficiency.

Torque Transducers. Torque transducers are mostly of the reluctive, photoelectric, or strain-gage type. The last is more widely used than the first two. The metal-foil strain gages in the transducer shown in Fig. 8.2.8 are located on the sensing shaft, which is enclosed in a cylindrical *torque sensor* housing. The leads from the gages are carried through the shaft up to slip rings. Brushes ride on the slip rings to provide stationary external connections. The brush assembly can be lifted off the slip rings to increase brush life during periods when torque is not monitored. In most modern strain-gage torque transducers the slip rings and brushes are replaced by a rotary transformer or by RF coupling.

Other Torque Transducers. Reluctive torque transducers use changes in shaft permeability, resulting from torque-induced stresses in the shaft, to change the voltage coupled from a primary winding to two secondary

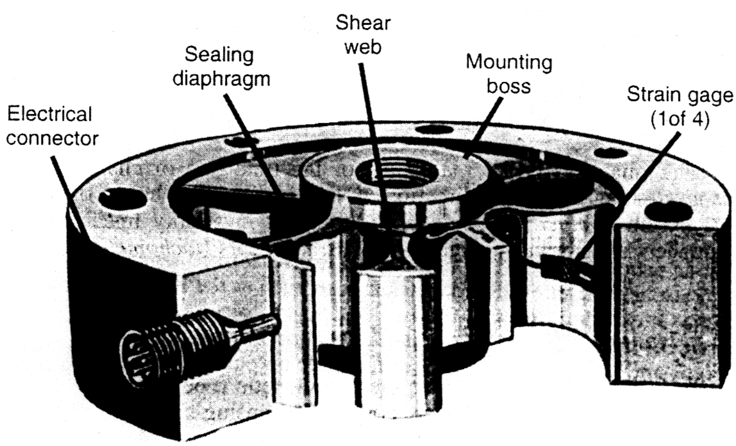

FIGURE 8.2.7 Strain-gage force transducer. (*Interface, Inc.*)

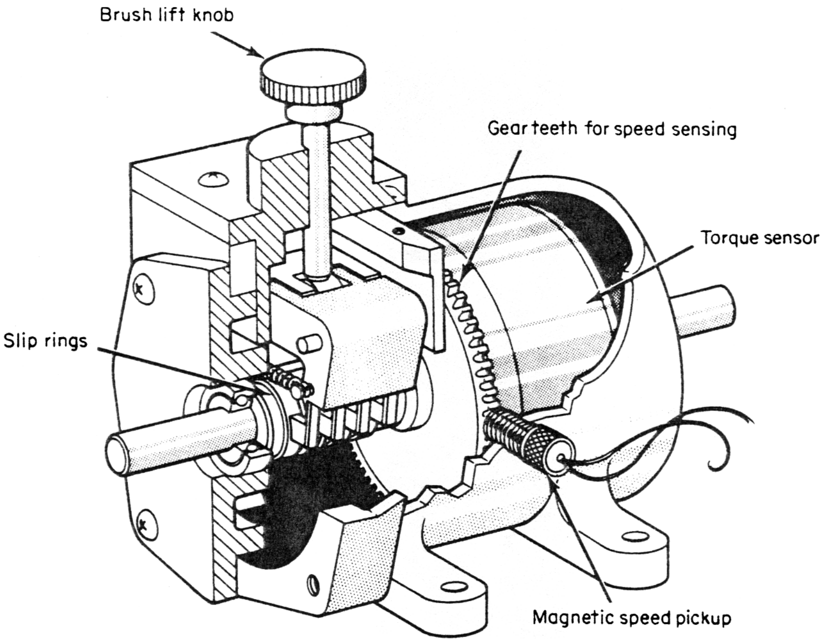

FIGURE 8.2.8 Strain-gage torque transducer. (*Lebow Associates, Inc.*)

windings. *Photoelectric torque transducers* use two incremental-encoder disks, one on each end of the shaft, to change the illumination on a light sensor when one disk undergoes a small angular deflection, because of torque, relative to the other disk.

Selection criteria include the usual range, accuracy, excitation, and output characteristics, case configuration and dimensional constraints, overload rating, the thermal environment, and, for torque transducers, maximum shaft speed and proximity of any magnetic fields that may cause reading errors. A frequent application of force transducers is in automatic weighing systems.

Speed and Velocity Transducers

Speed (a scalar quantity) is the magnitude of the time rate of change in displacement. *Velocity* (a vector quantity—magnitude and direction) is the time rate of change of displacement with respect to a reference system. *Velocity transducers* are almost invariably linear-velocity transducers, whereas speed transducers are normally angular-speed transducers (*tachometers*).

Velocity Transducers. Velocity transducers are usually of the electromagnetic type, exemplified by a coil in which a permanent-magnet core moves freely. The core has a sensing-shaft extension, and the shaft is attached to the object whose (usually oscillatory) velocity is to be measured. The rate at which lines of magnetic flux from the core are cut by the coil turns determines the amount of electromotive force generated in the coil; hence the output is proportional to the velocity of the measured point. In some designs the coil moves within a fixed magnetic field instead.

Tachometers. Tachometers are also predominantly of the electromagnetic type. Such angular-speed transducers as the *dc tachometer generator,* the *ac induction tachometer,* and the *ac permanent magnet tachometers (ac magneto)* are electric generators. Their output amplitude increases with angular (rotational) speed. In the case of the ac magneto, the output frequency also increases with speed. The output of a *toothed-rotor tachometer* also varies in both amplitude and frequency, but the frequency variation is much greater than the amplitude variation and represents the angular speed much more accurately.

The speed-sensing gear teeth and sensing coil (pickup) incorporated in the torque transducer of Fig. 8.2.8 constitute a toothed-rotor tachometer. A pulse is generated in the electromagnetic sensing coil every time a ferromagnetic tooth passes by it. Since there are 60 teeth on the gear shown in the illustration, 60 pulses per revolution are provided by the sensing coil. By counting the pulses over a fixed time interval the angular speed can be determined with very close accuracy. *Photoelectric tachometers* provide the same degree of accuracy, typically by chopping a beam between the light source and a light sensor into equidistant pulses by an incremental-encoder disk attached to the sensing shaft. The pulse-frequency output can also be converted into a dc output voltage if the degraded accuracy, resulting from the conversion, can be tolerated.

Selection criteria include, besides range and accuracy characteristics, the mounting position and required frequency response for velocity transducers, and the type of available readout or signal-conditioning and telemetry equipment in the case of tachometers.

Strain Transducers

Strain is the deformation of a solid resulting from *stress,* the force acting on a unit area in a solid. Strain is measured as the ratio of dimensional change to the total value of the dimension in which the change occurs. Essentially all strain transducers are resistive and are referred to as *strain gages.* Their essential characteristic is their sensitivity (*gage factor*), the ratio of the unit change in resistance to the unit change in dimension (length).

Strain Gages. Strain gages employ either a conductor or semiconductor, of small cross-sectional area, suitable for mounting to the measured surface so that it elongates or contracts with that surface and changes its resistance accordingly. Most types of metal gages are made of thin metal foil, die-cut or etched into the required pattern, or they can be deposited on an insulating substrate through a pattern mask by bombardment or evaporative methods. The metals used in strain gages are usually copper-nickel alloys; other alloys such as nickel-chromium, platinum-tungsten, and platinum-iridium are also used. *Semiconductor* gages are usually made from thin doped-silicon wafers or blocks.

Strain gages can be *bare* (*surface-transferable,* free-filament), bonded to an insulating carrier sheet on one side only, or completely *encapsulated* in a bondable (usually plastic) or weldable (metal) carrier, the latter insulated internally from the gage. Bare gages are normally supplied with a strippable insulating substrate (*carrier*). Since two or more gages are normally used to obtain a strain measurement, for temperature-compensation, linearity-compensation, and output-multiplication purposes, strain-gage *rosettes* are sometimes used, combining two, three, or four gages, mutually aligned as to their strain-sensing axes, on one carrier.

Selection criteria involve the desired type and size (always including gage length and width), type, and material of connecting leads and spacing between them on the gage itself, type of carrier or encapsulation, gage resistance, gage factor, transverse sensitivity tolerances, allowable overload (*strain limit*), and maximum excitation current for a given application. Semiconductor gages may have to be shielded from illumination, which can cause reading errors. Proper methods of attachment and of connection into a Wheatstone bridge circuit are very critical for strain gages.

TRANSDUCERS FOR FLUID-MECHANICAL QUANTITIES

Transducers for fluid-mechanical quantities can be used to measure density and flow of a homogeneous fluid. Transducers can also be used to measure humidity, moisture, and dew-point of a homogeneous gas. Liquid level sensors can determine several characteristics of a liquid or slurry within closed vessels.

Density Transducers

Density is the ratio of the mass of a homogeneous substance to a unit volume of that substance. Density transducers (*densitometers*) are used for the determination of the density of fluids (gases, liquids, and slurries).

They are, however, not related to densitometers used to measure optical density, as of a photographic image, or to equipment used to determine spectral density (e.g., power spectral density).

Three methods are primarily used for density sensing:

Sonic density sensing is achieved by an arrangement of piezoelectric sound (usually ultrasound) transmitters and receivers producing outputs proportional to the speed of sound in the fluid and to the acoustic impedance of the fluid. Since acoustic impedance varies with the product of speed of sound and density, a signal proportional to density can be derived from the transducer and signal conditioning system.

Radiation density sensing relies on the attenuation, owing to density, of the radiation passing from a radioisotope source, on one side of the fluid-carrying pipe or vessel, to a radiation detector on the opposite side.

Vibrating-element density sensing employs a simple mechanical structure, such as a cylinder or a plate, electromagnetically set into vibration at its resonant frequency. This frequency changes with density, and an output is produced, proportional to density, which is related directly to the square of the period of vibration.

Additional methods, used to infer density from other measurements, have also been employed in measurement systems.

Flow Transducers

Flow is the motion of a fluid. *Flow rate* is the time rate of motion expressed either as fluid volume per unit time (*volumetric flow rate*) or as fluid mass per unit time (*mass flow rate*). Transducers used for flow measurement (*flowmeters*) generally measure flow rate. Most flowmeters measure volumetric flow rate, which can be converted to mass flow rate by simultaneously measuring density and computing mass flow rate from the two measurements. Some flowmeters measure mass flow rate directly. Flow-sensing elements can be categorized as follows:

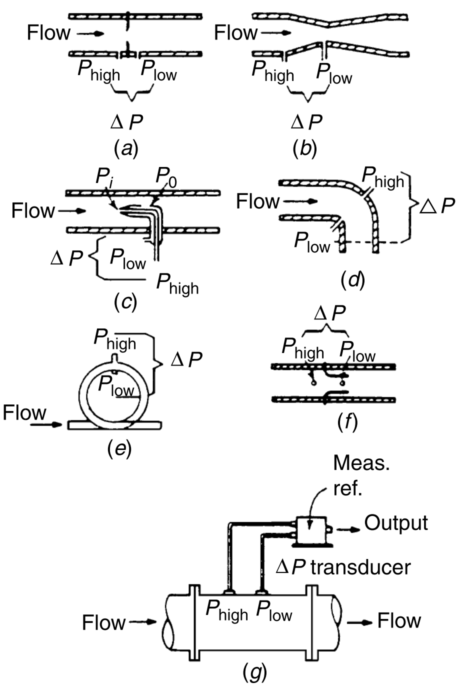

FIGURE 8.2.9 Flow measurement using differential pressure-sensing elements: (*a*) orifice plate; (*b*) venturi tube; (*c*) pitot tube; (*d*) centrifugal section (elbow); (*e*) centrifugal section (loop); (*f*) nozzle; (*g*) measurement of differential pressure due to flow rate. (*From Ref. 1 by permission*)

1. *Differential-pressure flow-sensing elements.* Sections of pipe provided with a restriction or curvature that produces a pressure differential ΔP proportional to flow rate across two points of the device (see Fig. 8.2.9). The output of a differential pressure transducer whose input ports are connected to these two points is representative of flow rate through the sensing element. Known relationships of ΔP versus flow rate exist for each type of element.
2. *Mechanical flow-sensing elements.* Freely moving elements, e.g., turbine or propeller, or mechanically restrained elements, e.g., a float in a vertical tapered tube, a spring-restrained plug, a hinged or cantilevered vane, whose displacement, deflection, or angular speed is proportional to flow rate.
3. *Flow sensing by fluid characteristics.* Certain transduction elements can be so designed and installed that they will interact with the moving fluid itself and produce an output relative to flow rate. The heated wire of a *hot-wire anemometer* transfers more of its heat to the fluid as the flow rate increases, thereby causing the resistance of the heated wire to decrease. When small amounts of radioisotope tracer material are added to the fluid, a radiation detector close to the moving fluid will respond with increasing output as the flow rate increases (*nucleonic flowmeter*).

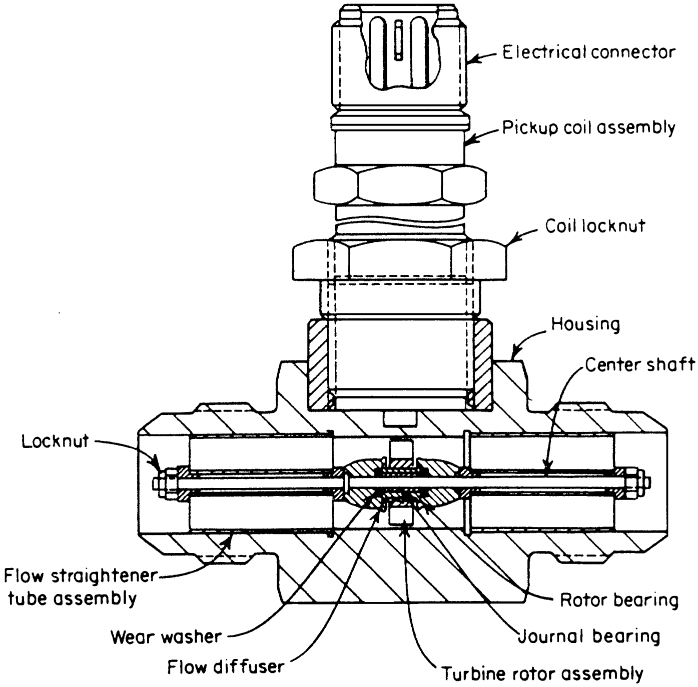

FIGURE 8.2.10 Turbine flowmeter. (*ITT Barton.*)

In the (*fluid-conductor*) *magnetic flowmeter* an increasing electromotive force is induced in an electrically conductive fluid, flowing through a transverse-magnetic field, as the flow rate increases. In the *thermal flowmeter* two thermocouple junctions are immersed in the moving fluid, one upstream, the other downstream, from an electric heater immersed in the same fluid, and the two junctions are connected as a differential thermocouple, the output of the latter increasing with mass flow rate. In a similar device, the *boundary-layer flowmeter,* only the portion of the fluid immediately adjacent to the inside wall of the pipe is heated and thermally sensed.

Turbine Flowmeters. The turbine flowmeter (see Fig. 8.2.10) is among the most widely used flow-rate transducers. Its operating principle is similar to that of the toothed-rotor tachometer. The bladed rotor (turbine) rotates at an angular speed proportional to volumetric flow rate. Rotational friction is reduced as much as possible by special bearing design. As each magnetic rotor blade cuts the magnetic flux of the pickup coil's pole piece, a pulse is induced in the pickup coil (sensing coil). A frequency meter is used to display the frequency output of the flowmeter, or a frequency-to-dc converter can be used to provide a dc voltage increase with flow rate. The rotor blades can be so machined that the variable-frequency ac voltage across the sensing coil terminals is virtually sinusoidal. This permits use of an FM demodulator as a frequency-to-dc converter. The number of turbine blades, the pitch of the blades, and the internal geometry of the flowmeter determine the range of output frequencies for a given flowrate range.

Oscillating-Fluid Flowmeters. In this device the fluid is the first forced into a swirling motion, then passes through a venturi-like cavity at a point of which the flow oscillates about the axis of the flowmeter. A fast-response temperature or force transducer at that point provides an output in terms of frequency of resistance changes. This frequency, proportional to flow rate and converted into voltage variations, can then be displayed on a counter after it has been amplified, filtered, and wave-shaped. Strain or pressure sensors are also used in such flowmeters.

Other Flowmeter Designs. Other flowmeter designs include the *ultrasonic flowmeter,* typically using pairs of piezoelectric transducers to establish sonic paths. Changes in flow rate produce corresponding changes in the propagation velocity of sound along the path. *Strain-gage flowmeters* are cantilevered vanes or beam-supported drag bodies that deflect or displace in response to fluid flow. The strain in the deflecting beam is then transduced by strain gages. A few types of *angular-momentum mass flowmeters* have been developed in which the fluid either imparts angular momentum to a circular tube through which it flows or receives angular momentum by a rotating impeller. The angular momentum is then used to cause an angular displacement or a torque in a mechanical member, either of which can be transduced to provide an output proportional to mass flow.

Selection criteria involve, first, a choice of either a flowmeter alone or a complete flow-rate or flow-measuring system that can include signal conditioning and display equipment and, when required, a flow totalizer. Among the essential flowmeter characteristics are the (mass or volumetric) flow-rate range, the properties and type(s) of the measured fluid (gas, liquid, mixed-phase, slurry), the nominal and maximum pressure and temperature of the fluid, the configuration, mechanical support, weight and provisions for connection of the flowmeter, the required time constant, and the output, as well as accuracy, specifications. The sensitivity of a turbine flowmeter is usually expressed as the *K factor,* stated in hertz (or cycles) per gallon, per liter, per cubic foot, or per cubic meter. Attention must also be paid to the length of straight pipe upstream and downstream of the flowmeter and the necessity for flow straighteners other than those incorporated in the transducer itself.

Humidity and Moisture Transducers

Humidity is a measure of the water vapor present in a gas. It is usually measured as relative humidity or dew-point temperature, sometimes as absolute humidity. *Relative humidity,* which is temperature-dependent, is the ratio of the water-vapor pressure actually present to water-vapor pressure required for saturation at a given temperature; it is expressed in percent (percent RH). The *dew point* is the temperature at which the saturation water-vapor pressure is equal to the partial pressure of the water vapor in the atmosphere. Hence any cooling of the atmosphere, even a slight amount below the dew point, produces water condensation. The relative humidity at the dew point is 100 percent RH. *Moisture* is the amount of liquid adsorbed or absorbed by a solid; it is also the amount of water adsorbed, absorbed, or chemically bound in a nonaqueous liquid. Humidity and moisture measurements are made by one of three methods: hygrometry, psychrometry, and dew-point determination.

Hygrometers. The hygrometer is a device that can measure humidity directly, with a single sensing element; it is usually calibrated in terms of relative humidity. Three types of hygrometric sensing elements are shown in Fig. 8.2.11. In the *resistive* humidity-transducer sensing element a change in ambient relative humidity produces a change in resistance of a conductive film between two electrodes. Carbon powder in a binder material has been used for such films, but hygroscopic salts, also in a binder material, are more common. Lithium chloride was used originally in such elements; more recently, sulfonated polystyrene and *electrolytic* elements (rather than resistive), such as phosphorous pentoxide, have come into use. The *mechanical* hygrometric element is the oldest type. It uses a material, such as human hair or animal membrane, which changes its dimensions with humidity. The resulting displacement on an attaching point on the material is then transduced into an output proportional to humidity. The *oscillating-crystal* hygrometric element consists of a quartz crystal with a hygroscopic coating, so that the total crystal mass changes as water is adsorbed on, or desorbed from, the coating. When the crystal is connected into an oscillator circuit, the oscillator output frequency will change with changes in humidity.

Several other types of hygrometric sensing elements have also been developed. In the *aluminium oxide element* an impedance (resistance and capacitive reactance) change occurs with changes in humidity. The *Brady array* also provides an ac output when excited with alternating current (at about 1 kHz). However, it differs from other devices in that it consists of an array of semiconducting crystal matrices that look electrically neutral to the water molecule. Vapor pressure then allows the molecules to drift in and out of the interstices, creating an exchange of energy within the structure. The *porous-glass-disk* hygrometric element has electrodes

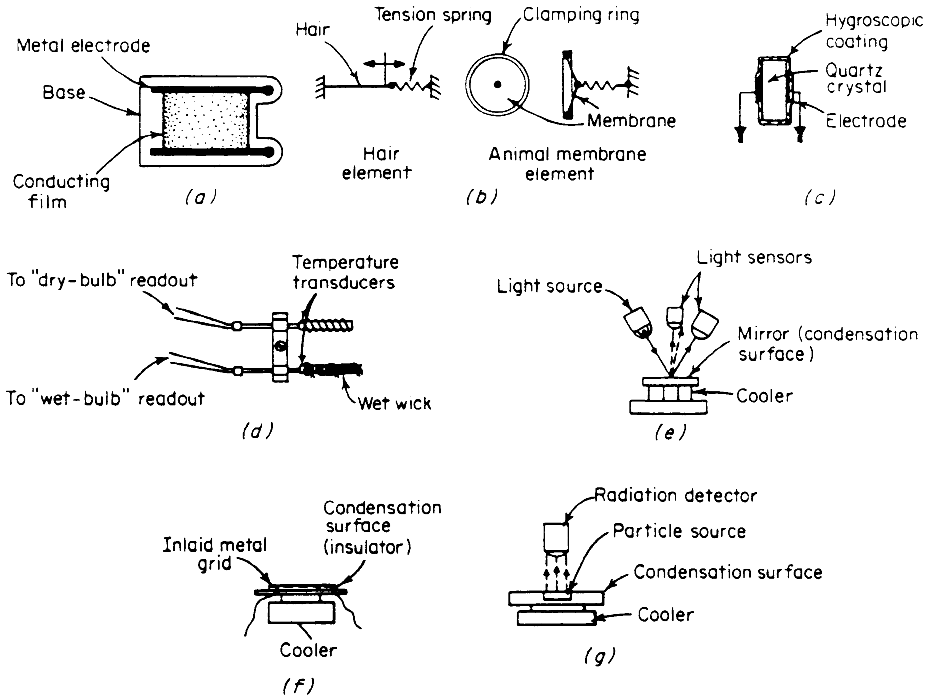

FIGURE 8.2.11 Sensing elements of humidity transducers: (*a*) resistive; (*b*) mechanical; (*c*) oscillating crystal; (*d*) psychometric; (*e*) photoelectric; (*f*) resistive; (*g*) nucleonic; (*e*) to (*g*) are dew-point sensors. (*From Ref. 1 by permission*)

plated on the two surfaces of the disk. When water vapors permeate the pores in the glass, it is decomposed electrolytically when a voltage is applied across the electrodes. The current necessary to decompose the water is then a measure of relative humidity.

Psychrometers. Psychrometers use two temperature-sensing elements (see Fig. 8.2.11*d*). One element, *dry bulb*, measures ambient temperature; the other, *wet bulb,* covered with a water-saturated wick or similar device, measures temperature reduction due to evaporative cooling. Relative humidity can be determined from the dry-bulb temperature reading, the differential temperature between dry-bulb and wet-bulb readings, and knowledge of the barometric pressure by referring to a *psychometric table* of numbers. Such tables are available from government agencies, e.g., weather service, as well as from manufacturers. The temperature-sensing elements are usually resistive (platinum- or nickel-wire windings or thermistors), sometimes thermoelectric.

Dew-Point Sensing Elements. Dew-point sensing elements are dual elements. The condensation-detection element senses the first occurrence of dew on a surface whose temperature is being lowered. The temperature-sensing element measures the temperature of this surface so that the dew point (the temperature at which condensation first occurs as the temperature is lowered) can be determined by monitoring the output of both elements simultaneously. Typical condensation detectors (see Fig. 8.2.11) include a photoelectric device in which light sensors detect the difference in light, reflected from a mirror that serves as the condensation surface, when the dew point is reached; a resistive element in which a change in conductivity occurs in an inlaid metal grid at the condensation surface when condensation occurs; and a nucleonic device in which a drop in particle flux, emitted from a radiation source at the condensation surface, indicates the dew point.

Auxiliaries. Resistive humidity transducers are generally more popular than other types when a transducer, rather than a complete measurement system, is required. Almost all types require ac excitation. The electrodes are spiral, helical, or loop-shaped to obtain as large a resistance change as feasible for a given element size. Other hygrometric transducers usually require at least an excitation and signal conditioning unit.

Psychrometric transducers are typically complemented by a signal conditioning and readout system. A small blower (*aspirator*) is often included to blow the ambient air over the two sensing elements so that a faster response can be obtained.

Dew-point humidity transducers require, as a minimum, a cooler (thermoelectric coolers are often used), its associated control circuit, and a power conditioning circuit, as well as the two sensing elements. However, several designs are miniaturized and require relatively little signal conditioning.

Selection criteria. Humidity transducer applications should first be examined to see whether relative humidity or dew point is to be measured. Relative humidity can, of course, also be inferred from psychrometric and dew-point readings but not without a look-up table or calculations. Among performance characteristics the measurement range is the most important; measurement accuracy can usually be improved when only a partial range needs to be measured. Other important characteristics include the temperature and the chemical properties of the ambient atmosphere or the measured material.

Liquid-Level Sensing

A large variety of sensing approaches and transducer types have been developed for the determination of the level of liquids and quasi liquids, e.g., slurries and powdered or granular solids, in open or enclosed vessels (such as tanks and ducts). Not only is the knowledge of the *level* itself important, but other measurements can be inferred from level. If the tank geometry and dimensions are additionally known, the *volume* of the liquid can be determined. If, additionally, the density of the liquid is known, its *mass* can be calculated.

Level is generally sensed by one of two methods: obtaining a discrete indication when a predetermined level has been reached (*point sensing*) or obtaining an analog representation of the level as it changes (*continuous sensing*). Point sensing is also used when it is only desired to establish whether a liquid or a gas exists at a certain point, e.g., in a pipe. The different level-sensing methods can be classified into those lending themselves primarily to point sensing, to continuous sensing, or both. It should be understood, of course, that point-sensing systems are usually simpler and cheaper than continuous sensing systems and should be used when only a discrete indication has to be obtained. Even when two or more discrete levels must be established in one vessel, the use of two or more point sensors may be preferable to a continuous sensing system. On the other hand, electronic circuitry can be used to provide one or more discrete level indications from a continuous sensing system.

Point Level-Sensing Methods. Point level-sensing methods are usually aimed at indicating the interface between a liquid and a gas, sometimes the interface between two different liquids. Three methods are illustrated in Fig. 8.2.12. *Heat-transfer sensing* is used by two types of sensors: the resistive sensor (wire-wound or thermistor) is heated to some degree by the current passing through it so that its resistance changes because of cooling when contacted by the liquid; the thermoelectric sensor detects the cooling, upon liquid contact, of a wire-wound heater it is in thermal contact with. *Optical sensing* relies either on the presence or absence of reflection of a light beam from the interface between a prism surface in contact with gas (reflection) or liquid (no reflection) or on the greater attenuation of a light beam when it passes through liquid on its way to a light sensor. In *damped-oscillation sensing* the mechanical vibration of an element, excited into such vibration electrically, is either stopped (in a magnetostrictive or piezoelectric element) or reduced in amplitude (e.g., in an oscillating-paddle element) in response to acoustic damping or viscous damping, respectively, when the measured fluid changes to a liquid.

Continuous Level Sensors. Three classic continuous level-sensing methods are illustrated in Fig. 8.2.13. The level, volume, or mass of a liquid in a tank of known geometry can be determined by *weighing* the tank continuously, as by means of a load cell (force transducer), and subtracting the tare weight of the tank or compensating for the tare weight. *Pressure sensing* relies on the pressure (*head*) developed at the base of a liquid column. This pressure increases with the column height and hence with level above the point at which pressure is sensed. The differential pressure P_D, measured by the differential-pressure transducer, on the tank shown in the illustration, is equal to the difference in pressures between the bottom and top of the tank ($P_L - P_H$). The *level-sensing float* mechanically actuates a transduction element, usually a potentiometer,

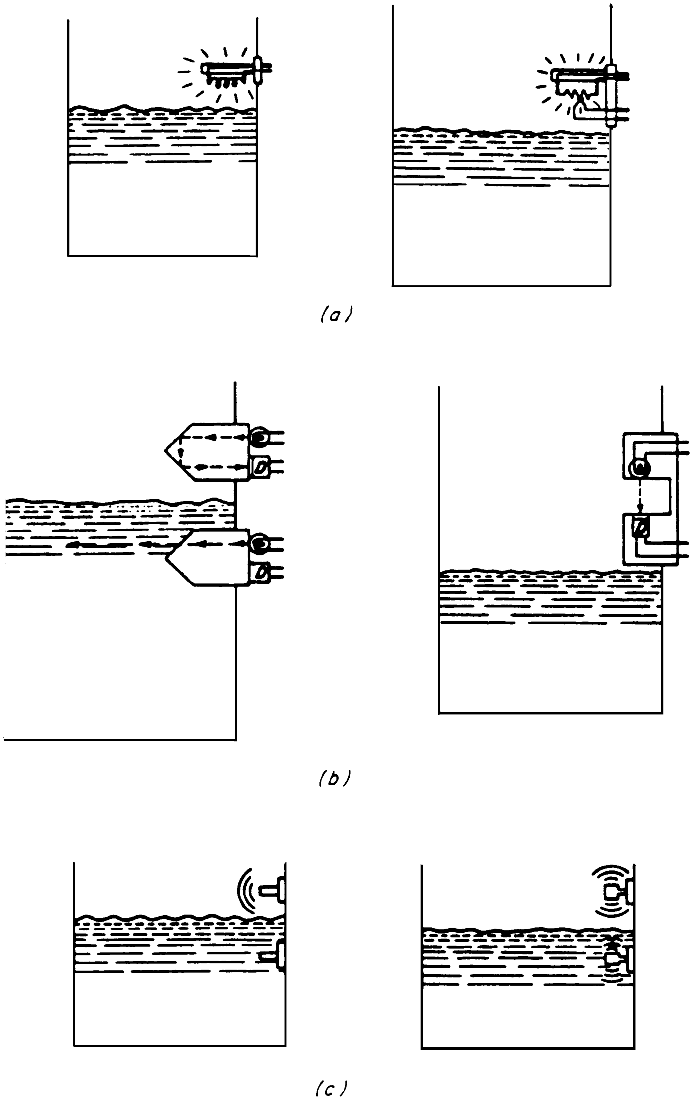

FIGURE 8.2.12 Point level-sensing methods: (*a*) by heat-transfer rate; (*b*) by optical means; (*c*) by oscillation damping. (*From Ref. 1 by permission*)

sometimes a reluctive element or one or more magnetic reed switches. A radically different method (not illustrated) is *cavity-resonance sensing,* where electromagnetic oscillations are excited (from a coupling element at the tank top) within the gaseous cavity enclosed by the liquid surface and the upper tank walls, and the change in resonant frequency, as the liquid surface changes in location, becomes a measure of liquid level.

Several methods are equally useful for point and continuous level sensing (see Fig. 8.2.14). *Conductivity level sensing* is usable with even mildly conductive liquids. The resistance between two electrodes (the tank wall may serve as one of the two) changes continuously (or suddenly, in the case of the point-sensor version) as the liquid level rises or falls.

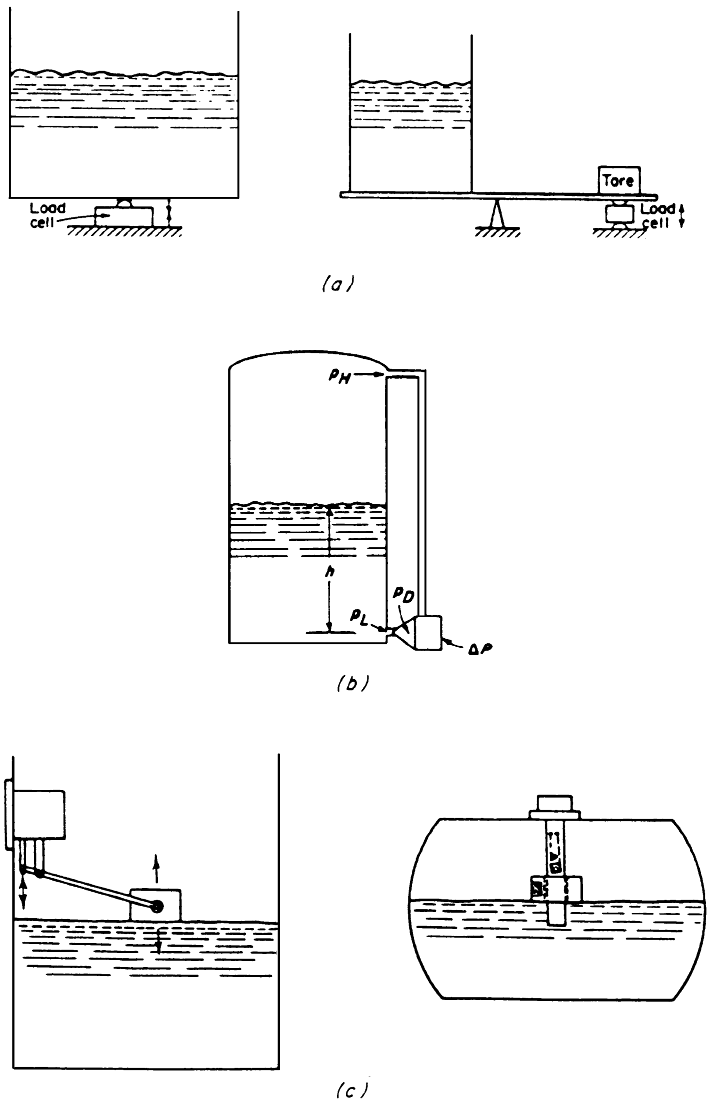

FIGURE 8.2.13 Continuous level-sensing methods: (*a*) by weighing; (*b*) by pressure sensing; (*c*) by float. (*From Ref. 1 by permission*)

Dielectric-variation (capacitive) sensing is used primarily for nonconductive liquids, which then play the role of dielectric materials between two (sometimes four) concentric electrodes that are used (and electrically connected) as plates of a capacitor. The capacitance changes continuously (or suddenly, for the point sensor) as the vertical distance h of the level changes. If it is necessary to compensate for changes in the liquid's characteristics during measurement, a reference capacitor, always submerged, can be employed so that the ratio of the capacitance change equals the ratio of the measured level to the vertical dimension of the reference capacitor ($\Delta C/\Delta C_R = h/h_R$).

Sonic level sensing uses ultrasound either emitted from a sound projector and detected by a sound receiver or emitted and detected by a single sound transceiver operating alternately in the transmit and receive mode.

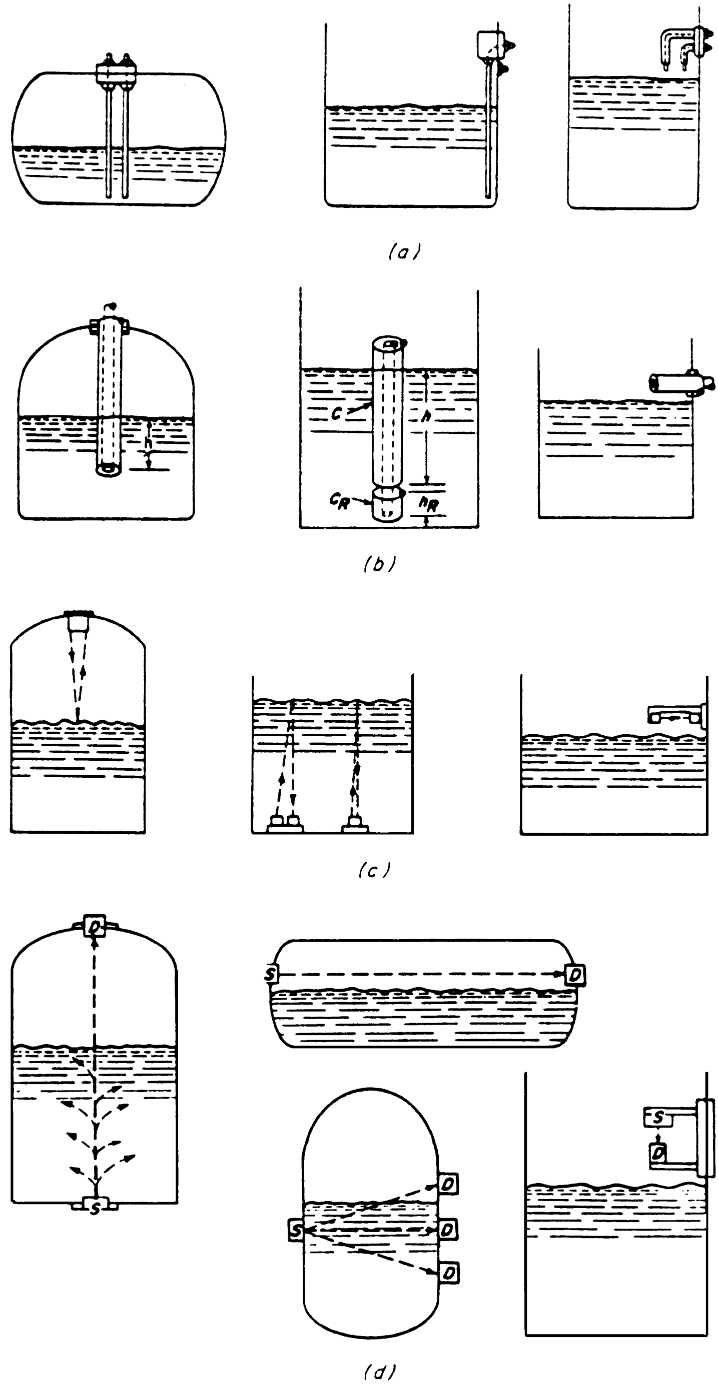

FIGURE 8.2.14 Continuous- and point-level sensing: (*a*) conductivity; (*b*) dielectric variation; (*c*) sonic sensing; (*d*) radiation sensing. (*From Ref. 1 by permission*)

An echo-ranging technique is commonly used, the liquid-gas interface (the liquid level) acting as the target. The difference in attenuation or travel time of the beam of sound between liquid or gas in its path can also be used for sonic level sensing, especially for point sensing.

Radiation sensing is a nucleonic sensing method employing usually one or more radioisotope sources and radiation detectors to indicate level changes by virtue of the changes in attenuation of the radiation in response to level changes. The attenuation in the liquid is caused mainly by absorption. Such nucleonic methods have also been used to study density profiles and the location and extent of vortices in tanks and of gas bubbles in pipes.

Liquid-Level Transducers. Liquid-level transducers, in their most common configuration, are probes, flange- or boss-mounted through the tank or duct wall. Some pipe-wall-mounted transducers are so designed that their sensing end is flush with the inside of the wall, to prevent obstructions to flow. Nucleonic transducer systems and some ultrasonic designs are attached to the outside of the wall.

The transduction principle of liquid-level transducers is given by the sensing technique employed. Dielectric-variation sensing demands capacitive transducers, using ac excitation having a frequency between 400 Hz and 200 kHz. Magnetostrictive and piezoelectric transducers, whose probe tip oscillates at a frequency in the vicinity of 40 kHz, find their application in the sonic, as well as the damped-oscillation, sensing techniques. Ionization-type, as well as solid-state, transducers are used in nucleonic systems. Photoelectric transducers are used in optical sensing systems. Potentiometric and reluctive transduction elements are found in float-actuated liquid-level transducers. Resistive transducers are used for heat-transfer sensing and, in a somewhat different form, for conductivity sensing. Thermoelectric elements are found in some heat-transfer sensors. Vibrating-element (notably vibrating-paddle) transducers find their use in damped-oscillation sensing systems.

Selection criteria involve, first of all, the choice of one or more point-level sensors or a continuous level sensor. After this choice has been made, together with an evaluation of end-to-end system requirements, the characteristics of the measured liquid are of primary importance. These include its conductivity, viscosity, temperature, chemical properties and, for installation in pipes or ducts, its flow rate and pressure. The transducer must also be designed and installed in such a manner as to prevent false level indications owing to slosh, spray, and splash or to adherence of liquid to the transducer with falling level.

Pressure and Vacuum Transducers

Pressure is force acting on a surface; it is measured as force per unit area, exerted at a given point. *Absolute pressure* is measured relative to zero pressure, *gage pressure* relative to ambient pressure, and *differential pressure* relative to a *reference pressure* or a range of reference pressures. A perfect *vacuum* is zero absolute pressure. Vacuum measurement, however, is the measurement of very low pressures.

Pressure-Sensing Elements. Pressure-sensing elements are almost invariably mechanical in nature (see Fig. 8.2.15). They can be described generally as thin-walled elastic members which deflect when the pressure on one side of their wall is not balanced by a pressure on the opposite side. The former pressure is the measured pressure; the latter is either a vacuum or near vacuum (for absolute-pressure transducers), the ambient atmosphere (for gage-pressure transducers), or some other pressure (for differential-pressure transducers).

The *diaphragm* is a circular plate fastened around its periphery so that its center will deflect when pressure is applied to it. It can be flat or, when a greater deflection is required, contain a number of concentric corrugations that increase the effective area upon which the force (pressure) can act. Two corrugated diaphragms, welded, brazed, or soldered together around their periphery, form a *capsule* sensing element (aneroid). Two or more capsules can be fastened together so that the pressure acts on all. The displacement obtainable at the end of such a multiple-capsule element nearly equals the displacement of one capsule multiplied by the number of capsules in the assembly. The *bellows* sensing element is typically made from a thin-walled tube formed into deep convolutions and sealed at one end, whose displacement can then be made to act on a transduction element. In the *straight-tube* sensing element, again sealed at one end, applied pressure causes an expansion of the tube diameter. This expansion, though slight, can be converted into a usable output by a transduction element.

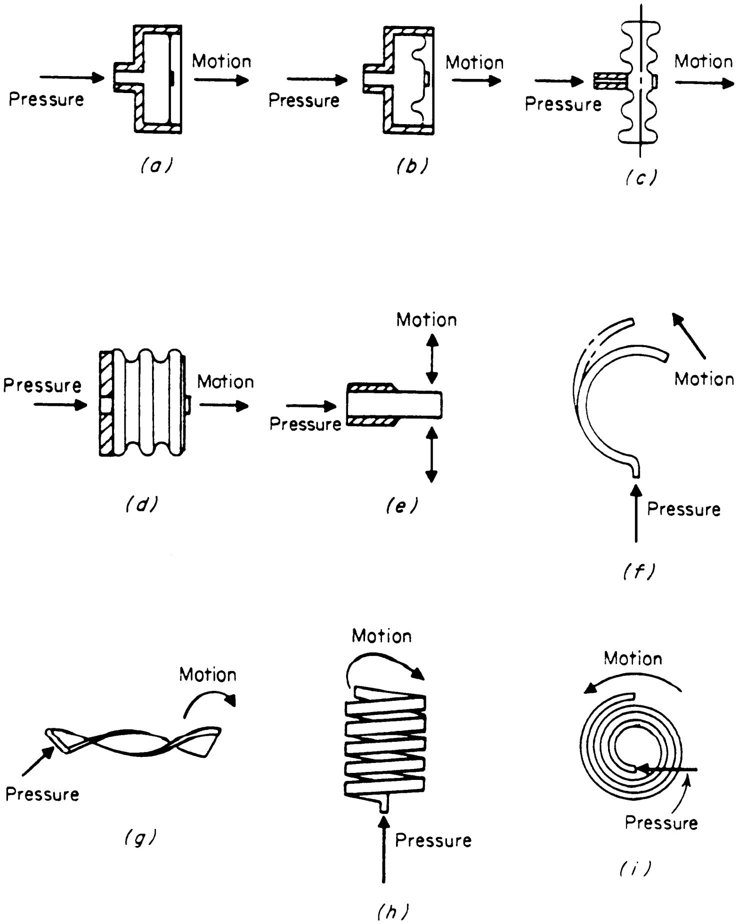

FIGURE 8.2.15 Pressure-sensing elements: (*a*) flat diaphragm; (*b*) corrugated diaphragm; (*c*) capsule; (*d*) bellows; (*e*) straight tube; (*f*) C-shaped Bourdon tube; (*g*) twisted Bourdon tube; (*h*) helical Bourdon tube; (*i*) spiral Bourdon tube. (*From Ref. 1 by permission*)

The *Bourdon tube* is one of the most widely used sensing elements, particularly for pressure ranges higher than 2 MPa (about 300 lb/in.^{2}). The Bourdon tube, elliptical in cross section and sealed at its tip, tends to straighten from its curved, twisted, helical, or spiral shape, thus causing the tip to deflect sufficiently to act on a transduction element. The number of turns or twists in a Bourdon tube tends to multiply the tip travel.

Pressure Transducers. Pressure transducers, using the sensing elements described above, provide their outputs by means of a large variety of transduction elements (see Table 8.2.1). Many designs are available with integrally packaged output- and excitation-conditioning circuitry. Certain designs, notably potentiometric, reluctive, and strain-gage transducers, are more prevalent than other types. Piezoelectric transducers are usable only for dynamic pressure measurements. Inductive transducers can be subject to severe temperature effects and are not used extensively.

A *potentiometric pressure transducer* features a dual-capsule sensing element that transfers its displacement to a lever-type wiper arm by means of a pushrod. The wiper then slides over the curved resistance

TABLE 8.2.1 Pressure Transducers

Transduction	Sensing elements	Type variations	Normal Excitation	Normal Output	Optional Excitation	Optional Output
Capacitive	Diaphragm	AC bridge unbalance	AC	AC	DC	DC
		Variable ionization	AC	DC		
		RF-tank-circuit detuning	AC	Freq.		
Inductive	Bellows	*LC* tank circuit	AC	Freq.		
	Diaphragm	AC bridge unbalance	AC	AC		
	Bourdon tube					
Piezoelectric	Diaphragm	Natural crystal	None	AC	DC	Amplified ac
		Synthetic crystal				
		Ceramic				
Potentiometric	Capsule	Wire-wound element	DC	DC		
	Bourdon tube	Continuous-resolution element (metal film, cermet, plastic, carbon film)				
Reluctive	Diaphragm	Inductance bridge	AC	AC	AC	DC
	Bourdon tube	Differential transformer			DC	DC
Strain gage	Diaphragm	Unbonded gages, metal wire	DC	DC	DC	Amplified dc
		Bonded gages, metal wire			DC	Digital
		Micro-machined				
	Straight tube	Bonded gages, metal foil; bonded gages, semiconductor; diffused semiconductor gages; evaporated-metal gages				
Servo type	Capsule	Null balance	AC	AC		Encoder (digital)
	Bellows	Force balance	AC	DC		Synchro
			DC	DC		Potentiometric
Vibrating element	Diaphragm	Vibrating wire	AC	Freq.	DC	Freq.
		Vibrating diaphragm				
	Straight tube	Vibrating cylinder				

element. Capsule elements are commonly used in such transducers for pressure ranges up to 2.5 MPa (about 360 lb/in.^{2}).

Reluctive pressure transducers use either the inductance bridge circuit or, primarily when only the normal ac output is required, the differential-transformer circuit. When inductance bridge transducers use a diaphragm sensing element, the magnetic diaphragm itself, positioned between two coils, acts as the armature which increases the inductance of one coil while decreasing the inductance of the other coil. When inductance bridge transducers use a Bourdon tube sensing element, a flat armature plate, positioned over two coils, tilts more toward one coil than toward the other as the Bourdon tube tip rotates slightly with applied pressure. In differential-transformer transducers the sensing-element displacement is used to move a magnetic core within the transformer.

Most *strain-gage pressure transducers* use a diaphragm sensing element, although at least one good design uses a straight tube. Most designs have a four-active-arm strain-gage bridge, with the gages either on the diaphragm or on a beam actuated by the diaphragm. Included in this category are solid-state pressure transducers, micromachined from a silicon base, with integrally diffused gages.

When the sensing-element displacement is not sufficient for a given transduction element, a mechanical amplification linkage can be inserted between the two elements. Special design considerations apply to differential-pressure transducers when the measured fluid (at one of the two pressure ports) must not come in contact with the transduction element. One solution to this problem has been to fill the affected inside portion of the transducer with a *transfer fluid*, sealed off by a thin *membrane* to which the measured fluid can be applied safely. Gage-pressure transducers have the inside of their case (which usually acts as the *reference cavity*) vented to the outside through a small hole (*gage vent*), equipped with a fine-mesh screen, a porous plug, or another filter to prevent internal contamination.

Flush-diaphragm transducers are designed for high-frequency-response applications where use of tubing, or even the cavity formed by a mounting boss, may reduce response; these transducers are so designed that the diaphragm is flush (when installed) with the inside surface of the pipe wall (or other wall) through which they are mechanically fastened.

Specification characteristics of pressure transducers deserve particular attention since pressure is one of the two most common measurands (the other is temperature). Table 8.2.2 lists those characteristics which should be considered when preparing a specification for a pressure tarnsducer. Not all these characteristics need always be specified; some can be omitted when sufficient knowledge of the application permits.

Vacuum Transducers. Vacuum transducers are an important subgroup of pressure transducers, though bearing little resemblance to them with regard to design and operation. The pressure constituting a practical dividing line between pressure and vacuum measurement is not well defined. Some pressure transducers are usable for very low pressure measurement. Generally, however, pressure measurements extending substantially below 133 Pa (= 1 torr) can be considered as vacuum measurements.

Vacuum transducers (see Table 8.2.3) exist in two major categories, given by their transduction principles.

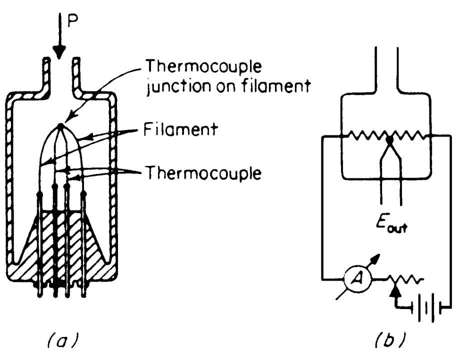

FIGURE 8.2.16 Thermoelectric thermoconductive vacuum transducer; (*a*) transducer; (*b*) typical circuit. (*From Ref. 1 by permission*)

Thermoconductive vacuum transducers measure pressure as a function of heat transfer by the measured gas. As the number of gas molecules within the transducer decreases, the quantity of heat transferred from a heated filament, through the gas, and to the case of the transducer, will decrease proportionally. The *Pirani gage,* as well as the *thermocouple gage* (which may use a thermopile instead of a single junction), both use this principle. A basic thermocouple gage is illustrated in Fig. 8.2.16.

Ionizing vacuum transducers measure pressure as a function of gas density by measuring ion current. Since different gases have different densities, the calibration of such a transducer will usually differ as well. The gas is usually ionized by electrons, except in one type using alpha particles for this purpose.

In thermionic vacuum transducers the electrons are emitted by a filamentary cathode, and positive ions are collected at the anode. Various modifications of the original triode type have helped to extend its lower range limit from 10^{-8} to 10^{-10} torr (*Bayard-Alpert gage,* by reducing internal x-ray effects) to 10^{-11} torr (*Nottingham gage,* by reducing electrostatic-charge effects) and to 10^{-12} torr (*Schuemann modification,* by virtually eliminating x-ray effects). The ion current, representative of pressure, is in the microampere region.

Several ionizing vacuum transducer types, whose electrons are emitted from either hot or ion-bombarded cold cathodes, use a magnetic field to increase the electron path length by forcing this path to be helical so that the probability of electron collisions with gas molecules is increased (*magnetron gages*). The hot-cathode versions include the *Lafferty gage.* The *Philips* (or *Penning*) *gage* and the *Redhead gage* are examples of the cold-cathode versions.

TABLE 8.2.2 Specification Characteristics for Pressure Transducers

Mechanical design characteristics	
Specified by user and manufacturer	**Stated by manufacturer**
Configuration and dimensions (shown on drawing)	Sensing element
Mountings (shown on drawing)	Transduction-element details
Type and location of pressure ports (shown on drawing)	Materials in contact with measured fluids
Type and location of electrical connections (shown on drawing)	Dead volume
Nature of pressure to be measured, including range	Type of damping (including type of damping oil if used)
Measured fluids	
Case sealing (explosion proof, burstproof, or waterproof enclosure)	
Isolation of transduction element	
Mounting and coupling torque	
Weight	
Identification	
Nameplate location (shown on drawing)	
Electrical design characteristics	
Excitation (nominal and limits)	
Power rating (optional)	
Input impedance (or element resistance)	
Output impedance	
Insulation resistance (or breakdown-voltage rating)	
Wiper noise (in potentiometric transducers)	
Output noise (in dc output transducers)	
Electrical connections and wiring diagram	
Integral provisions for simulated calibration (optional)	
Performance characteristics	
Individual specifications	**Error-band specifications**
Range	Range
End points	Full-scale output (nominal)
Full-scale output	End points (defining reference line)
Creep (optional)	Resolution (where applicable)
Resolution (where applicable)	Static error band
Linearity	Reference-pressure range*
Hysteresis	Warm-up period (optional)
Repeatability	Frequency response
Friction error	
Zero balance	
Zero shift	
Sensitivity shift	
Warm-up period (optional)	
Frequency response	
Operating temperature range	Operating temperature range
Temperature error or thermal zero shift and thermal sensitivity shift	Temperature error band
Temperature-gradient error	Temperature-gradient error
Ambient-pressure error	Ambient-pressure error band
Acceleration error	Acceleration error band
Vibration error	Vibration error band

(*Continued*)

TABLE 8.2.2 Specification Characteristics for Pressure Transducers (*Continued*)

Performance after exposure to:	Performance during and after exposure to:
Shock (triaxial)	High sound-pressure levels
Humidity	Sand and dust
Salt spray or salt atmosphere	Ozone
	Nuclear radiation
	High-intensity magnetic fields etc.

*Applies to differential-pressure transducers only.

Selection criteria for vacuum transducers (and any necessary ancillary equipment for them) are primarily the required measuring range; secondarily, size, weight, ruggedness, and complexity. Considerations for the selection of a pressure transducer are primarily range, type of excitation and output, accuracy and frequency response; secondarily, the properties of the measured fluid and environmental conditions.

Ranges of Pressure Transducers. Some of the pressure transducers described in this section are available for ranges up to 100 MPa (about 15,000 lb/in.^{2}). Special sensing devices have been designed for pressures up to 7 GPa (about 1 million lb/in.^{2}). Pressure transducers are also used to measure altitude (a known nonlinear relationship exists between atmospheric pressure and altitude above sea level), water depth (pressure increases at the rate of approximately 1 KPa/m (0.44 lb/in.^{2} ft) when descending below the water surface), and air speed (by measuring the difference between impact pressure, obtained from a pitot tube, and static pressure, while in flight).

TABLE 8.2.3 Vacuum Transducers

Sensing element	Common name	Output	Nominal range, torr
	Thermoconductive transduction		
Heated filament	Pirani gage	Resistance change	10^{-3}–1
	Thermocouple gage	Thermoelectric emf	10^{-3}–1
	Ionizing transduction		
Thermionic, triode	Bayard-Albert gage	Direct current	10^{-10}–10^{-3}
Photomultiplier		Direct current	10^{-15}–10^{-3}
Hot cathode, magnetic field	Hot-cathode magnetron gage (Laffety gage)	Direct current	10^{-14}–10^{-5}
Cold cathode, magnetic field	Cold-cathode magnetron gage (Philips gage, Penning gage)	Direct current	10^{-7}–10^{-3}
With flash filament		Direct current	10^{-12}–10^{-3}
With auxiliary cathode	Redhead gage	Direct current	10^{-13}–10^{-4}
Radioactive, alpha particles	Alphatron	DC voltage (from amplifier)	10^{-5}–1000
Beta particles		DC voltage (from amplifier)	10^{-8}–1000

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