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Force Measurement

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Force, which is a vector quantity, can be defined as an action that will cause an acceleration or a certain reaction of a body. This chapter will outline the methods that can be employed to determine the magnitude of these forces.

23.1 General Considerations

The determination or measurement of forces must yield to the following considerations: if the forces acting on a body do not produce any acceleration, they must form a *system of forces in equilibrium.* The system is then considered to be in static equilibrium. The forces experienced by a body can be classified into two categories: internal, where the individual particles of a body act on each other, and external otherwise. If a body is supported by other bodies while subject to the action of forces, deformations and/or displacements will be produced at the points of support or contact. The internal forces will be distributed throughout the body until equilibrium is established, and then the body is said to be in a state of tension, compression, or shear. In considering a body at a definite section, it is evident that all the internal forces act in pairs, the two forces being equal and opposite, whereas the external forces act singly.

23.2 Hooke's Law

The basis for force measurement results from the physical behavior of a body under external forces. Therefore, it is useful to review briefly the mechanical behavior of materials. When a metal is loaded in uniaxial tension, uniaxial compression, or simple shear (Figure 23.1), it will behave elastically until a critical value of normal stress (S) or shear stress (τ) is reached, and then it will deform plastically [1]. In the elastic region, the atoms are temporarily displaced but return to their equilibrium positions when the load is removed. Stress (S or τ) and strain (e or γ) in the elastic region are defined as indicated in Figure 23.2.

$$\nu = -\frac{e_2}{e_1} \tag{23.1}$$

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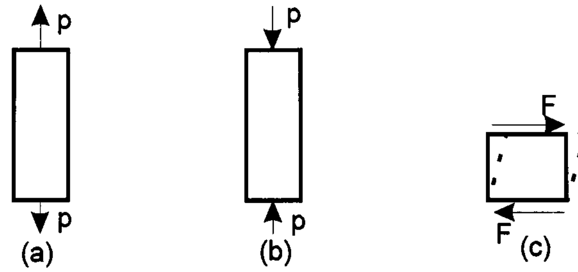

FIGURE 23.1 When a metal is loaded in uniaxial tension (*a*) uniaxial compression (*b*), or simple shear (*c*), it will behave elastically until a critical value of normal stress or shear stress is reached.

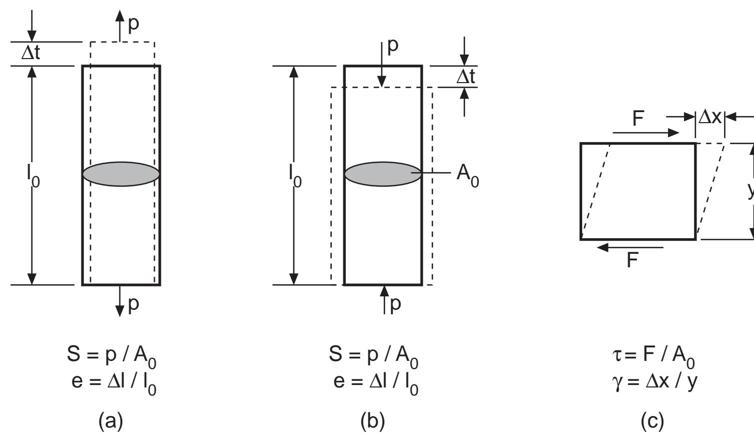

FIGURE 23.2 Elastic stress and strain for: (*a*) uniaxial tension; (*b*) uniaxial compression; (*c*) simple shear [1].

Poisson's ratio (ν) is the ratio of transverse (e_2) to direct (e_1) strain in tension or compression. In the elastic region, ν is between 1/4 and 1/3 for metals. The relation between stress and strain in the elastic region is given by Hooke's law:

$$S = E\, e \left(\text{tension or compression}\right) \tag{23.2}$$

$$\tau = G\gamma \left(\text{simple shear}\right) \tag{23.3}$$

where E and G are the Young's and shear modulus of elasticity, respectively. A small change in specific volume ($\Delta Vol/Vol$) can be related to the elastic deformation, which is shown to be as follows for an isotropic material (same properties in all directions).

$$\frac{\Delta Vol}{Vol} = e_1\left(1 - 2\nu\right) \tag{23.4}$$

The bulk modulus (K = reciprocal of compressibility) is defined as follows:

$$K = \Delta p \Big/ \left(\frac{\Delta Vol}{Vol}\right) \tag{23.5}$$

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where Δp is the pressure acting at a particular point. For an elastic solid loaded in uniaxial compression (S):

$$K = S\Bigg/\left(\frac{\Delta Vol}{Vol}\right) = \frac{S}{e_1\left(1-2\nu\right)} = \frac{E}{1-2\nu} \tag{23.6}$$

Thus, an elastic solid is compressible as long as ν is less than 1/2, which is normally the case for metals. Hooke's law (Equation 23.2) for uniaxial tension can be generalized for a three-dimensional elastic condition.

The theory of elasticity is well established and is used as a basis for force measuring techniques. Note that the measurement of forces in separate engineering applications is very application specific, and care must be taken in the selection of the measuring techniques outlined below.

Basic Methods of Force Measurement

An unknown force may be measured by the following means:

1. Balancing the unknown force against a standard mass through a system of levers.
2. Measuring the acceleration of a known mass.
3. Equalizing it to a magnetic force generated by the interaction of a current-carrying coil and a magnet.
4. Distributing the force on a specific area to generate pressure, and then measuring the pressure.
5. Converting the applied force into the deformation of an elastic element.

The aforementioned methods used for measuring forces yield a variety of designs of measuring equipment. The challenge involved with the task of measuring force resides primarily in sensor design. The basics of sensor design can be resolved into two problems:

1. Primary geometric, or physical constraints, governed by the application of the force sensor device.
2. The means by which the force can be converted into a workable signal form (such as electronic signals or graduated displacements).

The remaining sections will discuss the types of devices used for force to signal conversion and finally illustrate some examples of applications of these devices for measuring forces.

23.3 Force Sensors

Force sensors are required for a basic understanding of the response of a system. For example, cutting forces generated by a machining process can be monitored to detect a tool failure or to diagnose the causes of this failure in controlling the process parameters, and in evaluating the quality of the surface produced. Force sensors are used to monitor impact forces in the automotive industry. Robotic handling and assembly tasks are controlled by detecting the forces generated at the end effector. Direct measurement of forces is useful in controlling many mechanical systems.

Some types of force sensors are based on measuring a deflection caused by the force. Relatively high deflections (typically, several micrometers) would be necessary for this technique to be feasible. The excellent elastic properties of helical springs make it possible to apply them successfully as force sensors that transform the load to be measured into a deflection. The relation between force and deflection in the elastic region is demonstrated by Hooke's law. Force sensors that employ strain gage elements or piezoelectric (quartz) crystals with built-in microelectronics are common. Both impulsive forces and slowly varying forces can be monitored using these sensors.

Of the available force measuring techniques, a general subgroup can be defined as that of load cells. Load cells are comprised generally of a rigid outer structure, some medium that is used for measuring

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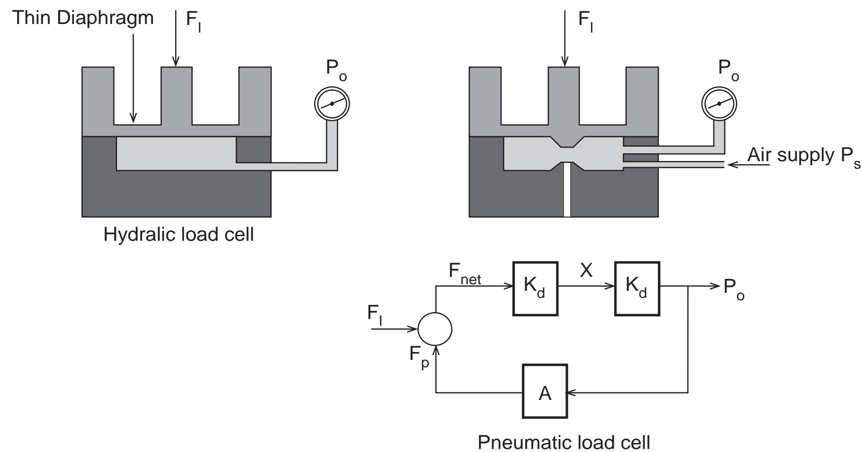

FIGURE 23.3 Different types of load cells [2].

the applied force, and the measuring gage. Load cells are used for sensing large, static or slowly varying forces with little deflection and are a relatively accurate means of sensing forces. Typical accuracies are of the order of 0.1% of the full-scale readings. Various strategies can be employed for measuring forces that are strongly dependent on the design of the load cell. For example, Figure 23.3 illustrates different types of load cells that can be employed in sensing large forces for relatively little cost. The hydraulic load cell employs a very stiff outer structure with an internal cavity filled with a fluid. Application of a load increases the oil pressure, which can be read off an accurate gage.

Other sensing techniques can be utilized to monitor forces, such as piezoelectric transducers for quicker response of varying loads, pneumatic methods, strain gages, etc. The proper sensing technique needs special consideration based on the conditions required for monitoring.

Strain Gage Load Cell

The strain gage load cell consists of a structure that elastically deforms when subjected to a force and a strain gage network that produces an electrical signal proportional to this deformation. Examples of this are beam and ring types of load cells.

Strain Gages

Strain gages use a length of gage wire to produce the desired resistance (which is usually about 120 Ω) in the form of a flat coil. This coil is then cemented (bonded) between two thin insulating sheets of paper or plastic. Such a gage cannot be used directly to measure deflection. It has to be first fixed properly to a member to be strained. After bonding the gage to the member, they are baked at about 195°F (90°C) to remove moisture. Coating the unit with wax or resin will provide some mechanical protection. The resistance between the member under test and the gage itself must be at least 50 MΩ. The total area of all conductors must remain small so that the cement can easily transmit the force necessary to deform the wire. As the member is stressed, the resulting strain deforms the strain gage and the cross-sectional area diminishes. This causes an increase in resistivity of the gage that is easily determined. In order to measure very small strains, it is necessary to measure small changes of the resistance per unit resistance ($\Delta R/R$). The change in the resistance of a bonded strain gage is usually less than 0.5%. A wide variety of gage sizes and grid shapes are available, and typical examples are shown in Figure 23.4.

The use of strain gages to measure force requires careful consideration with respect to rigidity and environment. By virtue of their design, strain gages of shorter length generally possess higher response frequencies (examples: 660 kHz for a gage of 0.2 mm and 20 kHz for a gage of 60 mm in length). The environmental considerations focus mainly on the temperature of the gage. It is well known that resistance is a function of temperature and, thus, strain gages are susceptible to variations in temperature. Thus, if it is known that the temperature of the gage will vary due to any influence, temperature compensation is required in order to ensure that the force measurement is accurate.

A Wheatstone bridge (Figure 23.5) is usually used to measure this small order of magnitude. In Figure 23.5, no current will flow through the galvanometer (G) if the four resistances satisfy a certain

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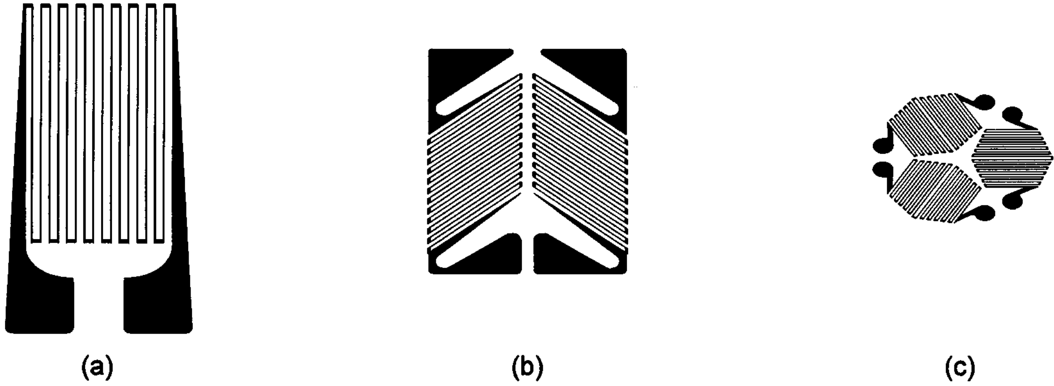

FIGURE 23.4 Configuration of metal-foil resistance strain gages: (*a*) single element; (*b*) two element; and (*c*) three element.

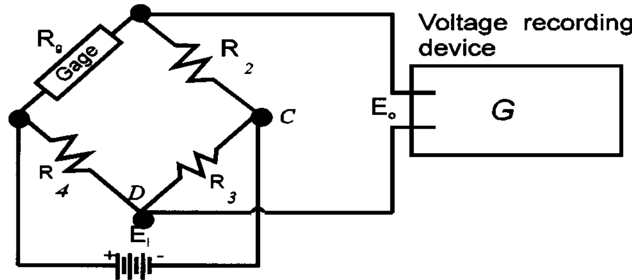

FIGURE 23.5 The Wheatstone bridge.

condition. In order to demonstrate how a Wheatstone bridge operates [3], a voltage scale has been drawn at points C and D of Figure 23.5. Assume that R_1 is a bonded gage and that initially Equation 23.7 is satisfied. If R_1 is now stretched so that its resistance increases by one unit ($+\Delta R$), the voltage at point D will be increased from zero to plus one unit of voltage ($+\Delta V$), and there will be a voltage difference of one unit between C and D that will give rise to a current through C. If R_4 is also a bonded gage, and at the same time that R_1 changes by $+\Delta R$, R_4 changes by $-\Delta R$, the voltage at D will move to $+2\Delta V$. Also, if at the same time, R_2 changes by $-\Delta R$, and R_3 changes by $+\Delta R$, then the voltage of point C will move to $-2\Delta V$, and the voltage difference between C and D will now be $4\Delta V$. It is then apparent that although a single gage can be used, the sensitivity can be increased fourfold if two gages are used in tension while two others are used in compression.

$$\frac{R_1}{R_4} = \frac{R_2}{R_3} \tag{23.7}$$

The grid configuration of the metal-foil resistance strain gages is formed by a photo-etching process. The shortest gage available is 0.20 mm; the longest is 102 mm. Standard gage resistance are 120 Ω and 350 Ω. A strain gage exhibits a resistance change $\Delta R/R$ that is related to the strain in the direction of the grid lines by the expression in Equation 23.8 (where S_g is the gage factor or calibration constant for the gage).

$$\frac{\Delta R}{R} = S_g \varepsilon \tag{23.8}$$

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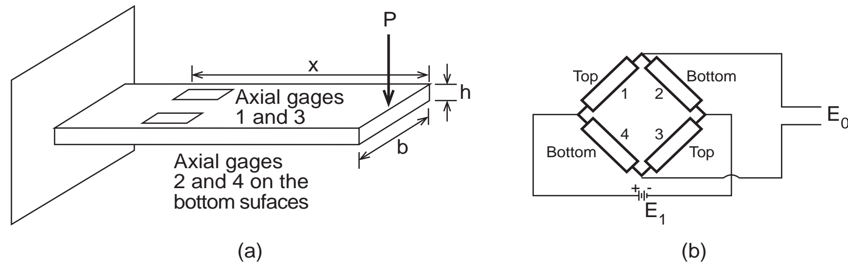

FIGURE 23.6 Beam-type load cells: (*a*) a selection of beam-type load cells (elastic element with strain gages); and (*b*) gage positions in the Wheatstone bridge.

Beam-Type Load Cell

Beam-type load cells are commonly employed for measuring low-level loads [3]. A simple cantilever beam (see Figure 23.6(*a*)) with four strain gages, two on the top surface and two on the bottom surface (all oriented along the axis of the beam) is used as the elastic member (sensor) for the load cell. The gages are wired into a Wheatstone bridge as shown in Figure 23.6(*b*). The load P produces a moment $M = Px$ at the gage location (x) that results in the following strains:

$$\varepsilon_1 = -\varepsilon_2 = \varepsilon_3 = -\varepsilon_4 = \frac{6M}{Ebh^2} = \frac{6Px}{Ebh^2} \tag{23.9}$$

where b is the width of the cross-section of the beam and h is the height of the cross-section of the beam. Thus, the response of the strain gages is obtained from Equation 23.10.

$$\frac{\Delta R_1}{R_1} = -\frac{\Delta R_2}{R_2} = \frac{\Delta R_3}{R_3} = -\frac{\Delta R_4}{R_4} = \frac{6S_g Px}{Ebh^2} \tag{23.10}$$

The output voltage E_o from the Wheatstone bridge, resulting from application of the load P, is obtained from Equation 23.11. If the four strain gages on the beam are assumed to be identical, then Equation 23.11 holds.

$$E_o = \frac{6S_g PxE_1}{Ebh^2} \tag{23.11}$$

The range and sensitivity of a beam-type load cell depends on the shape of the cross-section of the beam, the location of the point of application of the load, and the fatigue strength of the material from which the beam is fabricated.

Ring-Type Load Cell

Ring-type load cells incorporate a proving ring (see Figure 23.7) as the elastic element. The ring element can be designed to cover a very wide range of loads by varying the diameter D, the thickness t, or the depth w of the ring. Either strain gages or a linear variable-differential transformer (LVDT) can be used as the sensor.

The load P is linearly proportional to the output voltage E_o. The sensitivity of the ring-type load cell with an LVDT sensor depends on the geometry of the ring (R, t, and w), the material from which the ring is fabricated (E), and the characteristics of the LVDT (S and E_i). The range of a ring-type load cell is controlled by the strength of the material used in fabricating the ring.

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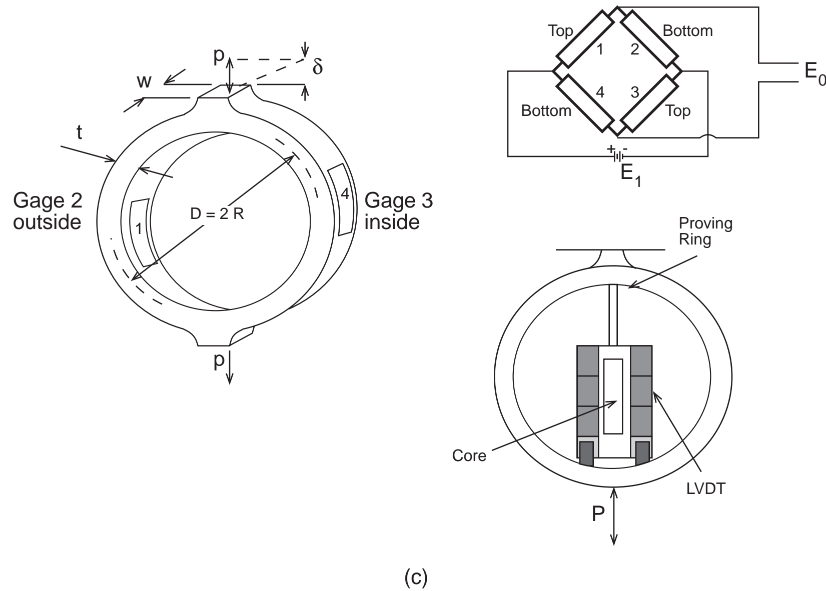

FIGURE 23.7 Ring-type load cells: (*a*) elastic element with strain-gage sensors; (*b*) gage positions in the Wheatstone bridge; and (*c*) elastic element with an LVDT sensor.

Piezoelectric Methods

A piezoelectric material exhibits a phenomenon known as the *piezoelectric effect.* This effect states that when asymmetrical, elastic crystals are deformed by a force, an electrical potential will be developed within the distorted crystal lattice. This effect is reversible. That is, if a potential is applied between the surfaces of the crystal, it will change its physical dimensions [4]. Elements exhibiting piezoelectric qualities are sometimes known as electrorestrictive elements.

The magnitude and polarity of the induced surface charges are proportional to the magnitude and direction of the applied force [4]:

$$Q = dF \tag{23.12}$$

where d is the charge sensitivity (a constant for a given crystal) of the crystal in C/N. The force F causes a thickness variation Δt meters of the crystal:

$$F = \frac{aY}{t}\Delta t \tag{23.13}$$

where a is area of crystal, t is thickness of crystal, and Y is Young's modulus.

$$Y = \frac{stress}{strain} = \frac{Ft}{a\Delta t} \tag{23.14}$$

The charge at the electrodes gives rise to a voltage $E_0 = Q/C$, where C is capacitance in farads between the electrodes and $C = \varepsilon a/t$ where ε is the absolute permittivity.

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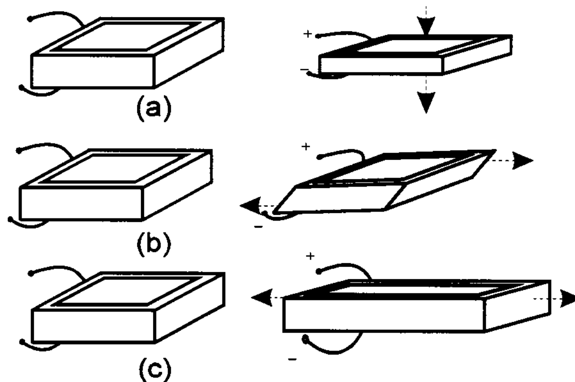

FIGURE 23.8 Modes of operation for a simple plate as a piezoelectric device [4].

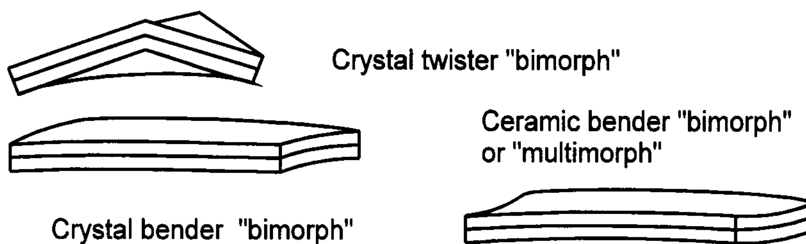

FIGURE 23.9 Curvature of "twister" and "bender" piezoelectric transducers when voltage applied [4].

$$E_o = \frac{dF}{C} = \frac{d}{\varepsilon}\frac{tF}{a} \tag{23.15}$$

The voltage sensitivity = $g = d/\varepsilon$ in volt m/N can be obtained as:

$$E_o = g\frac{t}{a}F = gtP \tag{23.16}$$

The piezoelectric materials used are quartz, tourmaline, Rochelle salt, ammonium dihydrogen phosphate (ADP), lithium sulfate, barium titanate, and lead zirconate titanate (PZT) [4]. Quartz and other earthly piezoelectric crystals are naturally polarized. However, synthetic piezoelectric materials, such as barium titanate ceramic, are made by baking small crystallites under pressure and then placing the resultant material in a strong dc electric field [4]. After that, the crystal is polarized, along the axis on which the force will be applied, to exhibit piezoelectric properties. Artificial piezoelectric elements are free from the limitations imposed by the crystal structure and can be molded into any size and shape. The direction of polarization is designated during their production process.

The different modes of operation of a piezoelectric device for a simple plate are shown in Figure 23.8 [4]. By adhering two crystals together so that their electrical axes are perpendicular, bending moments or torque can be applied to the piezoelectric transducer and a voltage output can be produced (Figure 23.9) [4]. The range of forces that can be measured using piezoelectric transducers are from 1 to 200 kN and at a ratio of 2×10^5.

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Piezoelectric crystals can also be used in measuring an instantaneous change in the force (dynamic forces). A thin plate of quartz can be used as an electronic oscillator. The frequency of these oscillations will be dominated by the natural frequency of the thin plate. Any distortion in the shape of the plate caused by an external force, alters the oscillation frequency. Hence, a dynamic force can be measured by the change in frequency of the oscillator.

Resistive Method

The resistive method employs the fact that when the multiple contact area between semiconducting particles (usually carbon) and the distance between the particles are changed, the total resistance is altered. The design of such transducers yields a very small displacement when a force is applied. A transducer might consist of 2 to 60 thin carbon disks mounted between a fixed and a movable electrode. When a force is applied to the movable electrode and the carbon disks move together by 5 to 250 μm per interface, the transfer function of their resistance against the applied force is approximately hyperbolic, that is, highly nonlinear. The device is also subject to large hysteresis and drift together with a high transverse sensitivity.

In order to reduce hysteresis and drift, rings are used instead of disks. The rings are mounted on an insulated rigid core and prestressed. This almost completely eliminates any transverse sensitivity error. The core's resonant frequency is high and can occur at a frequency as high as 10 kHz. The possible measuring range of such a transducer is from 0.1 kg to 10 kg. The accuracy and linear sensitivity of this transducer is very poor.

Inductive Method

The inductive method utilizes the fact that a change in mechanical stress of a ferromagnetic material causes its permeability to alter. The changes in magnetic flux are converted into induced voltages in the pickup coils as the movement takes place. This phenomenon is known as the *Villari effect* or *magnetostriction*. It is known to be particularly strong in nickel–iron alloys.

Transducers utilizing the Villari effect consist of a coil wound on a core of magnetostrictive material. The force to be measured is applied on this core, stressing it and causing a change in its permeability and inductance. This change can be monitored and used for determining the force.

The applicable range for this type of transducer is a function of the cross-sectional area of the core. The accuracy of the device is determined by a calibration process. This transducer has poor linearity and is subject to hysteresis. The permeability of a magnetostrictive material increases when it is subjected to pure torsion, regardless of direction. A flat frequency response is obtained over a wide range from 150 Hz to 15,000 Hz.

Piezotransistor Method

Devices that utilize *anisotropic stress effects* are described as piezotransistors. In this effect, if the upper surface of a *p–n* diode is subjected to a localized stress, a significant reversible change occurs in the current across the junction. These transistors are usually silicon nonplanar type, with an emitter base junction. This junction is mechanically connected to a diaphragm positioned on the upper surface of a typical TO-type can [4]. When a pressure or a force is applied to the diaphragm, an electronic charge is produced. It is advisable to use these force-measuring devices at a constant temperature by virtue of the fact that semiconducting materials also change their electric properties with temperature variations. The attractive characteristic of piezotransistors is that they can withstand a 500% overload.

Multicomponent Dynamometers Using Quartz Crystals As Sensing Elements

The Piezoelectric Effects in Quartz.

For force measurements, the *direct piezoelectric effect* is utilized. The direct longitudinal effect measures compressive force; the direct shear effect measures shear force in one direction. For example, if a disk of crystalline quartz (SiO_2) cut normally to the crystallographic *x*-axis is loaded by a compression force, it will yield an electric charge, nominally 2.26 pC/N. If a disk of crystalline quartz is cut normally to the

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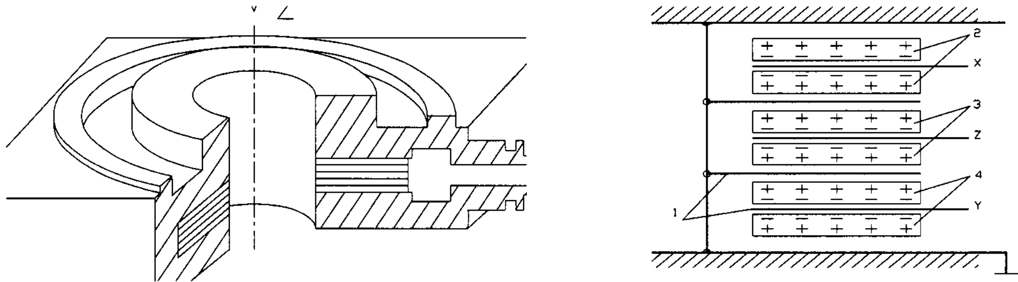

FIGURE 23.10 Three-component force transducer.

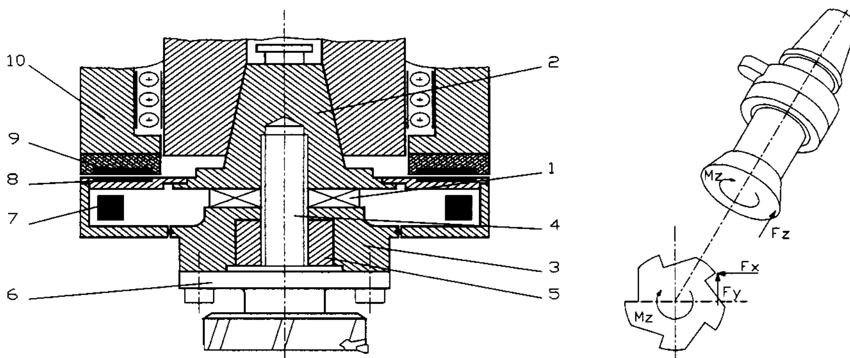

FIGURE 23.11 Force measuring system to determine the tool-related cutting forces in five-axis milling [6].

crystallographic y-axis, it will yield an electric charge (4.52 pC/N) if loaded by a shear force in one specific direction. Forces applied in the other directions will not generate any output [5].

A charge amplifier is used to convert the charge yielded by a quartz crystal element into a proportional voltage. The range of a charge amplifier with respect to its conversion factor is determined by a feedback capacitor. Adjustment to mechanical units is obtained by additional operational amplifiers with variable gain.

The Design of Quartz Multicomponent Dynamometers.
The main element for designing multicomponent dynamometers is the three-component force transducer (Figure 23.10). It contains a pair of X-cut quartz disks for the normal force component and a pair of Y-cut quartz disks (shear-sensitive) for each shear force component.

Three-component dynamometers can be used for measuring cutting forces during machining. Four three-component force transducers sandwiched between a base plate and a top plate are shown in Figure 23.10. The force transducer is subjected to a preload as shear forces are transmitted by friction. The four force transducers experience a drastic change in their load, depending on the type and position of force application. An overhanging introduction of the force develops a tensile force for some transducers, thus reducing the preload. Bending of the dynamometer top plate causes bending and shearing stresses. The measuring ranges of a dynamometer depend not only on the individual forces, but also on the individual bending stresses.

Measuring Signals Transmitted by Telemetry.
Figure 23.11 shows the newly designed force measuring system RCD (rotating cutting force dynamometer). A ring-shaped sensor (1) is fitted in a steep angle taper socket (2) and a base ring (3) allowing sensing of the three force components F_x, F_y and F_z at the cutting edge as well as the moment M_z. The

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Photo not available.

FIGURE 23.12 Capacitive force transducer.

physical operating principle of this measuring cell is based on the piezoelectric effect in quartz plates. The quartz plates incorporated in the sensor are aligned so that the maximum cross-sensitivity between the force components is 1%. As a result of the rigid design of the sensor, the resonant frequencies of the force measuring system range from 1200 Hz to 3000 Hz and the measuring ranges cover a maximum of 10 kN [6].

Force-proportional charges produced at the surfaces of the quartz plates are converted into voltages by four miniature charge amplifiers (7) in hybrid construction. These signals are then filtered by specific electrical circuitry to prevent aliasing effects, and digitized with 8 bit resolution using a high sampling rate (pulse-code modulation). The digitized signals are transmitted by a telemetric unit consisting of a receiver and transmitter module, an antenna at the top of the rotating force measuring system (8), as well as a fixed antenna (9) on the splash cover of the two-axis milling head (10). The electrical components, charge amplifier, and transmitter module are mounted on the circumference of the force measuring system [6].

The cutting forces and the moment measured are digitized with the force measuring system described above. They are modulated on an FM carrier and transmitted by the rotating transmitter to the stationary receiver. The signals transmitted are fed to an external measured-variable conditioning unit.

Measuring Dynamic Forces.
Any mechanical system can be considered in the first approximation as a weakly damped oscillator consisting of a spring and a mass. If a mechanical system has more than one resonant frequency, the lowest one must be taken into consideration. As long as the test frequency remains below 10% of the resonant frequency of the reference transducer (used for calibration), the difference between the dynamic sensitivity obtained from static calibration will be less than 1%. The above considerations assume a sinusoidal force signal. The static calibration of a reference transducer is also valid for dynamic calibration purposes if the test frequency is much lower (at least 10 times lower) than the resonant frequency of the system.

Capacitive Force Transducer

A transducer that uses capacitance variation can be used to measure force. The force is directed onto a membrane whose elastic deflection is detected by a capacitance variation. A highly sensitive force transducer can be constructed because the capacitive transducer senses very small deflections accurately. An electronic circuit converts the capacitance variations into dc-voltage variations [7].

The capacitance sensor illustrated in Figure 23.12 consists of two metal plates separated by an air gap. The capacitance C between terminals is given by the expression:

$$C = \varepsilon_o \varepsilon_r \frac{A}{h} \tag{23.17}$$

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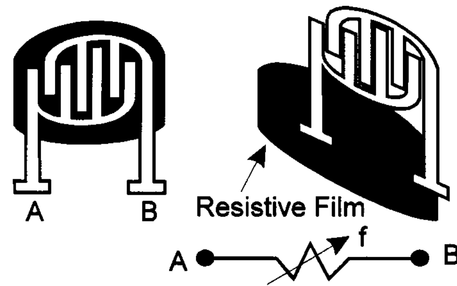

FIGURE 23.13 Diagram of a typical force sensing resistor (FSR).

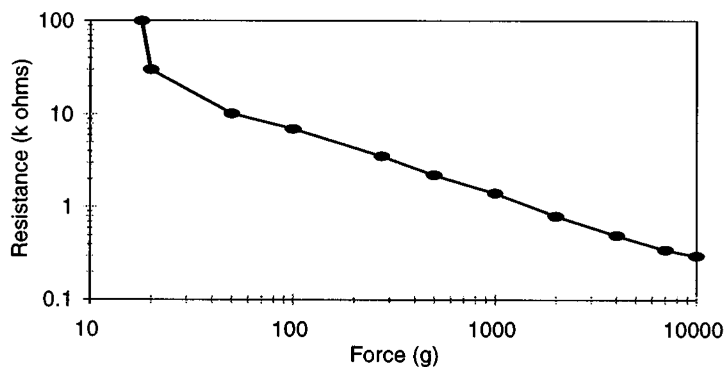

FIGURE 23.14 Resistance as a function of force for a typical force sensing resistor.

where C = Capacitance in farads (F)
ε_0 = Dielectric constant of free space
ε_r = Relative dielectric constant of the insulator
A = Overlapping area for the two plates
h = Thickness of the gap between the two plates

The sensitivity of capacitance-type sensors is inherently low. Theoretically, decreasing the gap h should increase the sensitivity; however, there are practical electrical and mechanical conditions that preclude high sensitivities. One of the main advantages of the capacitive transducer is that moving of one of its plate relative to the other requires an extremely small force to be applied. A second advantage is stability and the sensitivity of the sensor is not influenced by pressure or temperature of the environment.

Force Sensing Resistors (Conductive Polymers)

Force sensing resistors (FSRs) utilize the fact that certain polymer thick-film devices exhibit decreasing resistance with the increase of an applied force. A force sensing resistor is made up of two parts. The first is a resistive material applied to a film. The second is a set of digitating contacts applied to another film. Figure 23.13 shows this configuration. The resistive material completes the electrical circuit between the two sets of conductors on the other film. When a force is applied to this sensor, a better connection is made between the contacts; hence, the conductivity is increased. Over a wide range of forces, it turns out that the conductivity is approximately a linear function of force. Figure 23.14 shows the resistance of the sensor as a function of force. It is important to note that there are three possible regions for the sensor to operate. The first abrupt transition occurs somewhere in the vicinity of 10 g of force. In this

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region, the resistance changes very rapidly. This behavior is useful when one is designing switches using force sensing resistors.

FSRs should not be used for accurate measurements of force because sensor parts may exhibit 15% to 25% variation in resistance between each other. However, FSRs exhibit little hysteresis and are considered far less costly than other sensing devices. Compared to piezofilm, the FSR is far less sensitive to vibration and heat.

Magnetoresistive Force Sensors

The principle of *magnetoresistive force sensors* is based on the fact that metals, when cooled to low temperatures, show a change of resistivity when subjected to an applied magnetic field. Bismuth, in particular, is quite sensitive in this respect. In practice, these devices are severely limited because of their high sensitivity to ambient temperature changes.

Magnetoelastic Force Sensors

Magnetoelastic transducer devices operate based on the Joule effect; that is, a ferromagnetic material is dimensionally altered when subjected to a magnetic field. The principle of operation is as follows: Initially, a current pulse is applied to the conductor within the waveguide. This sets up a magnetic field circumference-wise around the waveguide over its entire length. There is another magnetic field generated by the permanent magnet that exists only where the magnet is located. This field has a longitudinal component. These two fields join vectorally to form a helical field near the magnet which, in turn, causes the waveguide to experience a minute torsional strain or twist only at the location of the magnet. This twist effect is known as the *Wiedemann effect* [8].

Magnetoelastic force transducers have a high frequency response (on the order of 20 kHz). Some of the materials that exhibit magnetoelastic include Monel metal, Permalloy, Cekas, Alfer, and a number of nickel–iron alloys. Disadvantages of these transducers include: (1) the fact that excessive stress and aging may cause permanent changes, (2) zero drift and sensitivity changes due to temperature sensitivity, and (3) hysteresis errors.

Torsional Balances

Balancing devices that utilize the deflection of a spring may also be used to determine forces. *Torsional balances* are equal arm scale force measuring devices. They are comprised of horizontal steel bands instead of pivots and bearings. The principle of operation is based on force application on one of the arms that will deflect the torsional spring (within its design limits) in proportion to the applied force. This type of instrument is susceptible to hysteresis and temperature errors and therefore is not used for precise measurements.

Tactile Sensors

Tactile sensors are usually interpreted as a touch sensing technique. Tactile sensors cannot be considered as simple touch sensors, where very few discrete force measurements are made. In tactile sensing, a force "distribution" is measured using a closely spaced array of force sensors.

Tactile sensing is important in both grasping and object identification operations. Grasping an object must be done in a stable manner so that the object is not allowed to slip or damaged. Object identification includes recognizing the shape, location, and orientation of a product, as well as identifying surface properties and defects. Ideally, these tasks would require two types of sensing [9]:

1. Continuous sensing of contact forces
2. Sensing of the surface deformation profile

These two types of data are generally related through stress–strain relations of the tactile sensor. As a result, almost continuous variable sensing of tactile forces (the sensing of the tactile deflection profile) is achieved.

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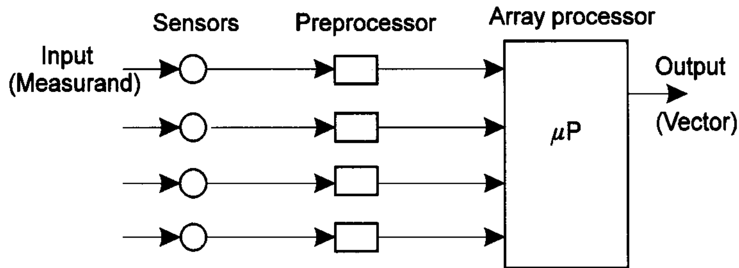

FIGURE 23.15 Tactile array sensor.

Tactile Sensor Requirements.
Significant advances in tactile sensing are taking place in the robotics area. Applications include automated inspection of surface profiles, material handling or parts transfer, parts assembly, and parts identification and gaging in manufacturing applications and fine-manipulation tasks. Some of these applications may need only simple touch (force–torque) sensing if the parts being grasped are properly oriented and if adequate information about the process is already available.

Naturally, the main design objective for tactile sensing devices has been to mimic the capabilities of human fingers [9]. Typical specifications for an industrial tactile sensor include:

1. Spatial resolution of about 2 mm
2. Force resolution (sensitivity) of about 2 g
3. Maximum touch force of about 1 kg
4. Low response time of 5 ms
5. Low hysteresis
6. Durability under extremely difficult working conditions
7. Insensitivity to change in environmental conditions (temperature, dust, humidity, vibration, etc.)
8. Ability to monitor slip

Tactile Array Sensor.
Tactile array sensors (Figure 23.15) consist of a regular pattern of sensing elements to measure the distribution of pressure across the finger tip of a Robot. The 8×8 array of elements at 2 mm spacing in each direction, provides 64 force sensitive elements. Table 23.1 outlines some of the characteristics of early tactile array sensors. The sensor is composed of two crossed layers of copper strips separated by strips of thin silicone rubber. The sensor forms a thin, compliant layer that can be easily attached to a variety of finger-tip shapes and sizes. The entire array is sampled by computer.

A typical tactile sensor array can consist of several sensing elements. Each element or taxel (Figure 23.16) is used to sense the forces present. Since tactile sensors are implemented in applications where sensitivity providing semblance to human touch is desired, an elastomer is utilized to mimic the human skin. The elastomer is generally a conductive material whose electrical conductivity changes locally when pressure is applied. The sensor itself consists of three layers: a protective covering, a sheet of conductive elastomer, and a printed circuit board. The printed circuit board consists of two rows of two "bullseyes," each with conductive inner and outer rings that compromise the taxels of the sensor. The outer rings are connected together and to a column-select transistor. The inner rings are connected to diodes (D) in Figure 23.16. Once the column in the array is selected, the current flows through the diodes, through the elastomer, and thence through a transistor to ground. As such, it is generally not possible to excite just one taxel because the pressure applied causes a local deformation in neighboring taxels. This situation is called *crosstalk* and is eliminated by the diodes [10].

Tactile array sensor signals are used to provide information about the contact kinematics. Several feature parameters, such as contact location, object shape, and the pressure distribution, can be obtained.

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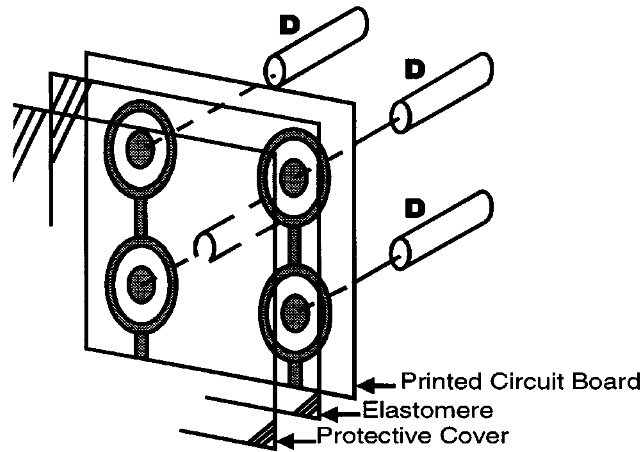

FIGURE 23.16 Typical taxel sensor array.

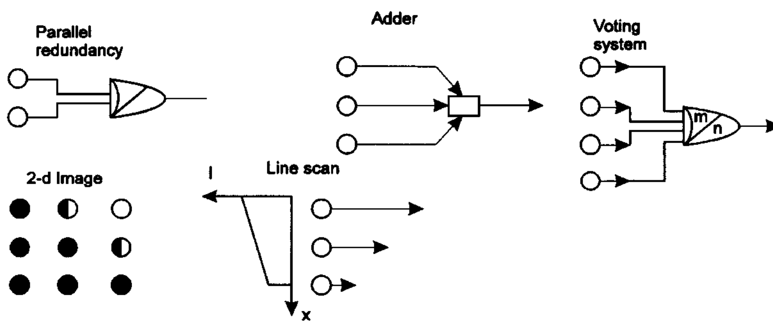

FIGURE 23.17 General arrangement of an intelligent sensor array system [9].

TABLE 23.1 Summary of Some of the Characteristics of Early Tactile Arrays Sensors

	Size of array		
Device parameter	(4 × 4)	(8 × 8)	(16 × 16)
Cell spacing (mm)	4.00	2.00	1.00
Zero-pressure capacitance (fF)	6.48	1.62	0.40
Rupture force (N)	18.90	1.88	0.19
Max. linear capacitance (fF)	4.80	1.20	0.30
Max. output voltage (V)	1.20	0.60	0.30
Max. resolution (bit)	9.00	8.00	8.00
Readout (access) time (μs)	—	<20	—

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The general layout of a sensor array system can be seen in Figure 23.17. An example of this is a contact and force sensing finger. This tactile finger has four contact sensors made of piezoelectric polymer strips on the surface of the fingertip that provide dynamic contact information. A strain gage force sensor provides static grasp force information.

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Further Information

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