CHAPTER 19

Translational Motion, Vibration, and Shock Measurement

Chapter Outline

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19.1 Introduction

Movement is an integral part of many systems and therefore sensors to measure motion are an important tool for engineers. Motion occurs in many forms. Simple movement causes a *displacement* in the body affected by it, though this can take two alternative forms according to whether it is motion in a straight line (*translational displacement*) or angular motion about an axis (*rotational displacement*). Displacement only describes the fact that a body has moved but does not define the speed at which the motion occurs. Speed is defined by the term *velocity*. As for displacement, velocity occurs in two forms, *translational velocity* describes the speed at which a body changes position when moving in a straight line and *rotational velocity* (sometimes called *angular velocity*) describes the speed at which a body turns about the axis of rotation. Finally, it is clear that changes in velocity occur during the motion of a body. To start with, the body is at rest and the velocity is zero. At the start of motion, there is a change in velocity from zero to some nonzero value. The term *acceleration* is used to describe the rate at which the velocity changes. As for displacement and velocity, acceleration also comes in two forms, *translational acceleration* describes the rate of change of translational velocity and *rotational acceleration* (sometimes called *angular acceleration*) describes the rate of change of rotational velocity.

With motion occurring in so many different forms, a review of the various sensors used to measure these different forms of motion would not conveniently fit within a single chapter. Therefore, this chapter only reviews sensors that are used for measuring translational motion, with those used for measuring rotational motion being deferred to the next chapter. The following sections therefore look in turn at the measurement of translational displacement, velocity, and acceleration.

The subjects of vibration and shock are also included in final sections of this chapter. Both of these are related to translational acceleration and therefore properly belong within this chapter on translational displacement. Vibrations consist of linear harmonic motion, and measurement of the accelerations involved in this motion is important in many industrial and other environments. Shock is also related to acceleration and characterizes the motion involved when a moving body is suddenly brought to rest, often when a falling body hits the floor. This normally involves large-magnitude deceleration (negative acceleration).

19.2 Displacement

Translational displacement transducers are instruments that measure the motion of a body in a straight line between two points. Apart from their use as a primary transducer measuring the motion of a body, translational displacement transducers are also widely used as a secondary component in measurement systems, where some other physical quantity such as pressure, force, acceleration, or temperature is translated into a translational motion by the primary measurement transducer. Many different types of translational displacement transducer exist and these, along with their relative merits and characteristics, are discussed in the following sections of this chapter. The factors governing the choice of a suitable type of instrument in any particular measurement situation are considered in the final section at the end of the chapter.

19.2.1 Resistive Potentiometer

The resistive potentiometer is perhaps the best-known displacement-measuring device. It consists of a resistance element with a movable contact as shown in Figure 19.1. A voltage V_s is applied across the two ends A and B of the resistance element and an output voltage V_0 is measured between the point of contact C of the sliding element and the end of the resistance element A. A linear relationship exists between the output voltage V_0 and the distance AC, which can be expressed by:

$$\frac{V_0}{V_s} = \frac{\mathrm{AC}}{\mathrm{AB}} \quad (19.1)$$

The body whose motion is being measured is connected to the sliding element of the potentiometer, so that translational motion of the body causes a motion of equal magnitude of the slider along the resistance element and a corresponding change in the output voltage V_0.

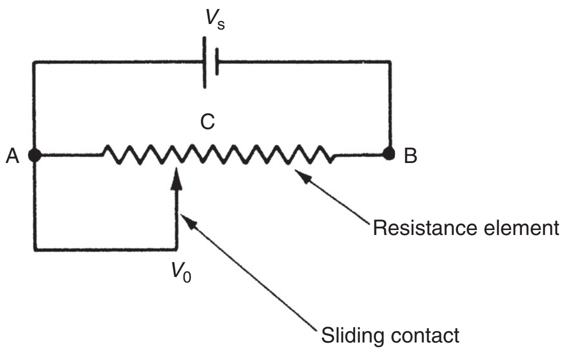

Figure 19.1
The resistive potentiometer.

Three different types of potentiometer exist, wire wound, carbon film, and plastic film, so named according to the material used to construct the resistance element. Wire-wound potentiometers consist of a coil of resistance wire wound on a nonconducting former. As the slider moves along the potentiometer track, it makes contact with successive turns of the wire coil. This limits the resolution of the instrument to the distance from one coil to the next. Much better measurement resolution is obtained from potentiometers using either a carbon film or a conducting plastic film for the resistance element. Theoretically, the resolution of these is limited only by the grain size of the particles in the film, suggesting that measurement resolutions up to 10^{-4} ought to be attainable. In practice, the resolution is limited by mechanical difficulties in constructing the spring system that maintains the slider in contact with the resistance track, although these types are still considerably better than wire-wound types.

Operational problems of potentiometers all occur at the point of contact between the sliding element and the resistance track. The most common problem is dirt under the slider, which increases the resistance and thereby gives a false output voltage reading, or in the worst case causes a total loss of output. High-speed motion of the slider can also cause the contact to bounce, giving an intermittent output. Friction between the slider and the track can also be a problem in some measurement systems where the body whose motion is being measured is moved by only a small force of a similar magnitude to these friction forces.

The life expectancy of potentiometers is normally quoted as a number of reversals, that is, as the number of times the slider can be moved backward and forward along the track. The values quoted for wire-wound, carbon-film, and plastic-film types are, respectively, 1, 5, and 30 million. In terms of both life expectancy and measurement resolution, therefore, the carbon- and plastic-film types are clearly superior, although wire-wound types do have one advantage in respect of their lower temperature coefficient. This means that wire-wound types exhibit much less variation in their characteristics in the presence of varying ambient temperature conditions.

A typical inaccuracy value that is quoted for translational motion resistive potentiometers is $\pm 1\%$ of full-scale reading. Manufacturers produce potentiometers to cover a large span of measurement ranges. At the bottom end of this span, instruments with a range of ± 2 mm are available while at the top end, instruments with a range of ± 1 m are produced.

The resistance of the instrument measuring the output voltage at the potentiometer slider can affect the value of the output reading, as discussed in Chapter 3. As the slider moves along the potentiometer track, the ratio of the measured resistance to that of the measuring instrument varies, and thus the linear relationship between the measured displacement and the voltage output is distorted as well. This effect is minimized when the potentiometer resistance is small relative to that of the measuring instrument. This is achieved first by using a very high-impedance measuring instrument and second by keeping the potentiometer resistance as small as possible. Unfortunately, the latter is incompatible with achieving high measurement sensitivity since this requires a high potentiometer resistance. A compromise between these two factors is therefore necessary. The alternative strategy of obtaining high measurement sensitivity by keeping the potentiometer resistance low and increasing the excitation voltage is not possible in practice because of the power-rating limitation. This restricts the allowable power loss in the potentiometer to its heat dissipation capacity.

The process of choosing the best potentiometer from a range of instruments that are available, taking into account power rating and measurement linearity considerations, is illustrated in the example below.

Example 19.1

The output voltage from a translational motion potentiometer of stroke length 0.1 m is to be measured by an instrument whose resistance is 10 kΩ. The maximum measurement error, which occurs when the slider is positioned two-thirds of the way along the element (i.e., when AC = 2AB/3 in Figure 19.1), must not exceed 1% of the full-scale reading. The highest possible measurement sensitivity is also required. A family of potentiometers having a power rating of 1 W per 0.01 m and resistances ranging from 100 Ω to 10 kΩ in 100 Ω steps are available. Choose the most suitable potentiometer from this range and calculate the sensitivity of measurement that it gives.

Solution

Referring to the labeling used in Figure 19.1, let the resistance of portion AC of the resistance element R_i and that of the whole length AB of the element be R_t. Also, let the resistance of the measuring instrument be R_m and the output voltage measured by it be V_m. When the voltage-measuring instrument is connected to the potentiometer, the net resistance across AC is the sum of two resistances in parallel (R_i and R_m) given by: $R_{AC} = \frac{R_i R_m}{R_i + R_m}$

Let the excitation voltage applied across the ends AB of the potentiometer be V and the resultant current flowing between A and B be I. Then I and V are related by:

$$I = \frac{V}{R_{AC} + R_{CB}} = \frac{V}{[R_i R_m / R_i + R_m] + R_t - R_i}$$

V_m can now be calculated as: $V_m = IR_{AC} = \dfrac{V R_i R_m}{\{[R_i R_m/(R_i + R_m)] + R_t - R_i\}\{R_i + R_m\}}$

If we express the voltage that exists across AC in the absence of the measuring instrument as V_0, then we can express the error due to the loading effect of the measuring instrument as: error $= V_0 - V_m$

From Eqn (19.1), $V_0 = (R_i V)/R_t$. Thus,

$$\text{Error} = V_0 - V_m$$
$$= V\left(\frac{R_i}{R_t}\right)\left(\frac{R_i R_m}{\{[R_i R_m/R_i + R_m] + R_t - R_i\}\{R_i + R_m\}}\right)\left(\frac{R_i^2(R_i - R_t)}{R_t\left[R_i R_t + R_m R_t - R_i^2\right]}\right) \tag{19.2}$$

Substituting $R_i = 2R_t/3$ into Eqn (19.2) to find the maximum error:

$$\text{Maximum error} = \frac{2R_t}{2R_t + 9R_m}$$

For a maximum error of 1%,

$$\frac{2R_t}{2R_t + 9R_m} = 0.01 \tag{19.3}$$

Substituting $R_m = 10{,}000\ \Omega$ into the above expression (19.3) gives $R_t = 454\ \Omega$. The nearest resistance values in the range of potentiometers available are 400 and 500 Ω. The value of 400 Ω has to be selected, as this is the only one that gives a maximum measurement error of less than 1%.

The thermal rating of the potentiometers is quoted as 1 W/0.01 m, i.e., 10 W for the total length of 0.1 m. By Ohm's law, maximum supply
Voltage $= \sqrt{\text{power} \times \text{resistance}} = \sqrt{10 \times 400} = 63.25$ V

Thus, the measurement sensitivity = 63.25/0.1 V/m = 632.5 V/m.

■

19.2.2 Linear Variable Differential Transformer

The linear variable differential transformer (LVDT) consists of a transformer with a single primary winding and two secondary windings connected in the series opposing manner shown in Figure 19.2. The object whose translational displacement is to be measured is physically attached to the central iron core of the transformer, so that all motions of the body are transferred to the core.

For an excitation voltage V_s given by $V_s = V_p \sin(\omega t)$, the emfs induced in the secondary windings V_a and V_b are given by:

$$V_a = K_a \sin(\omega t - \phi); \quad V_b = K_b \sin(\omega t - \phi).$$

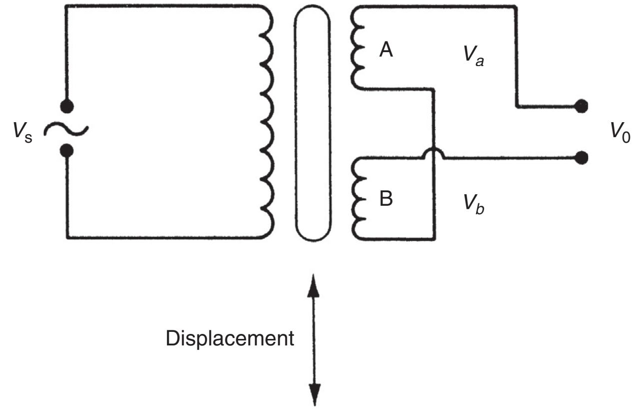

Figure 19.2
Linear variable differential transformer.

The parameters K_a and K_b depend on the amount of coupling between the respective secondary and primary windings and hence on the position of the iron core. With the core in the central position, $K_a = K_b$, and we have $V_a = V_b = K\sin(\omega t - \phi)$.

Because of the series opposition mode of connection of the secondary windings, $V_0 = V_a - V_b$, and hence with the core in the central position, $V_0 = 0$. Suppose now that the core is displaced upward (i.e., toward winding A) by a distance x. If then $K_a = K_1$ and $K_b = K_2$, we have $V_0 = (K_1 - K_2)\sin(\omega t - \phi)$.

If, alternatively, the core was displaced downward from the null position (i.e., toward winding B) by a distance x, the values of K_a and K_b would then be $K_a = K_2$ and $K_b = K_1$, and we would have:

$$V_0 = (K_2 - K_1)\sin(\omega t - \phi) = (K_1 - K_2)\sin(\omega t + [\pi - \phi]).$$

Thus, for equal magnitude displacements $+x$ and $-x$ of the core away from the central (null) position, the magnitude of the output voltage V_0 is the same in both cases. The only information about the direction of movement of the core is contained in the phase of the output voltage, which differs between the two cases by 180°. Therefore, if measurements of core position on both sides of the null position are required, it is necessary to measure the phase as well as the magnitude of the output voltage. The relationship between the magnitude of the output voltage and the core position is approximately linear over a reasonable range of movement of the core on either side of the null position, and is expressed using a constant of proportionality C as $V_0 = Cx$.

The only moving part in an LVDT is the central iron core. As the core is only moving in the air gap between the windings, there is no friction or wear during operation. For this reason, the instrument is a very popular one for measuring linear displacements and has a quoted life expectancy of 200 years. The typical inaccuracy is ±0.5% of full-scale reading and measurement resolution is almost infinite. Instruments are available to measure a wide span of measurements from ±100 μm to ±100 mm. The instrument can be made suitable for operation in corrosive environments by enclosing the windings within a nonmetallic barrier, which leaves the magnetic flux paths between the core and windings undisturbed. An epoxy resin is commonly used to encapsulate the coils for this purpose. One further operational advantage of the instrument is its insensitivity to mechanical shock and vibration.

Some problems that affect the accuracy of the LVDT are the presence of harmonics in the excitation voltage and stray capacitances, both of which cause a nonzero output of low magnitude when the core is in the null position. It is also impossible in practice to produce two identical secondary windings, and the small asymmetry that invariably exists between the secondary windings adds to this nonzero null output. The magnitude of this is always less than 1% of the full-scale output and in many measurement situations is of little consequence. Where necessary, the magnitude of these effects can be measured by applying known displacements to the instrument. Following this, appropriate compensation can be applied to subsequent measurements.

19.2.3 Variable Capacitance Transducers

Like variable inductance, the principle of variable capacitance is used in displacement-measuring transducers in various ways. The three most common forms of variable capacitance transducer are shown in Figure 19.3. In Figure 19.3(a), the capacitor plates are formed by two concentric, hollow, metal cylinders. The displacement to be measured is applied to the inner cylinder, which alters the capacitance. The second form, Figure 19.3(b), consists of two flat, parallel, metal plates, one of which is fixed and one of which is movable. Displacements to be measured are applied to the movable plate, and the capacitance changes as this moves. Both of these first two forms use air as the dielectric medium between the plates. The final form, Figure 19.3(c), has two flat, parallel, metal plates with a sheet of solid dielectric material between them. The displacement to be measured causes a capacitance change by moving the dielectric sheet.

Inaccuracies as low as ±0.01% are possible with these instruments, with measurement resolutions of 1 μm. Individual devices can be selected from manufacturers' ranges that measure displacements as small as 10^{-11} m or as large as 1 m. The fact that such instruments consist only of two simple conducting plates means that it is possible to fabricate devices that are tolerant to a wide range of environmental hazards such as extreme temperatures, radiation, and corrosive atmospheres. As there are no contacting moving parts, there is no friction or wear in operation and the life expectancy quoted is 200 years. The major problem with variable capacitance transducers is their high impedance. This makes them very susceptible to noise and means that the length and

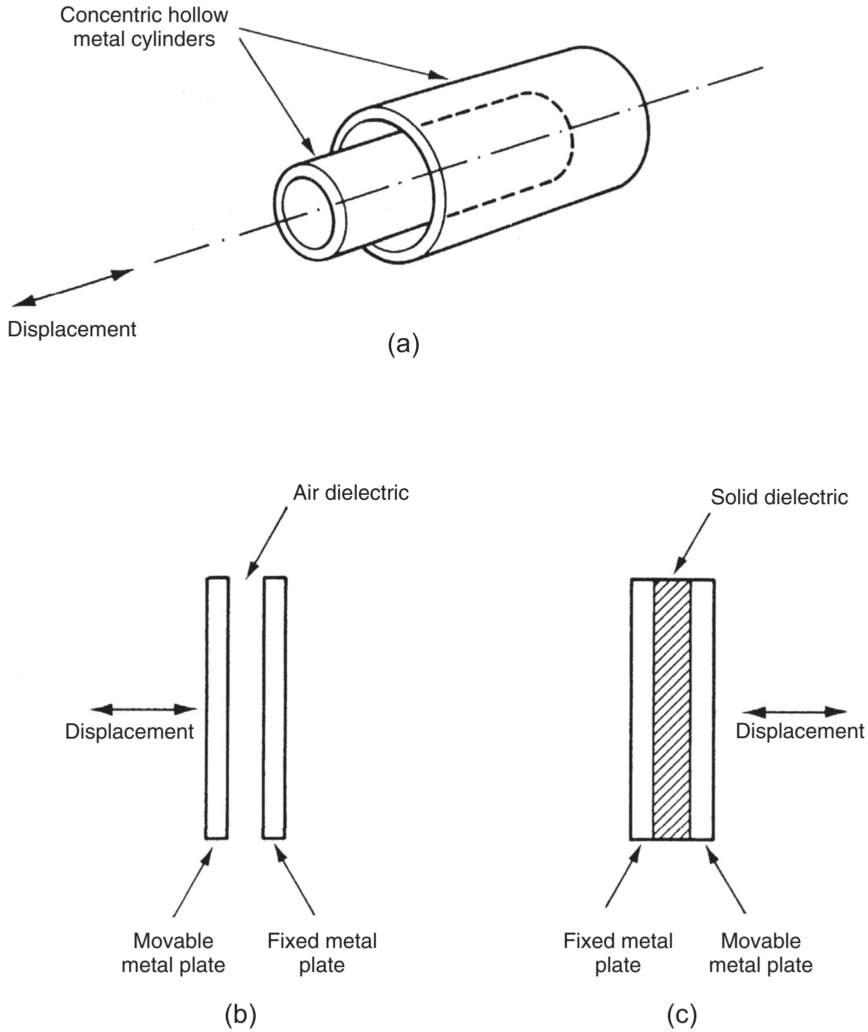

Figure 19.3
Variable capacitance transducer. (a) Concentric cylinder type; (b) flat plate type with air dielectric; (c) flat plate type with solid dielectric.

position of connecting cables need to be chosen very carefully. In addition, very high-impedance instruments need to be used to measure the value of the capacitance. Because of these difficulties, use of these devices tends to be limited to those few applications where the high accuracy and measurement resolution of the instrument are required.

19.2.4 Variable Inductance Transducers

One simple type of variable inductance transducer was shown earlier in Figure 13.1. This has a typical measurement range of 0–10 mm. An alternative form of variable inductance

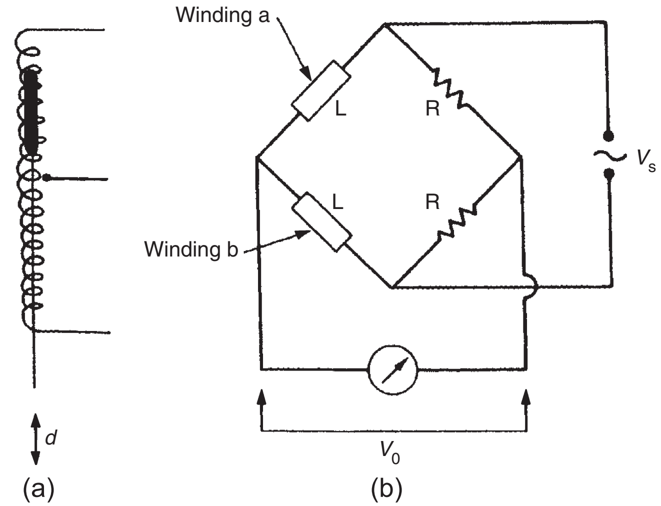

Figure 19.4
(a) Variable inductance transducers; (b) connection in bridge circuit.

transducer shown in Figure 19.4(a) has a very similar size and physical appearance to the LVDT, but has a center-tapped single winding. The two halves of the winding are connected, as shown in Figure 19.4(b), to form two arms of a bridge circuit that is excited with an alternating voltage. With the core in the central position, the output from the bridge is zero. Displacements of the core either side of the null position cause a net output voltage that is approximately proportional to the displacement for small movements of the core. Instruments in this second form are available to cover a wide span of displacement measurements. At the lower end of this span, instruments with a range of 0–2 mm are available, while at the top end, instruments with a range of 0–5 m can be obtained.

19.2.5 Strain Gauges

The principles of strain gauges were covered earlier in Chapter 13. Because of their very small range of measurement (typically 0–50 μm), strain gauges are normally only used to measure displacements within devices like diaphragm-based pressure sensors rather than as a primary sensor in their own right for direct displacement measurement. However, strain gauges can be used to measure larger displacements if the range of displacement measurement is extended by the scheme illustrated in Figure 19.5. In this, the displacement to be measured is applied to a wedge fixed between two beams carrying strain gauges. As the wedge is displaced downward, the beams are forced apart and strained, causing an output reading on the strain gauges. Using this method, displacements up to about 50 mm can be measured.

19.2.6 Piezoelectric Transducers

The piezoelectric transducer is effectively a force-measuring device that is used within many instruments that are designed to measure either force itself or the force-related

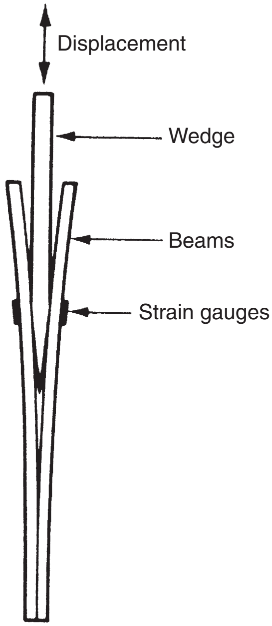

Figure 19.5
Strain gauges measuring large displacements.

quantities of pressure and acceleration. It is included within this discussion of linear displacement transducers because its mode of operation is to generate an emf that is proportional to the distance by which it is compressed. The device is manufactured from a crystal, which can be either a natural material such as quartz or a synthetic material such as lithium sulfate. The crystal is mechanically stiff (i.e., a large force is required to compress it), and consequently piezoelectric transducers can only be used to measure the displacement of mechanical systems that are stiff enough themselves to be unaffected by the stiffness of the crystal. When the crystal is compressed, a charge is generated on the surface that is measured as the output voltage. Unfortunately, as is normal with any induced charge, the charge leaks away over a period of time. Consequently, the output voltage–time characteristic is as shown in Figure 19.6. Because of this characteristic, piezoelectric transducers are not suitable for measuring static or slowly varying displacements, even though the time constant of the charge-decay process can be lengthened by adding a shunt capacitor across the device.

As a displacement-measuring device, the piezoelectric transducer has a very high sensitivity, about 1000 times better than the strain gauge. Its typical inaccuracy is ±1% of full-scale reading and its life expectancy is three million reversals.

19.2.7 Nozzle Flapper

The nozzle flapper is a displacement transducer that translates displacements into a pressure change. A secondary pressure-measuring device is therefore required within the

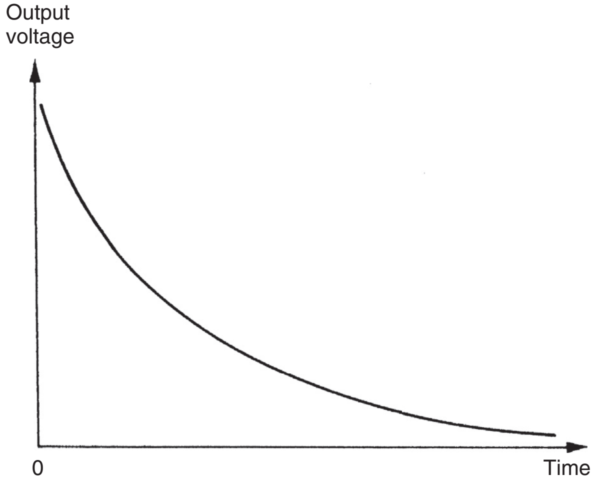

Figure 19.6
Voltage—time characteristic of piezoelectric transducer following step displacement.

instrument. The general form of a nozzle flapper is shown schematically in Figure 19.7. Fluid at a known supply pressure, P_s, flows through a fixed restriction and then through a variable restriction formed by the gap, x, between the end of the main vessel and the flapper plate. The body whose displacement is being measured is connected physically to the flapper plate. The output measurement of the instrument is the pressure P_0 in the chamber shown in Figure 19.7, and this is almost proportional to x over a limited range of movement of the flapper plate. The instrument typically has a first-order response characteristic. Air is very commonly used as the working fluid and this gives the instrument a time constant of about 0.1 s. The instrument has extremely high sensitivity but its range of measurement is quite small. A typical measurement range is ±0.05 mm with a measurement resolution of ±0.01 μm. One very common application of nozzle flappers is measuring the displacements within a load cell, which are typically very small.

19.2.8 Other Methods of Measuring Small/Medium-Sized Displacements

Apart from the methods outlined above, several other techniques for measuring small translational displacements exist, as discussed below. Some of these involve special instruments that have a very limited sphere of application, for instance, in measuring machine tool displacements.

Linear inductosyn

The linear inductosyn is an extremely accurate instrument that is widely used for axis measurement and control within machine tools. Typical measurement resolution is 2.5 μm.

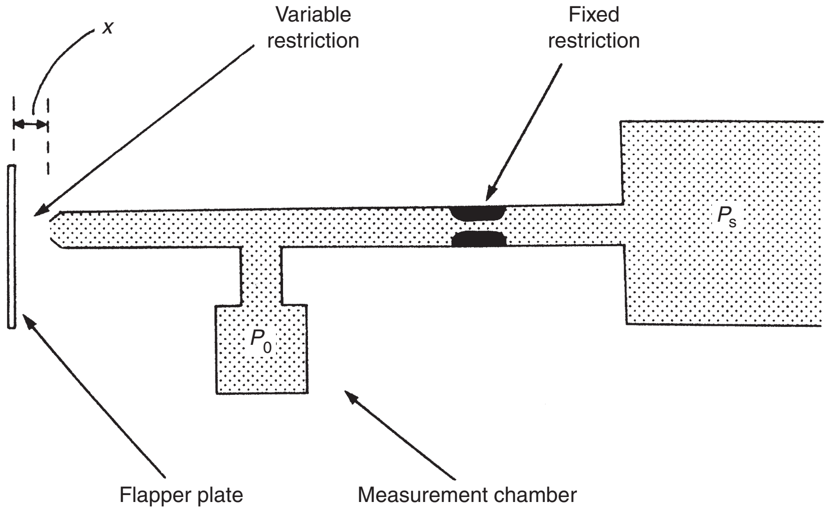

Figure 19.7
Nozzle flapper.

The instrument consists of two magnetically coupled parts that are separated by an air gap, typically 0.125 mm wide, as shown in Figure 19.8. One part, the track, is attached to the axis along which displacements are to be measured. This would generally be the bed of a machine tool. The other part, the slider, is attached to the body that is to be measured or positioned. This would usually be a cutting tool.

The track, which may be several meters long, consists of a fine metal wire formed into the pattern of a continuous rectangular waveform and deposited onto a glass base. The typical pitch (cycle length), s, of the pattern is 2 mm, and this extends over the full length of the track. The slider is usually about 50 mm wide and carries two separate wires formed into continuous rectangular waveforms that are displaced with respect to each other by one-quarter of the cycle pitch, that is, by 90 electrical degrees. The wire waveform on the track is excited by an applied voltage given by $V_s = V\sin(\omega t)$.

This excitation causes induced voltages in the slider windings. When the slider is positioned in the null position such that its first winding is aligned with the winding on the track, the output voltages on the two slider windings are given by $V_1 = 0$; $V_2 = V\sin(\omega t)$.

For any other position, the slider-winding voltages are given by:

$$V_1 = V\ \sin(\omega t)\sin(2\pi x/s); \quad V_2 = V\ \sin(\omega t)\cos(2\pi x/s)$$

where x is the displacement of the slider away from the null position.

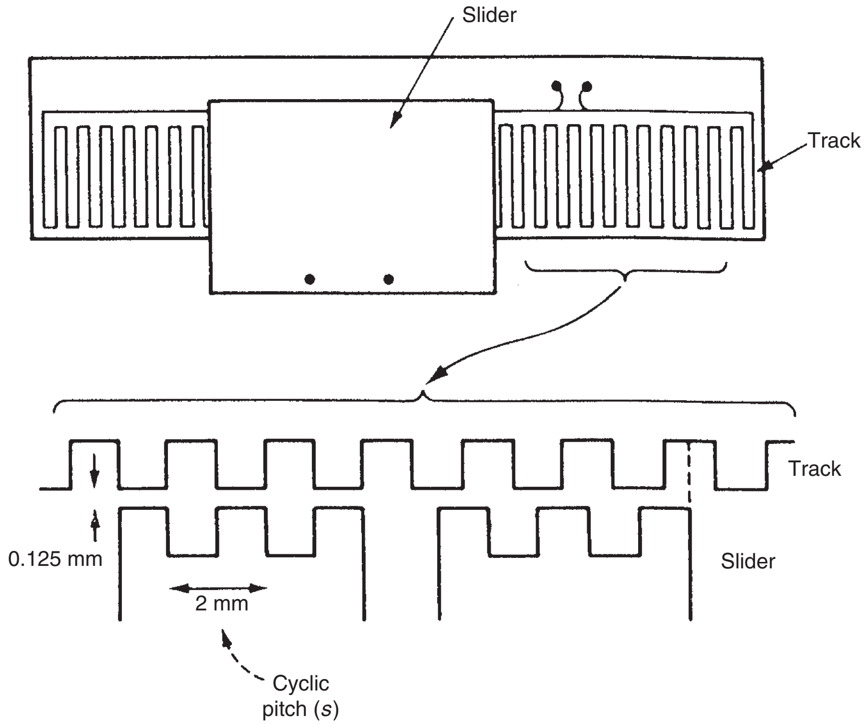

Figure 19.8
Linear inductosyn

Consideration of these equations for the slider-winding outputs shows that the pattern of output voltages repeats every cycle pitch. Therefore, the instrument can only discriminate displacements of the slider within one cycle pitch of the windings. This means that the typical measurement range of an inductosyn is only 2 mm. This is of no use in normal applications, and therefore an additional displacement transducer with coarser resolution but larger measurement range has to be used as well. This coarser measurement is commonly made by translating the linear displacements by suitable gearing into rotary motion, which is then measured by a rotational displacement transducer.

One slight problem with the inductosyn is the relatively low level of electromagnetic coupling between the track and slider windings. Compensation for this is made by using a high-frequency excitation voltage (5–10 kHz is common).

Translation of linear displacements into rotary motion

In some applications, it is inconvenient to measure linear displacements directly, either because there is insufficient space to mount a suitable transducer or because it is inconvenient for other reasons. A suitable solution in such cases is to translate the translational motion into rotational motion by suitable gearing. Any of the rotational displacement transducers discussed in the next chapter can then be applied.

Integration of output from velocity transducers and accelerometers

If velocity transducers or accelerometers already exist in a system, displacement measurements can be obtained by integration of the output from these instruments. However, this only gives information about the relative position with respect to some arbitrary starting point. It does not yield a measurement of the absolute position of a body in space unless all motions away from a fixed starting point are recorded.

Laser interferometer

The standard interferometer has been used for over 100 years for accurate measurement of displacements. The laser interferometer is a relatively recent development that uses a laser light source instead of the conventional light source used in a standard interferometer. The laser source extends the measurement range of the instrument by a significant amount while maintaining the same measurement resolution found in a standard interferometer. In the particular form of laser interferometer shown in Figure 19.9, a dual-frequency helium–neon (He–Ne) laser is used that gives an output pair of light waves at a nominal frequency of 5×10^{14} Hz. The two waves differ in frequency by 2×10^{6} Hz and have opposite polarization. This dual-frequency output waveform is split into a measurement beam and a reference beam by the first beam splitter.

The reference beam is sensed by the polarizer and photodetector, A, which converts both waves in the light to the same polarization. The two waves interfere constructively and

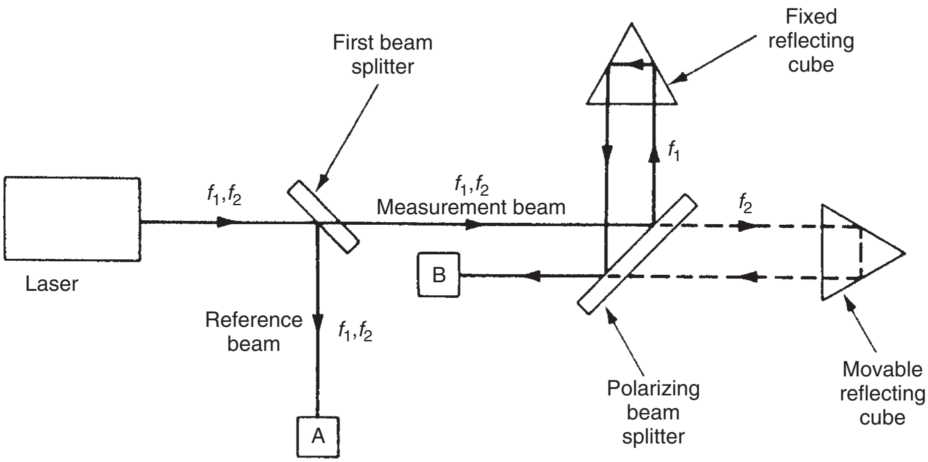

Figure 19.9
Laser interferometer.

destructively alternately, producing light–dark flicker at a frequency of 2×10^6 Hz. This excites a 2 MHz electrical signal in the photodetector.

The measurement beam is separated into two component frequencies by a polarizing beam splitter. Light of the first frequency, f_1, is reflected by a fixed reflecting cube into a photodetector and polarizer, B. Light of the second frequency, f_2, is reflected by a movable reflecting cube and also enters B. The displacement to be measured is applied to the movable cube. With the movable cube in the null position, the light waves entering B produce an electrical signal output at a frequency of 2 MHz, which is the same frequency as the reference signal output from A. Any displacement of the movable cube causes a Doppler shift in the frequency f_2 and changes the output from B. The frequency of the output signal from B varies between 0.5 and 3.5 MHz according to the speed and direction of movement of the movable cube. The outputs from A and B are amplified and subtracted. The resultant signal is fed to a counter whose output indicates the magnitude of the displacement in the movable cube and whose rate of change indicates the velocity of motion.

This technique is used in applications requiring high-accuracy measurement, such as machine tool control. Such systems can measure displacements over ranges of up to 2 m with an inaccuracy of only a few parts per million. They are therefore an attractive alternative to the inductosyn, in having both high-measurement resolution and a large measurement range within one instrument.

Fotonic sensor

The fotonic sensor is one of many recently developed instruments that make use of fiber-optic techniques. It consists of a light source, a light detector, a fiber-optic light transmission system, and a plate that moves with the body whose displacement is being measured, as shown on Figure 19.10. Light from the outward fiber-optic cable travels across

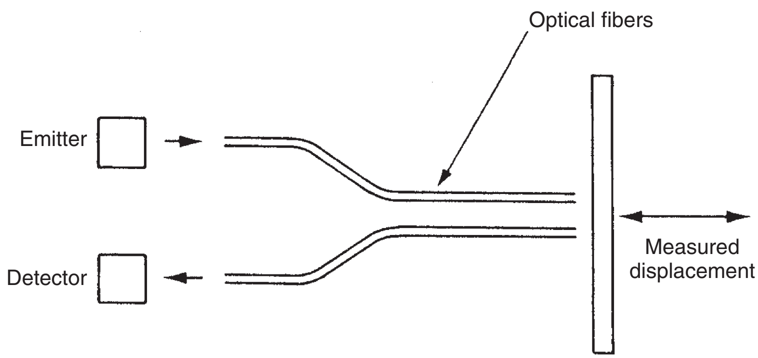

Figure 19.10
Fotonic sensor.

the air gap to the plate and some of it is reflected back into the return fiber-optic cable. The amount of light reflected back from the plate is a function of the air gap length, x, and hence of the plate displacement. Measurement of the intensity of the light carried back along the return cable to the light detector allows the displacement of the plate to be calculated. Common applications of fotonic sensors are measuring diaphragm displacements in pressure sensors and measuring the movement of bimetallic temperature sensors.

Noncontacting optical sensor

Figure 19.11 shows an optical technique that is used to measure small displacements. The motion to be measured is applied to a vane, whose displacement progressively shades one of a pair of monolithic photodiodes that are exposed to infrared radiation. A displacement measurement is obtained by comparing the output of the reference (unshaded) photodiode with that of the shaded one. The typical range of measurement is ±0.5 mm with an inaccuracy of ±0.1% of full scale. Such sensors are used in some intelligent pressure-measuring instruments based on Bourdon tubes or diaphragms as described in Chapter 15.

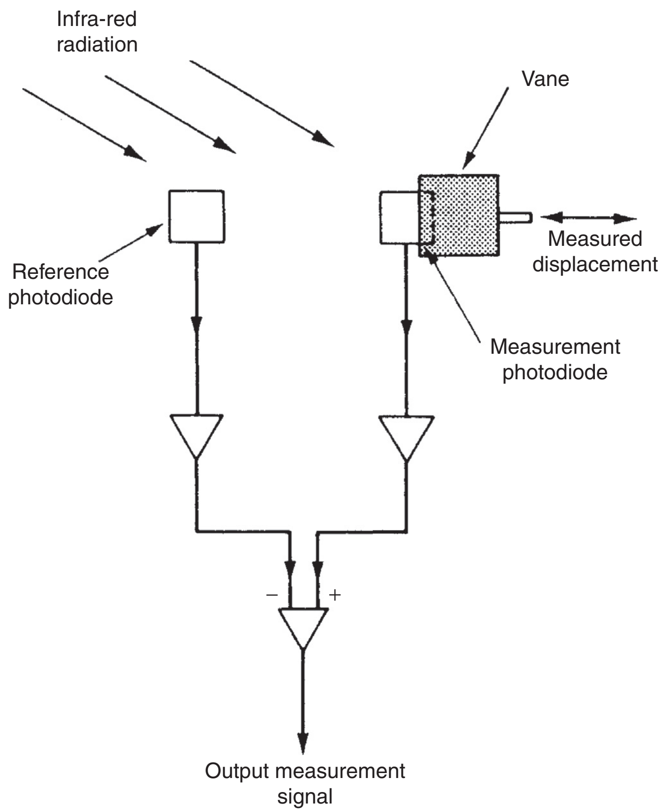

Figure 19.11
Noncontacting optical sensor.

19.2.9 Measurement of Large Displacements (Range Sensors)

One final class of instruments that has not been mentioned so far consists of those designed to measure relatively large translational displacements. These are usually known as range sensors and measure the motion of a body with respect to some fixed datum point. Most range sensors use an energy source and energy detector, but measurement using a rotary potentiometer and a spring-loaded drum provides an alternative method.

Energy source/detector-based range sensors

The fundamental components in energy source/detector-based range sensors are an energy source, an energy detector, and an electronic means of timing the time of flight of the energy between the source and detector. The form of energy used is either ultrasonic or light. In some systems, both energy source and detector are fixed on the moving body and operation depends on the energy being reflected back from the fixed boundary as in Figure 19.12(a). In other systems, the energy source is attached to the moving body and the energy detector is located within the fixed boundary, as shown in Figure 19.12(b).

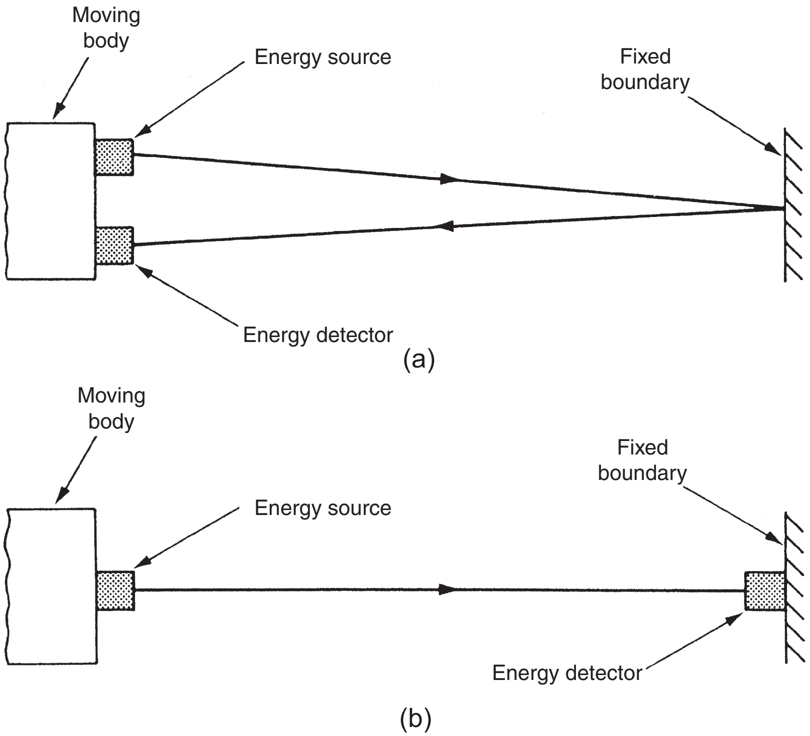

Figure 19.12
Range sensors. (a) Energy source and detector on moving body; (b) energy source on moving body and energy detector on reflective boundary.

In ultrasonic systems, the energy is transmitted from the source in high-frequency bursts. A frequency of at least 20 KHz is usual, and 40 KHz is common for measuring distances up to 5 m. By measuring the time of flight of the energy, the distance of the body from the fixed boundary can be calculated, using the fact that the speed of sound in air is 340 m/s. Because of difficulties in measuring the time of flight with sufficient accuracy, ultrasonic systems are not suitable for measuring distances of less than about 300 mm. Measurement resolution is limited by the wavelength of the ultrasonic energy and can be improved by operating at higher frequencies. At higher frequencies, however, attenuation of the magnitude of the ultrasonic wave as it passes through air becomes significant. Therefore, only low frequencies are suitable if large distances are to be measured. The typical inaccuracy of ultrasonic range finding systems is ±0.5% of full scale.

Optical range finding systems generally use a laser light source. The speed of light in air is about 3×10^8 m/s, so that light takes only a few nanoseconds to travel a meter. In consequence, such systems are only suitable for measuring very large displacements where the time of flight is long enough to be measured with reasonable accuracy.

Rotary potentiometer and spring-loaded drum

Another method for measuring large displacements that are beyond the measurement range of common displacement transducers is shown in Figure 19.13. This consists of a steel wire attached to the body whose displacement is being measured: the wire passes round

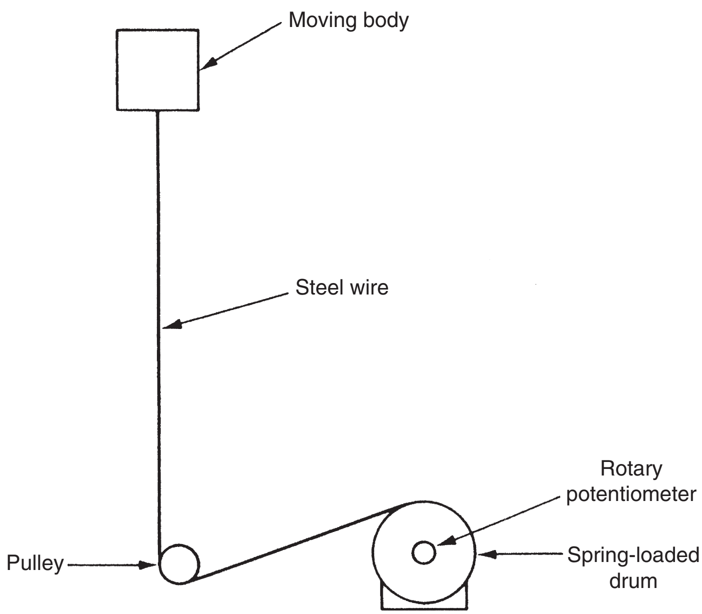

Figure 19.13
System for measuring large displacements.

a pulley and onto a spring-loaded drum whose rotation is measured by a rotary potentiometer. A multiturn potentiometer is usually required for this to give an adequate measurement resolution. With this measurement system, it is possible to reduce measurement uncertainty to as little as ±0.01% of full-scale reading.

19.2.10 Proximity Sensors

For the sake of completeness, it is proper to conclude this chapter on translational displacement transducers with consideration of proximity sensors. Proximity detectors provide information on the displacement of a body with respect to some boundary, but only insofar as to say whether the body is less than or greater than a certain distance away from the boundary. The output of a proximity sensor is thus binary in nature: the body is, or is not, close to the boundary.

Like range sensors, proximity detectors make use of an energy source and detector. The detector is a device whose output changes between two states when the magnitude of the incident reflected energy exceeds a certain threshold level. A common form of proximity sensor uses an infrared light-emitting diode (LED) source and a phototransistor. Light triggers the transistor into a conducting state when the LED is within a certain distance from a reflective boundary and the reflected light exceeds a threshold level. This system is physically small, occupying a volume of only a few cubic centimeters. If even this small volume is obtrusive, then fiber-optic cables can be used to transmit light from a remotely mounted LED and phototransistor. The threshold displacement detected by optical proximity sensors can be varied between 0 and 2 m.

Another form of proximity sensor uses the principle of varying inductance. Such devices are particularly suitable for operation in aggressive environmental conditions and they can be made vibration and shock resistant by vacuum encapsulation techniques. The sensor contains a high-frequency oscillator whose output is demodulated and fed via a trigger circuit to an amplifier output stage. The oscillator output radiates through the surface of the sensor and, when the sensor surface becomes close to an electrically or magnetically conductive boundary, the output voltage is reduced because of the interference with the flux paths. At a certain point, the output voltage is reduced sufficiently for the trigger circuit to change state and reduce the amplifier output to zero. Inductive sensors can be adjusted to change state at displacements in the range of 1−20 mm.

A third form of proximity sensor uses the capacitive principle. These can operate in similar conditions to inductive types. The threshold level of displacement detected can be varied between 5 and 40 mm.

Fiber-optic proximity sensors also exist where the amount of reflected light varies with the proximity of the fiber ends to a boundary, as shown earlier in Figure 13.2(c).

19.2.11 Choosing Translational Measurement Transducers

Choice between the various translational motion transducers available for any particular application depends mainly on the magnitude of the displacement to be measured, although the operating environment is also relevant.

The requirement to measure displacements of less than 2 mm usually occurs as part of an instrument that is measuring some other physical quantity such as pressure, and several types of device have evolved to fulfill this task. The LVDT, strain gauges, fotonic sensor, variable capacitance transducers and the noncontacting optical transducer all find application in measuring diaphragm or Bourdon tube displacements within pressure transducers. Load cell displacements are also very small, and these are commonly measured by nozzle flapper devices.

For measurements within the range of 2 mm to 2 m, the number of suitable instruments grows. Both the relatively cheap potentiometer and the LVDT, which is somewhat more expensive, are commonly used for such measurements. Variable inductance and variable capacitance transducers are also used in some applications. Additionally, strain gauges measuring the strain in two beams forced apart by a wedge (see Section 19.2.5) can measure displacements up to 50 mm. If very high measurement resolution is required, either the linear inductosyn or the laser interferometer is used.

Finally, range sensors are normally used if the displacement to be measured exceeds 2 m.

As well as choosing sensors according to the magnitude of displacement to be measured, the measurement environment is also sometimes relevant. If the environmental operating conditions are severe (e.g., hot, radioactive, or corrosive atmospheres), devices that can be easily protected from these conditions must be chosen, such as the LVDT, variable inductance, and variable capacitance instruments.

19.2.12 Calibration of Translational Displacement Measurement Transducers

Most translational displacement transducers measuring displacements up to 50 mm can be calibrated at the workplace level by using standard micrometers to measure a set of displacements and compare the reading from the displacement transducer being calibrated when it is reading the same set of displacements. Such micrometers can provide a reference standard with an inaccuracy of ±0.003% of full-scale reading. If better accuracy is required, micrometer-based calibrators are available from several manufacturers that reduce the measurement inaccuracy down to ±0.001% of full-scale reading.

For sensors that measure displacements exceeding 50 mm (including those classified as range sensors), the usual calibration tool is a laser interferometer. This can provide measurement uncertainty down to ±0.0002% of full-scale reading. According to which laser interferometer model is chosen, a measurement range up to 50 m is possible. Obviously, laser interferometers are expensive devices which are also physically very large for a model measuring up to 50 m, and therefore calibration services using these are usually devolved to specialist calibration companies or instrument manufacturers.

19.3 Velocity

Translational velocity cannot be measured directly and therefore must be calculated indirectly by other means as set out below.

19.3.1 Differentiation of Displacement Measurements

Differentiation of position measurements obtained from any of the translational displacement transducers described in Section 19.2 can be used to produce a translational velocity signal. Unfortunately, the process of differentiation always amplifies noise in a measurement system. Therefore, if this method has to be used, a low-noise instrument such as a DC excited carbon-film potentiometer or laser interferometer should be chosen. In the case of potentiometers, AC excitation must be avoided because of the problem that harmonics in the power supply would cause.

19.3.2 Integration of the Output of an Accelerometer

Where an accelerometer is already included within a system, integration of its output can be performed to yield a velocity signal. The process of integration attenuates rather than amplifies measurement noise, and this is therefore an acceptable technique in terms of measurement accuracy.

19.3.3 Conversion to Rotational Velocity

Conversion from translational to rotational velocity is the final measurement technique open to the system designer and it is the one that is most commonly used. This conversion enables any of the rotational velocity-measuring instruments described in Chapter 20 to be applied.

19.3.4 Calibration of Velocity Measurement Systems

Since translational velocity is never measured directly, the calibration procedure used depends on the system used for velocity measurement. If a velocity measurement is being calculated from a displacement or acceleration measurement, the traceability of system calibration requires that the associated displacement or acceleration transducer used is correctly calibrated. The only other measurement technique is conversion of the translational velocity into rotational velocity, in which case the system calibration depends on the calibration of the rotational velocity transducer used.

19.4 Acceleration

The only class of device available for measuring acceleration is the accelerometer. These are available in a wide variety of types and ranges designed to meet particular measurement requirements. They have a frequency response between zero and a high value, and have a form of output that can be readily integrated to give displacement and velocity measurements. The frequency response of accelerometers can be improved by altering the level of damping in the instrument. Such adjustment must be done carefully, however, because frequency response improvements are only achieved at the expense of degrading the measurement sensitivity. Besides their use for general-purpose motion measurement, accelerometers are widely used to measure mechanical shocks and vibrations.

Most forms of accelerometer consist of a mass suspended by a spring and damper inside a housing, as shown in Figure 19.14. The accelerometer is rigidly fastened to the body undergoing acceleration. Any acceleration of the body causes a force, F_a, on the mass, M, given by $F_a = M\ddot{x}$.

This force is opposed by the restraining effect, F_s, of a spring with spring constant K, and the net result is that the mass is displaced by a distance x from its starting position such that $F_s = Kx$.

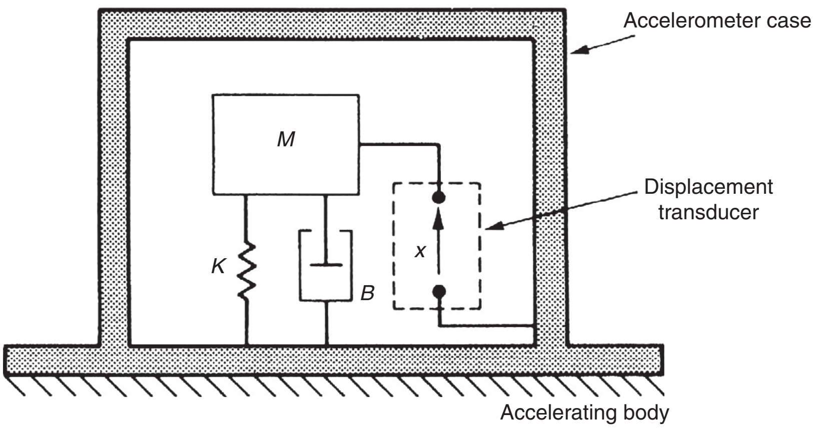

Figure 19.14
Structure of an accelerometer.

In steady state, when the mass inside is accelerating at the same rate as the case of the accelerometer,

$$F_a = F_s \text{ and so, } Kx = M\ddot{x} \quad \text{or} \quad \ddot{x} = (Kx)/M \tag{19.4}$$

This is the equation of motion of a second-order system, and, in the absence of damping, the output of the accelerometer would consist of nondecaying oscillations. A damper is therefore included within the instrument, which produces a damping force, F_d, proportional to the velocity of the mass M given by $F_d = B\dot{x}$.

This modifies the previous equation of motion (19.4) to the following:

$$Kx + B\dot{x} = M\ddot{x} \tag{19.5}$$

One important characteristic of accelerometers is their sensitivity to accelerations at right angles to the sensing axis (the direction along which the instrument is designed to measure acceleration). This is defined as *the cross-sensitivity* and is specified in terms of the output, expressed as a percentage of the full-scale output, when an acceleration of some specified magnitude (e.g., 30g) is applied at 90° to the sensing axis.

The acceleration reading is obtained from the instrument by measurement of the displacement of the mass within the accelerometer. Many different displacement-measuring techniques are used in the various types of accelerometer that are commercially available. Different types of accelerometer also vary in terms of the type of spring element and form of damping used.

Resistive potentiometers are one such displacement-measuring instrument used in accelerometers. These are used mainly for measuring slowly varying accelerations and low-frequency vibrations in the range of 0–50g. The measurement resolution obtainable is about 1 in 400 and typical values of cross-sensitivity are ±1%. Inaccuracy is about ±1% and life expectancy is quoted at two million reversals. A typical size and weight are 125 cm^3 and 500 g.

Strain gauges and piezoresistive sensors are also used in accelerometers for measuring accelerations up to 200g. These serve as the spring element as well as measuring mass displacement, thus simplifying the instrument's construction. Their typical characteristics are a resolution of 1 in 1000, inaccuracy of ±1%, and cross-sensitivity of 2%. They have a major advantage over potentiometer-based accelerometers in terms of their much smaller size and weight (3 cm^3 and 25 g).

Another displacement transducer found in accelerometers is the LVDT. This device can measure accelerations up to 700g with a typical inaccuracy of ±1% of full scale. They are of a similar physical size to potentiometer-based instruments but are lighter in weight (100 g).

Accelerometers based on variable inductance displacement-measuring devices have extremely good characteristics and are suitable for measuring accelerations up to $40g$. Typical specifications of such instruments are inaccuracy ±0.25% of full scale, resolution 1 in 10,000, and cross-sensitivity 0.5%. Their physical size and weight are similar to potentiometer-based devices. Instruments with an output in the form of a varying capacitance also have similar characteristics.

The other common displacement transducer used in accelerometers is the piezoelectric type. The major advantage of using piezoelectric crystals is that they also act as the spring and damper within the instrument. In consequence, the device is quite small (15 cm^3) and very low mass (50 g), but because of the nature of piezoelectric crystal operation, such instruments are not suitable for measuring constant or slowly time-varying accelerations. As the electrical impedance of a piezoelectric crystal is itself high, the output voltage must be measured with a very high-impedance instrument to avoid loading effects. Many recent piezoelectric crystal-based accelerometers incorporate a high-impedance charge amplifier within the body of the instrument. This simplifies the signal-conditioning requirements external to the accelerometer but can lead to problems in certain operational environments because these internal electronics are exposed to the same environmental hazards as the rest of the accelerometer. Typical measurement resolution of this class of accelerometer is 0.1% of full scale with an inaccuracy of ±1%. Individual instruments are available to cover a wide range of measurements from $0.03g$ full scale up to $1000g$ full scale. *Intelligent accelerometers* are also now available that give even better performance through inclusion of processing power to compensate for environmentally induced errors.

Recently, *MEMS sensors* have become available for measuring acceleration. These find application in things like crash sensing in vehicle air bags. They are also used in computer game controllers, cell phones, and for shake detection in digital cameras. At present, two forms of MEMS accelerometer exist. The *cantilever beam accelerometer* (Figure 19.15) consists of a small mass subject to the measured acceleration that is mounted on a thin silicon cantilever-shaped membrane. In the example shown in Figure 19.15, the displacement of the membrane due to the acceleration force is measured by piezoresistors deposited on the membrane. However, a variation on this type of accelerometer uses varying capacitance to measure the displacement by etching a variable capacitor plate into the membrane. The *balanced force accelerometer* (Figure 19.16) is the alternative form of MEMS device available for measuring acceleration. This consists of a thin silicon structure attached to springs at both ends. The silicon structure acts as the accelerometer mass. The device has three electrodes, one movable central electrode attached to one side of the silicon structure and two fixed electrodes attached to the casing of the device and located either side of the central electrode Figure 19.16(a). When the device becomes subject to an acceleration force, the mass moves to one side until the opposing spring forces balance the acceleration force Figure 19.16(b). As the mass moves, the central

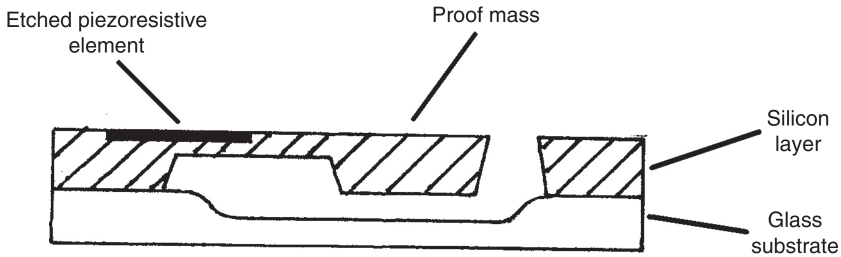

Figure 19.15
Cantilever beam accelerometer.

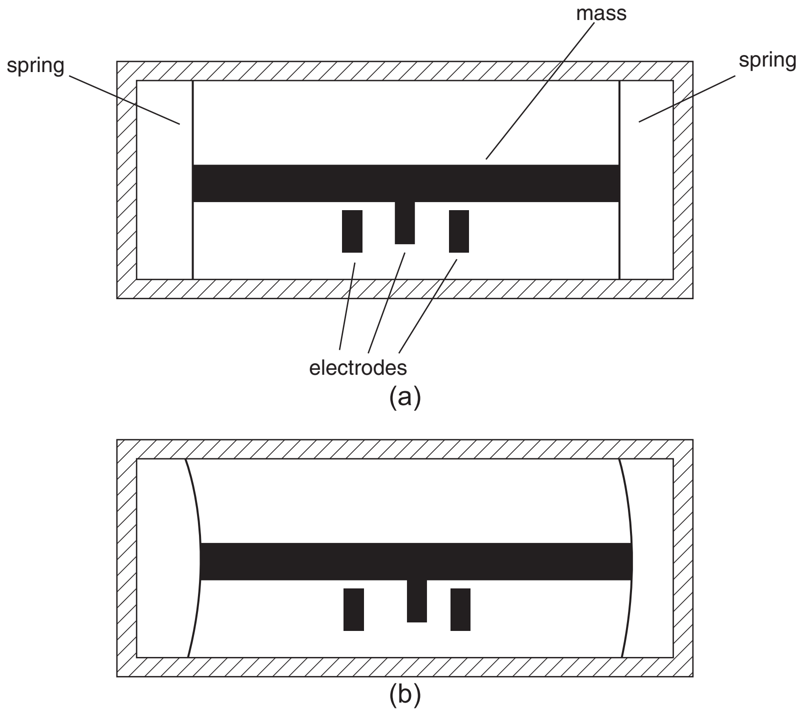

Figure 19.16
Balanced force accelerometer. (a) Sensor with zero acceleration applied; (b) sensor with deflection of mass due to applied acceleration.

electrode attached to it moves closer to one of the fixed electrodes and further away from the other. The amount of movement of the mass, and hence the acceleration measured, is then calculated from the change in capacitance between the electrodes.

Two forms of fiber-optic-based accelerometer also exist. One form measures the effect on light transmission intensity caused by a mass subject to acceleration resting on a multimode fiber. The other form measures the change in phase of light transmitted through a monomode fiber that has a mass subject to acceleration resting on it.

19.4.1 Selection of Accelerometers

In choosing between the different types of accelerometer for a particular application, the mass of the instrument is particularly important. This should be very much less than that of the body whose motion is being measured, in order to avoid loading effects that affect the accuracy of the readings obtained. In this respect, instruments based on strain gauges are best.

19.4.2 Calibration of Accelerometers

The primary method of calibrating accelerometers is to mount them on a table rotating about a vertical axis such that the sensing axis of the accelerometer is pointing toward the axis of rotation of the table. The acceleration, a, is then given by:

$$a = r(2\pi v)^2$$

where r is the radius of rotation measured from the center of the rotating table to the center of the accelerometer mass and v is the velocity of rotation of the table (in revolutions per second).

This obviously requires that the rotational speed of the table is measured accurately by a calibrated sensor. Provided that this condition is met, various reference acceleration values can be generated by changing the rotational speed of the table.

19.5 Vibration

19.5.1 Nature of Vibration

Vibrations are very commonly encountered in the operation of machinery and industrial plant, and therefore measurement of the accelerations associated with such vibrations is extremely important in industrial environments. The peak accelerations involved in such vibrations can be of $100g$ or greater in magnitude, while both the frequency of oscillation and the magnitude of displacements from the equilibrium position in vibrations have a tendency to vary randomly. Vibrations normally consist of linear harmonic motion that can be expressed mathematically as:

$$X = X_o \sin(\omega t) \tag{19.6}$$

where X is the displacement from the equilibrium position at any general point in time, X_o is the peak displacement from the equilibrium position, and ω is the angular frequency of the oscillations. By differentiating Eqn (19.6) with respect to time, an expression for the velocity v of the vibrating body at any general point in time is obtained as:

$$v = -\omega X_o \cos(\omega t) \tag{19.7}$$

Differentiating Eqn (19.7) again with respect to time, we obtain an expression for the acceleration, α, of the body at any general point in time as:

$$\alpha = -\omega^2 X_o \sin(\omega t) \tag{19.8}$$

Inspection of Eqn (19.8) shows that the peak acceleration is given by:

$$\alpha_{peak} = \omega^2 X_o \tag{19.9}$$

This square law relationship between peak acceleration and oscillation frequency is the reason why high values of acceleration occur during relatively low-frequency oscillations. For example, an oscillation at 10 Hz produces peak accelerations of 2g.

Example 19.2

A pipe carrying a fluid vibrates at a frequency of 60 Hz with displacements of 8 mm from the equilibrium position. Calculate the peak acceleration.

Solution

From Eqn (19.9), $\alpha_{peak} = \omega^2 X_o = (2\pi 60)^2 \times (0.008) = 1137.0\ \text{m/s}^2$.

Using the fact that the standard acceleration due to gravity, g, is 9.81 m/s^2, this answer can be expressed alternatively as: $\alpha_{peak} = 1137.0/9.81 = 115.9g$.

19.5.2 Vibration Measurement

It is apparent that the intensity of vibration can be measured in terms of either displacement, velocity, or acceleration. Acceleration is clearly the best parameter to measure at high frequencies. However, because displacements are large at low frequencies according to Eqn (19.9), it would seem that measuring either displacement or velocity would be best at low frequencies. The amplitude of vibrations can be measured by various forms of displacement transducer. Fiber-optic-based devices are particularly attractive and can give measurement resolution as high as 1 μm. Unfortunately, there are considerable practical difficulties in mounting and calibrating displacement and velocity transducers and therefore they are rarely used. Because of this, vibration is usually measured by accelerometers at all frequencies. The most common type of transducer used is the piezoaccelerometer, which has typical inaccuracy levels of ±2%.

The frequency response of accelerometers is particularly important in vibration measurement in view of the inherently high-frequency characteristics of the measurement situation. The bandwidth of both potentiometer-based accelerometers and accelerometers using variable inductance type displacement transducers only goes up to 25 Hz. Accelerometers that include either the LVDT or strain gauges can measure frequencies up to 150 Hz and the latest instruments using piezoresistive strain gauges have bandwidths up to 2 kHz. Finally, inclusion of piezoelectric crystal displacement transducers yields an instrument with a bandwidth that can be as high as 7 kHz.

When measuring vibration, consideration must be given to the fact that attaching an accelerometer to the vibrating body will significantly affect the vibration characteristics if the body has a small mass. The effect of such "loading" of the measured system can be quantified by the following equation:

$$a_1 = a_b\left(\frac{m_b}{m_b + m_a}\right),$$

where a_1 is the acceleration of the body with accelerometer attached, a_b is the acceleration of the body without the accelerometer, m_a is the mass of the accelerometer, and m_b is the mass of the body. Such considerations emphasize the advantage of piezoaccelerometers for measuring vibration, as these have a lower mass than other forms of accelerometer and so contribute least to this system-loading effect.

As well as an accelerometer, a vibration measurement system requires other elements to translate the accelerometer output into a recorded signal, as shown in Figure 19.17. The three other necessary elements are a signal-conditioning element, a signal analyzer, and a signal recorder. The signal-conditioning element amplifies the relatively weak output signal from the accelerometer and also transforms the high output impedance of the accelerometer to a lower impedance value. The signal analyzer then converts the signal into the form required for output. The output parameter may be either displacement, velocity, or acceleration (by integrating the acceleration measurement as appropriate), and this may be expressed as either the peak value, rms value, or average absolute value. The final element of the measurement system is the signal recorder. All elements of the measurement system, and especially the signal recorder, must be chosen very carefully to avoid distortion of the vibration waveform. The bandwidth should be such that it is at least a factor of 10 better than the bandwidth of the vibration frequency components at both ends. Thus, its lowest frequency limit should be less than or equal to 0.1 times the fundamental frequency of vibration and its upper frequency limit should be greater than or equal to 10 times the highest significant vibration frequency component.

If the frequency of vibration has to be known, the stroboscope is a suitable instrument to measure this. If the stroboscope is made to direct light pulses at the body at the same frequency as the vibration, the body will apparently stop vibrating.

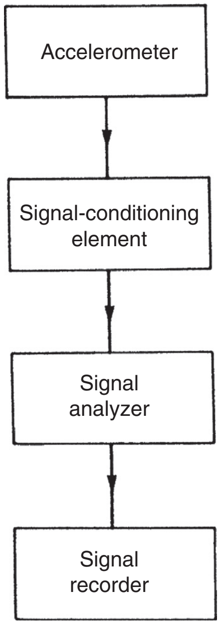

Figure 19.17
Vibration measurement system.

19.5.3 Calibration of Vibration Sensors

Calibration of the accelerometer used within a vibration measurement system is normally carried out by mounting the accelerometer in a back-to-back configuration with a reference calibrated accelerometer on an electromechanically excited vibrating table.

19.6 Shock

Shock describes a type of motion where a moving body is brought suddenly to rest, often because of a collision. This is very common in industrial situations, and usually involves a body being dropped and hitting the floor. Shocks characteristically involve large-magnitude deceleration (e.g., 500*g*) that last for a very short time (e.g., 5 ms). An instrument having a very high-frequency response is required for shock measurement, and, for this reason, piezoelectric crystal-based accelerometers are commonly used. Again, other elements for analyzing and recording the signal are required as shown in Figure 19.18 and described in the last section. A storage oscilloscope is a suitable instrument for recording the output signal, as this allows the time duration as well as the acceleration levels in the shock to be measured. Alternatively, if a permanent record is required, the screen of a standard oscilloscope can be photographed.

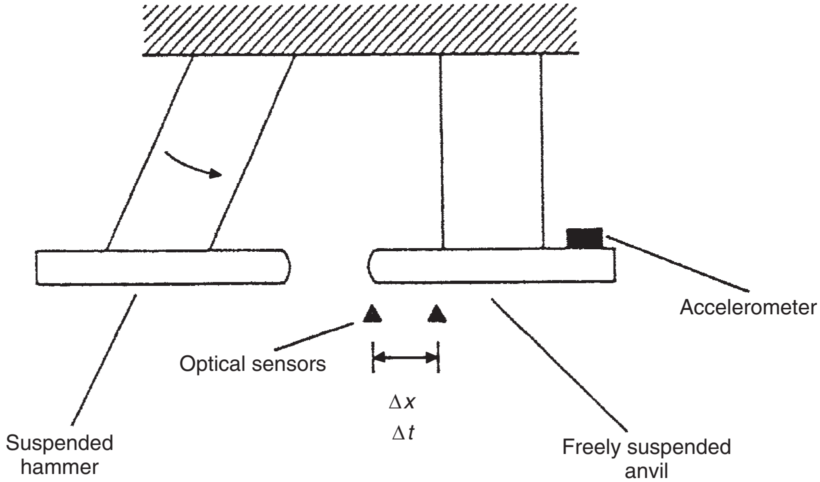

Figure 19.18
Shock measurement.

Example 19.3

A body is dropped from a height of 10 m and suffers a shock when it hits the ground. If the duration of the shock is 5 ms, calculate the magnitude of the shock in terms of g.

Solution

The equation of motion for a body falling under gravity gives the following expression for the terminal velocity, v: $v = \sqrt{2gx}$, where x is the height through which the body falls. Having calculated v, the average deceleration during the collision can be calculated as $\alpha = v/t$, where t is the time duration of the shock. Substituting the appropriate numerical values into these expressions: $v = \sqrt{(2 \times 9.81 \times 10)} = 14.0$ m/s; $\alpha = 14.0/0.005 = 2801$ m/s=286g.

19.6.1 Calibration of Shock Sensors

Calibration of the accelerometer used within a shock sensor is frequently carried out using a pneumatic shock exciter. This device consists of a piston within a circular tube. High-pressure air is applied to one face of the piston, but it does not move initially because it is held at the end of the tube by a mechanical latching mechanism. When the latch is released, the piston accelerates at a high rate until it is brought to rest by a padded anvil at the other end of the tube. The accelerometer being calibrated and a calibrated reference accelerometer are both mounted on the anvil. By varying the characteristics of the padding, the deceleration level and hence magnitude of the shock produced on the anvil can be varied.

19.7 Summary

This chapter has been concerned with the measurement of translational (in a straight line) motion. This can take the form of either displacement, velocity (rate of change of displacement), or acceleration (rate of change of velocity). We have looked at sensors for measuring each of these and, in the case of acceleration, we have also studied vibration and shock measurement, since both of these involve acceleration measurement.

Our study of displacement sensors started with the resistive potentiometer, where we learned that potentiometers came in three different forms, wire wound, carbon film, and plastic film. We then moved onto look at the LVDT, variable capacitance and variable inductance sensors. We noted that strain gauges were used to measure very small displacements (typically up to 50 μm in magnitude). We also noted that force-measuring piezoelectric sensors could also be regarded as displacement sensors since their mode of operation is to generate an emf that is proportional to the distance by which it is compressed by the applied force. We also discussed the nozzle flapper, which measures displacements by converting them into a pressure change. We then moved onto summarize some other techniques for measuring small- and medium-sized displacements, including translating linear motion into rotational motion, integrating the output from velocity and acceleration sensors, and using specialist devices like the linear inductosyn, laser interferometer, fotonic sensor, and noncontacting optical sensor. Moving the discussion onto measurement of relatively large displacements, we noted that could be achieved by several devices that are commonly called range sensors. We also included some mention of proximity sensors, since these properly belong within the classification of displacement sensors, although they are a special case in that their binary form of output merely indicates whether the sensor is, or is not, within some threshold distance of a boundary. Finally, before leaving the subject of displacement measurement, we looked at the techniques used to calibrate them.

Our discussion of translational velocity measurement introduced us to the fact that this cannot be measured directly. We then went onto at the only three ways to measure it, these being differentiation of position measurements, integration of the output of an accelerometer, and conversion from translational to rotational velocity. Finally, we considered how measurements obtained via each of the techniques could be calibrated.

In the case of acceleration measurement, we observed that this could only be measured by some form of accelerometer. We noted that attributes like frequency response and cross-sensitivity were important as well as measurement accuracy in accelerometers. We discovered that almost all accelerometers work on the principle that a mass inside them displaces when subject to acceleration. Accelerometers differ mainly in the technique used to measure this mass displacement, and we looked in turn at devices that use the resistive potentiometer, strain gauge, piezoresistive sensor, LVDT, variable inductance sensor, and variable capacitance sensor, respectively. We then looked at the one exception to the rule that accelerometers contain a moving mass. This is the piezoelectric accelerometer. Finally, we looked at the primary method of calibrating accelerometers using a rotating table.

We then concluded the chapter by looking at vibration and shock measurement. Both of these involve accelerations, and therefore both need an accelerometer to quantify their magnitude. Starting with vibration, we noted that this was a common phenomenon, especially in industrial situations. We learned that vibration consists of linear harmonic in which the peak acceleration can exceed 100*g* and where the oscillation frequency and peak amplitude can vary randomly. We noted that the amplitude of vibration could be calculated from a measurement of the peak acceleration, and we went onto look at the suitability of various forms of accelerometer for such measurement.

Finally, we considered shock measurement. This revealed that very large-magnitude decelerations are involved in the phenomenon of shock, which typically occurs when a falling body hits the floor or a collision occurs between two solid objects. High-frequency response is particularly important in shock measurement and the most suitable device to measure this is a piezoelectric crystal-based accelerometer.

19.8 Problems

19.1 Discuss the mode of operation and characteristics of a linear motion potentiometer.
19.2 What is an LVDT? How does it work?
19.3 Explain how the following two instruments work and discuss their main operating characteristics and uses: (a) variable capacitance transducer and (b) variable inductance transducer.
19.4 Sketch a linear inductosyn. How does it work? What are its main characteristics?
19.5 What is a laser interferometer and what are its principle characteristics? Explain how it works with the aid of a sketch.
19.6 What are range sensors? Describe two main types of range sensor.
19.7 Discuss the main types of proximity sensor available, mentioning particularly their suitability for operation in harsh environments.

19.8 What are the main considerations in choosing a translational motion transducer for a particular application? Give examples of some types of translational motion transducer and the applications that they are suitable for.

19.9 Discuss the usual calibration procedures for translational displacement measurement transducers at the workplace level of calibration.

19.10 What are the main ways of measuring translational velocities? How are such measurements calibrated?

19.11 What are the principles of operation of a linear motion accelerometer? What features would you expect to see in a high-quality accelerometer?

19.12 What types of displacement sensor are used within accelerometers? What are the relative merits of these alternative displacement sensors?

19.13 Write down mathematical equations that describes the phenomenon of vibration. Explain and discuss the main ways of measuring vibration.

19.14 When an accelerometer is attached to a vibrating body, it has a loading effect that alters the characteristics of the vibration. Write down a mathematical equation that describes this loading effect. How can this loading effect be minimized?

19.15 A translational motion potentiometer of stroke length 200 mm is to be used in a particular measurement situation. The output voltage from the potentiometer is to be measured by an instrument whose resistance is 15 kΩ. The maximum measurement error, which occurs when the slider is positioned two-thirds of the way along the element (i.e., when AC = 2AB/3 in Figure 19.1), must not exceed 0.5% of the full-scale reading. The highest possible measurement sensitivity is also required. A family of potentiometers having a power rating of 0.1 W per mm and resistances ranging from 100 Ω to 10 kΩ in 100 Ω steps are available. Choose the most suitable potentiometer from this range and calculate the measurement sensitivity that it provides.

19.16 (a) Show that the expression for the peak acceleration α in a vibrating body is given by:

$$\alpha = -\omega^2 X_o \sin(\omega t)$$

where X_o is the peak displacement from the equilibrium position and ω is the angular frequency of the oscillations.

(b) A pipe carrying a fluid vibrates at a frequency of 50 Hz with displacements of 7 mm from the equilibrium position. Calculate the peak acceleration.

19.17 A body is dropped from a height of 15 m and suffers a shock when it hits the ground. If the duration of the shock is 3 ms, calculate the magnitude of the shock in terms of g. (Assume $g = 9.81$ m/s^2).