CHAPTER 13

Sensor Technologies

Chapter Outline

Measurement and Instrumentation. http://dx.doi.org/10.1016/B978-0-12-800884-3.00013-7

13.1 Introduction

We are now moving into the second part of the book, where we will look in detail at the range of sensors available for measuring various physical quantities. As we study these sensors, we will quickly come to realize that a wide range of different physical principles are involved in their operation. It will also become apparent that the physical principles on which they operate is often an important factor in choosing a sensor for a given application, since a sensor using a particular principle may perform much better than one using a different principle in given operating conditions. It is therefore prudent to devote this chapter to a study of the various physical principles that are exploited in measurement sensors before going on to the separate chapters devoted to measurement of various physical quantities. The physical principles that we shall examine are capacitance change, resistance change, magnetic phenomena (inductance, reluctance, and eddy currents), the Hall effect, properties of piezoelectric materials, resistance change in stretched/strained wires (strain gauges), properties of piezoresistive materials, light transmission (both along an air path and along a fiber optic cable), properties of ultrasound, transmission of radiation, and properties of micromachined structures (microsensors and nanosensors). It should be noted that the chosen order of presentation of these is arbitrary and does not imply anything about the relative popularity of these various principles. It must also be pointed out that the list of technologies covered in this chapter is not a full list of all the technologies that are used in sensors, but rather a list of technologies that are common to several different sensors that measure different physical quantities. Many other technologies are used in the measurement of single physical quantities. Temperature measurement is a good example of this, as several of the sensors used are based on technologies that are not covered in this chapter.

13.2 Capacitive Sensors

Capacitive sensors consist of two parallel metal plates in which the dielectric between the plates is either air or some other medium. The capacitance C is given by $C = \varepsilon_o \varepsilon_r A/d$, where ε_o is the absolute permittivity, ε_r is the relative permittivity of the dielectric medium between the plates, A is the area of the plates, and d is the distance between them. Two forms of capacitive device exist which differ according to whether the distance between the plates is fixed or not.

Capacitive devices in which the distance between the plates is variable are primarily used as displacement sensors. Motion of the moveable capacitive plate relative to a fixed one changes the capacitance. Such devices can be used directly as a displacement sensor by applying the motion to be measured to the moveable capacitor plate. Capacitive displacement sensors commonly form part of instruments measuring pressure, sound, or acceleration, as explained in later chapters.

In the alternative form of capacitor, the distance between the plates is fixed. Variation in capacitance is achieved by changing the dielectric constant of the material between the plates in some way. One application is where the dielectric medium is air and the device is used as a humidity sensor by measuring the moisture content of the air. Another common application is as a liquid level sensor, where the dielectric is part air and part liquid according to the level of the liquid that the device is inserted in. Both of these applications are discussed in greater detail in later chapters. This principle is used in devices to measure moisture content, humidity values, and liquid level, as discussed in later chapters.

13.3 Resistive Sensors

Resistive sensors rely on the variation of the resistance of a material when the measured variable is applied to it. This principle is most commonly applied in temperature measurement using resistance thermometers or thermistors. It is also used in displacement measurement using strain gauges or piezoresistive sensors. In addition, some moisture meters work on the resistance-variation principle. All of these applications are considered further in later chapters.

13.4 Magnetic Sensors

Magnetic sensors utilize the magnetic phenomena of inductance, reluctance, and eddy currents to indicate the value of the measured quantity, which is usually some form of displacement.

Inductive sensors translate movement into a change in the mutual inductance between magnetically coupled parts. One example of this is the inductive displacement transducer shown in Figure 13.1. In this, the single winding on the central limb of an "E"-shaped

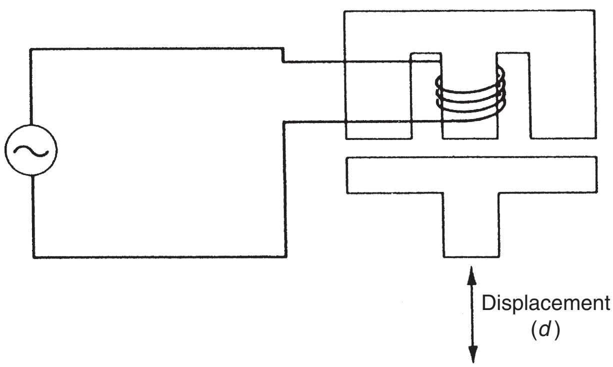

Figure 13.1
Inductive displacement sensor.

ferromagnetic body is excited with an alternating voltage. The displacement to be measured is applied to a ferromagnetic plate in close proximity to the "E" piece. Movements of the plate alter the flux paths and hence cause a change in the current flowing in the winding. By Ohm's law, the current flowing in the winding is given by $I = V/\omega L$. For fixed values of ω and V, this equation becomes $I = 1/KL$, where K is a constant. The relationship between L and the displacement d, applied to the plate is a nonlinear one, and hence the output current/displacement characteristic has to be calibrated.

The inductance principle is also used in differential transformers to measure translational and rotational displacements.

In *variable reluctance sensors*, a coil is wound on a permanent magnet rather than on an iron core as in variable inductance sensors. Such devices are commonly used to measure rotational velocities. Figure 13.2 shows a typical instrument in which a ferromagnetic gearwheel is placed next to the sensor. As the tip of each tooth on the gearwheel moves toward and away from the pick-up unit, the changing magnetic flux in the pick-up coil causes a voltage to be induced in the coil whose magnitude is proportional to the rate of change of flux. Thus, the output is a sequence of positive and negative pulses whose frequency is proportional to the rotational velocity of the gearwheel.

Eddy current sensors consist of a probe containing a coil, as shown in Figure 13.3, that is excited at a high frequency, which is typically 1 MHz. This is used to measure the displacement of the probe relative to a moving metal target. Because of the high frequency of excitation, eddy currents are induced only in the surface of the target, and the current magnitude reduces to almost zero at a short distance inside the target. This allows the sensor to work measure the displacement of very thin targets, such as the steel diaphragm of a pressure sensor. The eddy currents alter the inductance of the probe coil, and this change can be translated into a DC voltage output that is proportional to the distance between the probe and the target. Measurement resolution as high as 0.1 μm can be achieved. The sensor can also work with a nonconductive target if a piece of aluminum tape is fastened to it.

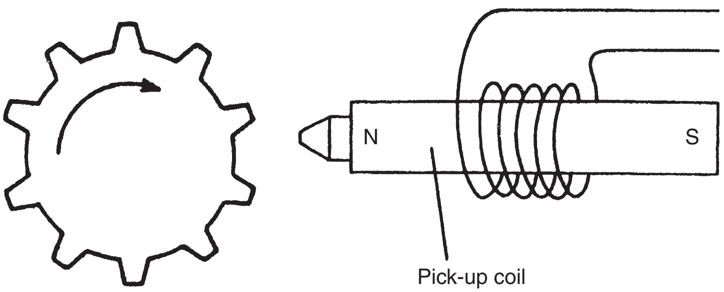

Figure 13.2
Variable reluctance sensor.

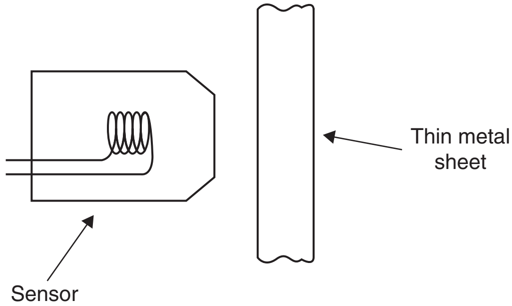

Figure 13.3
Eddy current sensor.

13.5 Hall Effect Sensors

Basically, a Hall effect sensor is a device that is used to measure the magnitude of a magnetic field. It consists of a conductor carrying a current that is aligned orthogonally with the magnetic field, as shown in Figure 13.4. This produces a transverse voltage difference across the device that is directly proportional to the magnetic field strength. For an excitation current I and magnetic field strength B, the output voltage is given by $V = KIB$, where K is known as the Hall constant.

The conductor in Hall effect sensors is usually made from a semiconductor material as opposed to a metal, because a larger voltage output is produced for a magnetic field of a given size. In one common use of the device as a proximity sensor, the magnetic field is provided by a permanent magnet that is built into the device. The magnitude of this field changes when the device becomes close to any ferrous metal object or boundary. The Hall

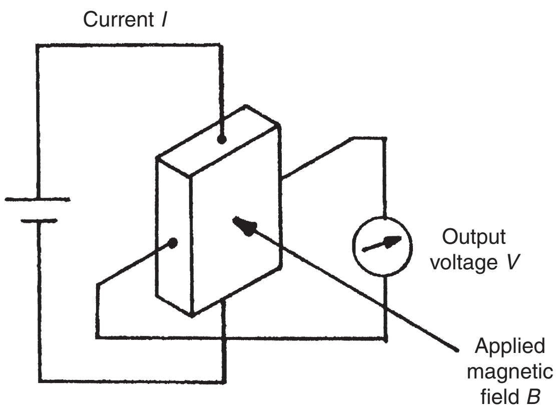

Figure 13.4
Principles of Hall effect sensor.

effect is also commonly used in computer keyboard push buttons. When a button is depressed, a magnet attached underneath the button moves past a Hall effect sensor. This generates an induced voltage in the sensor which is converted by a trigger circuit into a digital output. Such push-button switches can operate at high frequencies without contact bounce.

13.6 Piezoelectric Transducers

Piezoelectric transducers produce an output voltage when a force is applied to them. They can also operate in the reverse mode where an applied voltage produces an output force. They are frequently used as ultrasonic transmitters and receivers. They are also used as displacement transducers, particularly as part of devices measuring acceleration, force, and pressure. In ultrasonic receivers, the sinusoidal amplitude variations in the ultrasound wave received are translated into sinusoidal changes in the amplitude of the force applied to the piezoelectric transducer. In a similar way, the translational movement in a displacement transducer is caused by mechanical means to apply a force to the piezoelectric transducer. Piezoelectric transducers are made from piezoelectric materials. These have an asymmetrical lattice of molecules that distorts when a mechanical force is applied to it. This distortion causes a reorientation of electric charges within the material, resulting in a relative displacement of positive and negative charges. The charge displacement induces surface charges on the material of opposite polarity between the two sides. By implanting electrodes into the surface of the material, these surface charges can be measured as an output voltage. For a rectangular block of material, the induced voltage is given by:

$$V = \frac{kFd}{A} \tag{13.1}$$

where F is the applied force in g, A is the area of the material in mm, d is the thickness of the material, and k is the piezoelectric constant. The polarity of the induced voltage depends on whether the material is compressed or stretched.

The input impedance of the instrument used to measure the induced voltage must be chosen carefully. Connection of the measuring instrument provides a path for the induced charge to leak away. Hence, the input impedance of the instrument must be very high, particularly where static or slowly varying displacements are being measured.

Materials exhibiting piezoelectric behavior include natural ones such as quartz, synthetic ones such as lithium sulfate and ferroelectric ceramics such as barium titanate. The piezoelectric constant varies widely between different materials. Typical values of k are 2.3 for quartz and 140 for barium titanate. Applying Eqn (13.1) for a force of 1g applied to a crystal of area 100 mm^2 and thickness 1 mm gives an output of 23 μV for quartz and 1.4 mV for barium titanate.

Certain polymeric films such as polyvinylidine also exhibit piezoelectric properties. These have a higher voltage output than most crystals and are very useful in many applications where displacement needs to be translated into a voltage. However, they have very limited mechanical strength and are unsuitable for applications where resonance might be generated in the material.

The piezoelectric principle is invertible, and therefore distortion in a piezoelectric material can be caused by applying a voltage to it. This is commonly used in ultrasonic transmitters, where the application of a sinusoidal voltage at a frequency in the ultrasound range causes a sinusoidal variation in the thickness of the material and results in a sound wave being emitted at the chosen frequency. This is considered further in the section below on ultrasonic transducers.

13.7 Strain Gauges

Strain gauges are devices that experience a change in resistance when they are stretched or strained. They are able to detect very small displacements, usually in the range of 0–50 μm, and are typically used as part of other transducers, for example diaphragm pressure sensors that convert pressure changes into small displacements of the diaphragm. Measurement inaccuracies as low as ±0.15% of full scale reading are achievable and the quoted life expectancy is usually three million reversals. Strain gauges are manufactured to various nominal values of resistance, of which 120, 350, and 1000 Ω are very common. The typical maximum change of resistance in a 120-Ω device would be 5 Ω at maximum deflection.

The traditional type of strain gauge consists of a length of metal resistance wire formed into a zigzag pattern and mounted onto a flexible backing sheet, as shown in Figure 13.5(a). The wire is nominally of circular cross-section. As strain is applied to the gauge, the shape of the cross-section of the resistance wire distorts, changing the

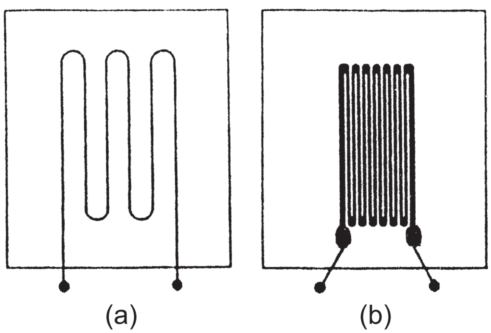

Figure 13.5
Strain gauges. (a) Wire type; (b) foil type.

cross-sectional area. As the resistance of the wire per unit length is inversely proportional to the cross-sectional area, there is a consequential change in resistance. The input–output relationship of a strain gauge is expressed by the *gauge factor*, which is defined as the change in resistance (R) for a given value of strain (S), that is, *gauge factor* $= \delta R/\delta S$.

In recent years, wire-type gauges have largely been replaced, either by metal-foil types as shown in Figure 13.5(b), or by semiconductor types. Metal-foil types are very similar to metal-wire types except the active element consists of a piece of metal-foil cut into a zigzag pattern. Cutting a foil into the required shape is much easier than forming a piece of resistance wire into the required shape, and this makes the devices cheaper to manufacture. A popular material in metal strain gauge manufacture is a copper–nickel–manganese alloy, which is known by the trade name of "Advance." Semiconductor types have piezoresistive elements, which are considered in greater detail in the next section. Compared with metal gauges, semiconductor types have a much superior gauge factor (up to 100 times better) but they are more expensive. Also, while metal gauges have an almost zero temperature coefficient, semiconductor types have a relatively high temperature coefficient.

In use, strain gauges are bonded to the object whose displacement is to be measured. The process of bonding presents a certain amount of difficulty, particularly for semiconductor types. The resistance of the gauge is usually measured by a DC bridge circuit and the displacement is inferred from the bridge output measured. The maximum current that can be allowed to flow in a strain gauge is in the region of 5–50 mA depending on the type. Thus, the maximum voltage that can be applied is limited and consequently, as the resistance change in a strain gauge is typically small, the bridge output voltage is also small and amplification has to be carried out. This adds to the cost of using strain gauges.

13.8 Piezoresistive Sensors

A piezoresistive sensor is made from semiconductor material in which a p-type region has been diffused into an n-type base. The resistance of this varies greatly when the sensor is compressed or stretched. This is frequently used as a strain gauge, where it produces a significantly higher gauge factor than that given by metal wire or foil gauges. Also, measurement uncertainty can be reduced down to $\pm 0.1\%$. It is also used in semiconductor-diaphragm pressure sensors and in semiconductor accelerometers.

It should also be mentioned that the term "piezoresistive sensor" is sometimes used to describe all types of strain gauge, including metal types. However, this is incorrect since only about 10% of the output from a metal strain gauge is generated by piezoresistive effects, with the remainder arising out of the dimensional cross-section change in the wire or foil. Proper piezoelectric strain gauges, which are alternatively known as *semiconductor strain gauges*, produce most (about 90%) of their output through piezoresistive effects, and only a small proportion of the output is due to dimensional changes in the sensor.

13.9 Optical Sensors

Optical sensors are based on the transmission of light between a light source and a light detector, as shown in Figure 13.6. The transmitted light can travel along either an air path or a fiber optic cable. Either form of transmission gives immunity to electromagnetically induced noise, and also provides greater safety than electrical sensors when used in hazardous environments.

13.9.1 Optical Sensors (Air Path)

Air path optical sensors are commonly used to measure proximity, translational motion, rotational motion, and gas concentration. These uses are discussed in more detail in later chapters. A number of different types of light source and light detector are used.

Light sources

Light sources suitable for transmission across an air path include tungsten filament lamps, laser diodes, and light-emitting diodes (LEDs). However, as the light from tungsten lamps is usually in the visible part of the light frequency spectrum, it is prone to interference from the sun and other sources. Hence, infrared LEDs or infrared laser diodes are usually preferred. These emit light in a narrow frequency band in the infrared region and are not affected by sunlight.

Light detectors

The main forms of light detector used with optical systems are photoconductors (photoresistors), photovoltaic devices (photocells), phototransistors, and photodiodes.

Photoconductive devices are sometimes known by the alternative name of *photoresistors*. They convert changes in incident light into changes in resistance, with

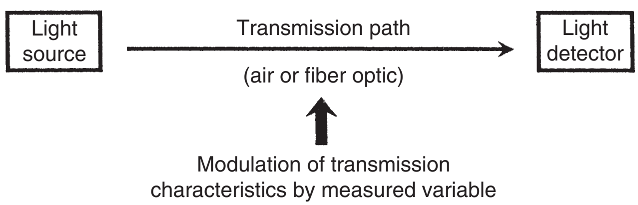

Figure 13.6
Operating principles of optical sensors.

the resistance reducing according to the intensity of light to which they are exposed. They are made from various materials such as cadmium sulfide, lead sulfide, and indium antimonide.

Photovoltaic devices are often called *photocells*. They are also commonly known as *solar cells* when a number of them are used in an array as a means of generating energy from sunlight. They are made from various types of semiconductor material. Their basic mode of operation is to generate an output voltage whose magnitude is a function of the magnitude of the incident light that they are exposed to.

Photodiodes are devices where the output current is a function of the amount of incident light. Again, they are made from various types of semiconductor material.

Phototransistor is effectively a standard bipolar transistor with a transparent case that allows light to reach its base—collector junction. It has an output in the form of an electrical current and could be regarded as a photodiode with an internal gain. This gain makes it more sensitive to light than a photodiode, particularly in the infrared region, but it has a slower response time. It is an ideal partner for infrared LED and laser diode light sources.

13.9.2 Optical Sensors (Fiber Optic)

Instead of using air as the transmission medium, optical sensors can use fiber optic cable to transmit light between a source and a detector. Fiber optic cables can be made from either plastic or glass fibers or a combination of the two, though it is now rare to find cables made only from glass fibers since these are very fragile. Cables made entirely from plastic fibers have particular advantages for sensor applications because they are cheap and have a relatively large diameter of 0.5—1.0 mm, making connection to the transmitter and receiver easy. However, plastic cables cannot be used in certain hostile environments where they would be severely damaged. The cost of the fiber optic cable itself is insignificant for sensing applications, as the total cost of the sensor is dominated by the cost of the transmitter and receiver.

Fiber optic sensors characteristically enjoy long life. For example, the life expectancy of reflective fiber optic switches is quoted at 10 million operations. Their accuracy is also good, with $\pm 1\%$ of full scale reading being quoted as a typical inaccuracy level for a fiber optic pressure sensor. Further advantages are their simplicity, low cost, small size, high reliability, and capability of working in many kinds of hostile environment. The only significant difficulty in designing a fiber optic sensor is in ensuring that the proportion of light entering the cable is maximized. This is the same difficulty that was described earlier when we were discussing the use of fiber optic cables for signal transmission.

Two major classes of fiber optic sensor exist, intrinsic sensors and extrinsic sensors. In *intrinsic sensors*, the fiber optic cable itself is the sensor, whereas in *extrinsic sensors*, the fiber optic cable is only used to guide light to/from a conventional sensor.

Intrinsic sensors

In intrinsic sensors, the physical quantity being measured causes some measurable change in the characteristics of the light transmitted by the cable. The modulated light parameters are one or more of the following:

- Intensity
- Phase
- Polarization
- Wavelength
- Transit time

Sensors that modulate light intensity tend to use mainly multimode fibers, but only monomode cables are used to modulate other light parameters. A particularly useful feature of intrinsic fiber optic sensors is that they can, if required, provide distributed sensing over distances of up to 1 m.

Light intensity is the simplest parameter to manipulate in intrinsic sensors because only a simple source and detector are required. The various forms of switches shown in Figure 13.7 are perhaps the simplest form of these, as the light path is simply blocked and unblocked as the switch changes state. Modulation of the intensity of transmitted light also takes place in various simple forms of proximity, displacement, pressure, pH, and smoke sensors. Some of these are sketched in Figure 13.8. In proximity and displacement sensors (the latter are sometimes given the special name *Fotonic sensors*), the amount of reflected light varies with the distance between the fiber ends and a boundary. In pressure sensors, the refractive index of the fiber, and hence the intensity of light transmitted, varies according to the mechanical deformation of the fibers caused by pressure. In the pH probe, the amount of light reflected back into the fibers depends on the pH-dependent color of the chemical indicator in the solution around the probe tip. Finally, in a form of smoke detector, two fiber optic cables placed either side of a space detect any reduction in the intensity of light transmission between them caused by the presence of smoke.

A simple form of accelerometer can be made by placing a mass subject to the acceleration on a multimode fiber. The force exerted by the mass on the fiber causes a change in the intensity of light transmitted, hence allowing the acceleration to be determined. The typical inaccuracy quoted for this device is $\pm 0.02g$ in the measurement range of $\pm 5g$ and $\pm 2\%$ in the measurement range up to $100g$.

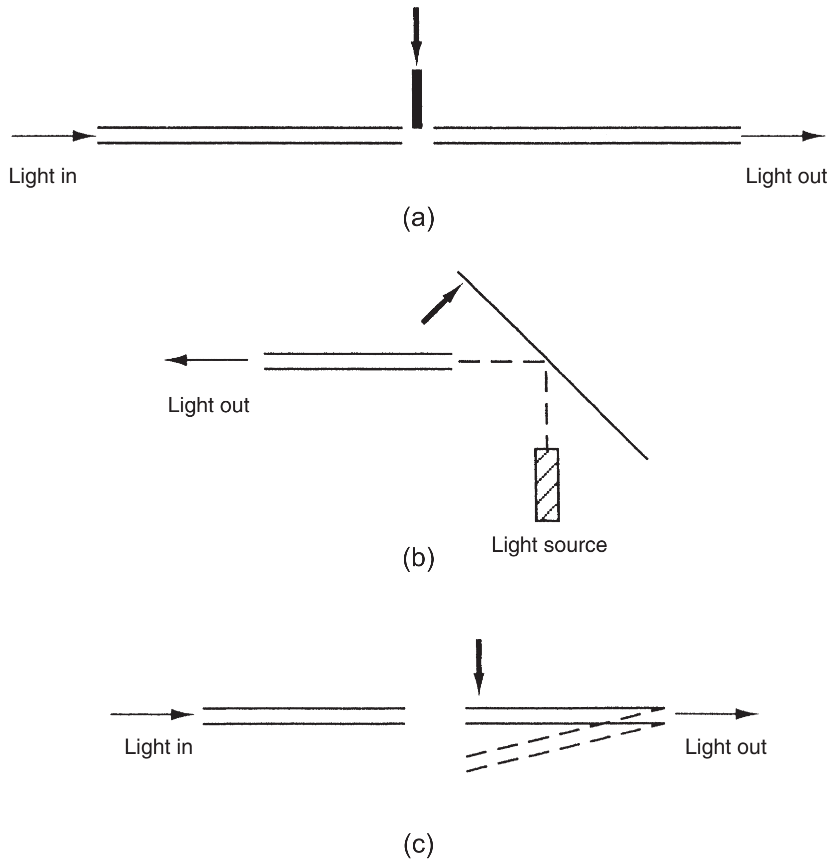

Figure 13.7
Intrinsic fiber optic sensors. (a) Shutter switch; (b) reflective switch; (c) optical switch.

A similar principle is used in probes that measure the internal diameter of tubes. The probe consists of eight strain-gauged cantilever beams that track changes in diameter, giving a measurement resolution of 20 μm.

A slightly more complicated method of effecting light intensity modulation is the variable shutter sensor shown in Figure 13.9. This consists of two fixed fibers with two collimating lenses and a variable shutter between them. Movement of the shutter changes the intensity of light transmitted between the fibers. This is used to measure the displacement of various devices such as Bourdon tubes, diaphragms, and bimetallic thermometers.

Yet another type of intrinsic sensor uses cable where the core and cladding have similar refractive indices but different temperature coefficients. This is used as a temperature sensor. Temperature rises cause the refractive indices to become even closer together and losses from the core to increase, thus reducing the quantity of light transmitted.

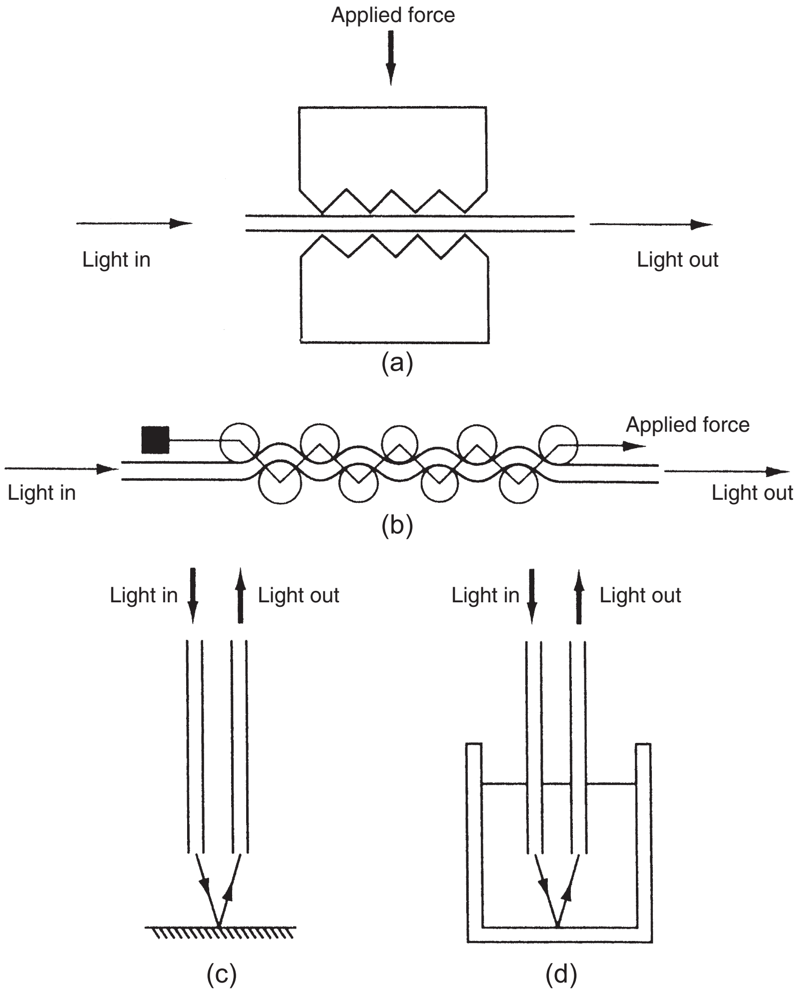

Figure 13.8
Intensity-modulating sensors. (a) Simple pressure sensor; (b) roller-chain pressure sensor (microbend sensor); (c) proximity sensor; (d) pH sensor.

Refractive index variation is also used in a form of intrinsic sensor used for cryogenic leak detection. The fiber used for this has a cladding whose refractive index becomes greater than that of the core when it is cooled to cryogenic temperatures. The fiber optic cable is laid in the location where cryogenic leaks might occur. If any leaks do occur, light traveling in the core is transferred to the cladding, where it is attenuated. Cryogenic leakage is thus indicated by monitoring the light transmission characteristics of the fiber.

A further use of refractive index variation is found in devices that detect oil in water. They use a special form of cable where the cladding used is sensitive to oil. Any oil present diffuses into the cladding and changes the refractive index, thus increasing light losses

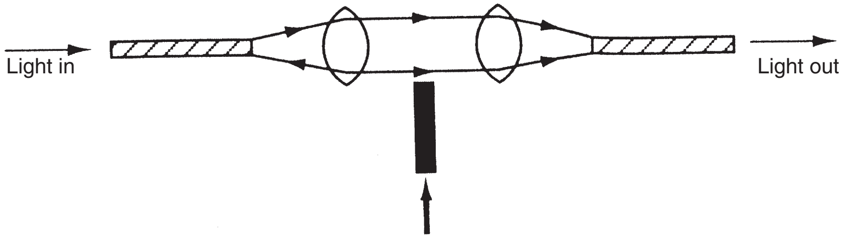

Figure 13.9
Variable shutter sensor.

from the core. Unclad fibers are used in a similar way. In these, any oil present settles on the core and allows light to escape.

The *cross-talk sensor* measures several different variables by modulating the intensity of light transmitted. It consists of two parallel fibers that are close together and where one or more short lengths of adjacent cladding are removed from the fibers. When immersed in a transparent liquid, there are three different effects that each causes a variation in the intensity of light transmitted. Thus, the sensor can perform three separate functions. First, it can measure temperature according to the temperature-induced variation in the refractive index of the liquid. Second, it can act as a level detector, as the transmission characteristics between the fiber changes according to the depth of the liquid. Third, it can measure the refractive index of the liquid itself when used under controlled temperature conditions.

The refractive index of a liquid can be measured in an alternative way by using an arrangement where light travels across the liquid between two cable ends that are fairly close together. The angle of the cone of light emitted from the source cable, and hence the amount of light transmitted into the detector, is dependent on the refractive index of the liquid.

The use of materials where the fluorescence varies according to the value of the measurand can also be used as part of intensity-modulating intrinsic sensors. Fluorescence-modulating sensors can give very high sensitivity and are potentially very attractive in biomedical applications where requirements exist to measure very small quantities such as low oxygen and carbon monoxide concentrations, low blood pressure levels, etc. Similarly, low concentrations of hormones, steroids, etc. may be measured.

Further examples of intrinsic fiber optic sensors that modulate light intensity are described later in Chapter 17 (level measurement) and Chapter 19 (measuring small displacements).

As mentioned previously, the phase, polarization, wavelength, and transit time can be modulated as well as intensity in intrinsic sensors. Monomode cables are used almost exclusively in these types of intrinsic sensor.

Phase modulation normally requires a coherent (laser) light source. It can provide very high sensitivity in displacement measurement but cross sensitivity to temperature and strain degrades its performance. Additional problems are maintaining frequency stability of the light source and manufacturing difficulties in coupling the light source to the fiber. Various versions of this class of instrument exist to measure temperature, pressure, strain, magnetic fields, and electric fields. Field-generated quantities such as electric current and voltage can also be measured. In each case, the measurand causes a phase change between a measuring and a reference light beam that is detected by an interferometer.

The principle of phase modulation has also been used in the fiber optic accelerometer (where a mass subject to acceleration rests on a fiber), and in fiber strain gauges (where two fibers are fixed on the upper and lower surfaces of a bar under strain). The fiber optic gyroscope described in Chapter 20 is a further example of a phase-modulating device.

Devices using polarization modulation require special forms of fiber that maintain polarization. Polarization changes can be affected by electrical fields, magnetic fields, temperature changes, and mechanical strain. Each of these parameters can therefore be measured by polarization modulation.

Various devices that modulate the wavelength of light are used for special purposes. However, the only common wavelength-modulating fiber optic device is the form of laser Doppler flowmeter that uses fiber optic cables, as described in Chapter 16.

Fiber optic devices using modulation of the transit time of light are uncommon because of the speed of light. Measurement of the transit time for light to travel from a source, be reflected off an object, and travel back to a detector, is only viable for extremely large distances. However, a few special arrangements have evolved which use transit time modulation. These include instruments such as the optical resonator, which can measure both mechanical strain and temperature. Temperature-dependent wavelength variation also occurs in semiconductor crystal beads (e.g., aluminum gallium arsenide). This is bonded to the end of a fiber optic cable and excited from an LED at the other end of the cable. Light from the LED is reflected back along the cable by the bead at a different wavelength. Measurement of the wavelength change allows temperatures in the range up to 200 °C to be measured accurately. A particular advantage of this sensor is its small size, typically 0.5 mm diameter at the sensing tip. Finally, to complete the catalog of transit time devices, the frequency modulation in a piezoelectric quartz crystal used for gas sensing can also be regarded as a form of time domain modulation.

Extrinsic sensors

Extrinsic fiber optic sensors use a fiber optic cable, normally a multimode one, to transmit modulated light from a conventional sensor such as a resistance thermometer. A major feature of extrinsic sensors, which makes them so useful in such a large number of applications, is their ability to reach places that are otherwise inaccessible. One example of this is the insertion of fiber optic cables into the jet engines of aircraft to measure temperature by transmitting radiation into a radiation pyrometer located remotely from the engine. Fiber optic cable can be used in the same way to measure the internal temperature of electrical transformers, where the extreme electromagnetic fields present make other measurement techniques impossible.

An important advantage of extrinsic fiber optic sensors is the excellent protection against noise corruption that they give to measurement signals. Unfortunately, the output of many sensors is not in a form that can be transmitted by a fiber optic cable, and conversion into a suitable form must therefore take place prior to transmission. For example, a platinum resistance thermometer (PRT) translates temperature changes into resistance changes. The PRT therefore needs electronic circuitry to convert the resistance changes into voltage signals and thence into a modulated light format, and this in turn means that the device needs a power supply. This complicates the measurement process and means that low voltage power cables must be routed with the fiber optic cable to the transducer. One particular adverse effect of this is that the advantage of intrinsic safety is lost. One solution to this problem is to use a power source in the form of electronically generated pulses driven by a lithium battery. Alternatively, power can be generated by transmitting light down the fiber optic cable to a photocell. Both of these solutions provide intrinsically safe operation.

Piezoelectric sensors lend themselves particularly to use in extrinsic sensors because the modulated frequency of a quartz crystal can be readily transmitted into a fiber optic cable by fitting electrodes to the crystal that are connected to a low power LED. Resonance of the crystal can be created either by electrical means or by optical means using the photothermal effect. The photothermal effect describes the principle where, if light is pulsed at the required oscillation frequency and directed at a quartz crystal, the localized heating, and thermal stress caused in the crystal results in it oscillating at the pulse frequency. Piezoelectric extrinsic sensors can be used as part of various pressure, force, and displacement sensors. At the other end of the cable, a phase-locked loop is typically used to measure the transmitted frequency.

Fiber optic cables are also now commonly included in digital encoders, where the use of fibers to transmit light to and from the discs allows the light source and detectors to be located remotely. This allows the devices to be smaller, which is a great advantage in many applications where space is at a premium.

Distributed sensors

A number of discrete sensors can be distributed along a fiber optic cable to measure different physical variables along its length. Alternatively, sensors of the same type, which are located at various points along a cable, provide distributed sensing of a single measured variable.

13.10 Ultrasonic Transducers

Ultrasonic devices are used in many fields of measurement, particularly for measuring fluid flow rates, liquid levels, and translational displacements. Details of such applications can be found in later chapters.

Ultrasound is a band of frequencies in the range above 20 kHz, that is, above the sonic range that humans can usually hear. Measurement devices that use ultrasound consist of one device that transmits an ultrasound wave and another device that receives the wave. Changes in the measured variable are determined either by measuring the change in time taken for the ultrasound wave to travel between the transmitter and receiver, or alternatively, by measuring the change in phase or frequency of the transmitted wave.

The most common form of ultrasonic element is a piezoelectric crystal contained in a casing, as illustrated in Figure 13.10. Such elements can operate interchangeably as either a transmitter or receiver. These are available with operating frequencies that vary between 20 kHz and 15 MHz. The principles of operation, by which an alternating voltage generates an ultrasonic wave and vice versa, have already been covered in the section above on piezoelectric transducers.

For completeness, mention should also be made of capacitive ultrasonic elements. These consist of a thin, dielectric membrane between two conducting layers. The membrane is stretched across a backplate and a bias voltage is applied. When a varying voltage is applied to the element, it behaves as an ultrasonic transmitter and an ultrasound wave is produced. The system also works in the reverse direction as an ultrasonic receiver. Elements with resonant frequencies in the range between 30 kHz and 3 MHz can be obtained.

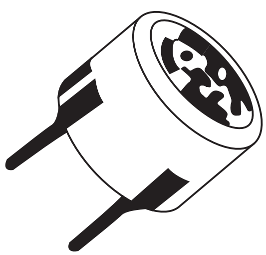

Figure 13.10
Ultrasonic sensor.

13.10.1 Transmission Speed

The transmission speed of ultrasound varies according to the medium through which it travels. Transmission speeds for some common media are given in Table 13.1.

When transmitted through air, the speed of ultrasound is affected by environmental factors such as temperature, humidity, and air turbulence. Of these, temperature has the largest effect. The velocity of sound through air varies with temperature according to:

$$V = 331.6 + 0.6T \ \ \mathrm{m/s} \tag{13.2}$$

where T is the temperature in °C. Thus, even for a relatively small temperature change of 20° from 0 to 20 °C, the velocity changes from 331.6 to 343.6 m/s.

Humidity changes have a much smaller effect on speed. If the relative humidity increases by 20%, the corresponding increase in the transmission velocity of ultrasound is 0.07% (corresponding to an increase from 331.6 to 331.8 m/s at 0 °C).

Changes in air pressure itself have negligible effect on the velocity of ultrasound. Similarly, air turbulence normally has no effect. However, if turbulence involves currents of air at different temperatures, then random changes in ultrasound velocity occur according to Eqn (13.2).

13.10.2 Directionality of Ultrasound Waves

An ultrasound element emits a spherical wave of energy, although the peak energy is always in a particular direction. The magnitude of energy emission in any direction is a function of the angle made with respect to the direction that is normal to the face of the ultrasonic element. The peak emission occurs along a line that is normal to the transmitting face of the ultrasonic element, and this is loosely referred to as the "direction of travel." At any angle other than the "normal" one, the magnitude of transmitted energy is less than the peak value. Figure 13.11 shows the characteristics of the emission for a range of ultrasonic elements. This is shown in terms of the attenuation of the transmission magnitude (measured in dB) as the angle with respect to the "normal" direction increases. For many purposes, it is useful to treat the transmission as a conical volume of energy,

Table 13.1: Transmission speed of ultrasound through different media

Medium	Velocity (m/s)
Air	331.6
Water	1440
Wood (pine)	3320
Iron	5130
Rock (granite)	6000

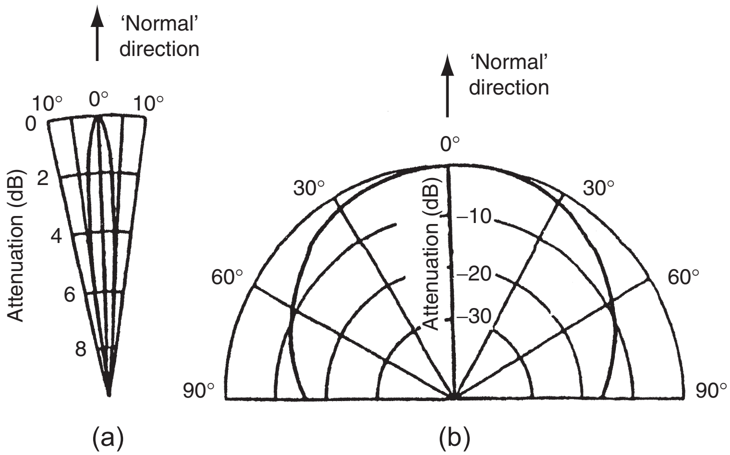

Figure 13.11
Ultrasonic emission characteristics. (a) Narrow angle of peak emission; (b) wide angle of peak emission.

with the edges of the cone defined as the transmission angle where the amplitude of the energy in the transmission is −6 dB compared with the peak value (i.e., where the amplitude of the energy is half that in the normal direction). Using this definition, a 40-kHz ultrasonic element has a transmission cone of ±50° and a 400-kHz one has a transmission cone of ±3°.

It should be noted that air currents can deflect ultrasonic waves such that the peak emission is no longer normal to the face of the ultrasonic element. It has been shown experimentally that an air current moving with a velocity of 10 km/h deflects an ultrasound wave by 8 mm over a distance of 1 m.

13.10.3 Relationship between Wavelength, Frequency, and Directionality of Ultrasound Waves

The frequency and wavelength of ultrasound waves are related according to:

$$\lambda = v/f \tag{13.3}$$

where λ is the wavelength, v is the velocity, and f is the frequency of the ultrasound waves.

This shows that the relationship between λ and f depends on the velocity of the ultrasound and hence varies according to the nature and temperature of the medium through which it travels. Table 13.2 compares the nominal frequencies, wavelengths, and transmission cones (−6 dB limits) for three different types of ultrasonic element.

It is clear from Table 13.2 that the directionality (cone angle of transmission) reduces as the nominal frequency of the ultrasound transmitter increases. However, the cone angle

Table 13.2: Comparison of frequency, wavelength, and cone angle for various ultrasonic transmitters

Nominal frequency (kHz)	23	40	400
Wavelength (in air at 0 °C)	14.4	8.3	0.83
Cone angle of transmission (−6 dB limits)	±80°	±50°	±3°

also depends on factors other than the nominal frequency, particularly on the shape of the transmitting horn in the element, and different models of ultrasonic element with the same nominal frequency can have substantially different cone angles.

13.10.4 Attenuation of Ultrasound Waves

Ultrasound waves suffer attenuation in the amplitude of the transmitted energy according to the distance traveled. The amount of attenuation also depends on the nominal frequency of the ultrasound and the adsorption characteristics of the medium through which it travels. The amount of adsorption depends not only on the type of transmission medium but also on the level of humidity and dust in the medium.

The amplitude X_d of the ultrasound wave at a distance d from the emission point can be expressed as:

$$\frac{X_d}{X_0} = \frac{\sqrt{e^{-\alpha d}}}{fd} \tag{13.4}$$

where X_0 is the magnitude of the energy at the point of emission, f is the nominal frequency of the ultrasound, and α is the attenuation constant that depends on the ultrasound frequency, the medium that the ultrasound travels through and any pollutants in the medium such as dust or water particles.

13.10.5 Ultrasound as a Range Sensor

The basic principles of an ultrasonic range sensor are to measure the time between transmission of a burst of ultrasonic energy from an ultrasonic transmitter and receipt of that energy by an ultrasonic receiver. Then, the distance d can be calculated from:

$$d = vt \tag{13.5}$$

where v is the ultrasound velocity and t is the measured energy transit time. An obvious difficulty in applying this equation is the variability of v with temperature according to Eqn (13.2). One solution to this problem is to include an extra ultrasonic transmitter/receiver pair in the measurement system in which the two elements are positioned a known distance apart. Measurement of the transmission time of energy between this fixed pair provides the necessary measurement of velocity and hence compensation for any environmental temperature changes.

The degree of directionality in the ultrasonic elements used for range measurement is unimportant as long as the receiver and transmitter are positioned carefully so as to face each other exactly (i.e., such that the "normal" lines to their faces are coincident). Thus, directionality imposes no restriction on the type of element suitable for range measurement. However, element choice is restricted by the attenuation characteristics of different types of element, and relatively low-frequency elements have to be used for the measurement of large ranges.

Measurement resolution and accuracy

The best measurement resolution that can be obtained with an ultrasonic ranging system is equal to the wavelength of the transmitted wave. As wavelength is inversely proportional to frequency, high-frequency ultrasonic elements would seem to be preferable. For example, while the wavelength and hence resolution for a 40-kHz element is 8.6 mm at room temperature (20 °C), it is only 0.86 mm for a 400-kHz element. However, choice of element also depends on the required range of measurement. The range of higher-frequency elements is much reduced compared with low-frequency ones due to the greater attenuation of the ultrasound wave as it travels away from the transmitter. Hence, choice of element frequency has to be a compromise between measurement resolution and range.

The best measurement accuracy obtainable is equal to the measurement resolution value, but this is only achieved if the electronic counter used to measure the transmission time starts and stops at exactly the same point in the ultrasound cycle (usually the point in the cycle corresponding to peak amplitude is used). However, the sensitivity of the ultrasonic receiver also affects measurement accuracy. The amplitude of the ultrasound wave that is generated in the transmitter ramps up to full amplitude in the manner shown in Figure 13.12. The receiver has to be sensitive enough to detect the peak of the first cycle, which can usually be arranged. However, if the range of measurement is large, attenuation of the ultrasound wave may cause the amplitude of the first cycle to become less than the threshold level that the receiver is set to detect. In this case, only the second cycle will be detected and there will be an additional measurement error equal to one wavelength. For large transmission distances, even the second cycle may be undetected, meaning that the receiver only "sees" the third cycle.

13.10.6 Effect of Noise in Ultrasonic Measurement Systems

Signal levels at the output of ultrasonic measurement systems are usually of low amplitude and are therefore prone to contamination by electromagnetic noise. Because of this, it is

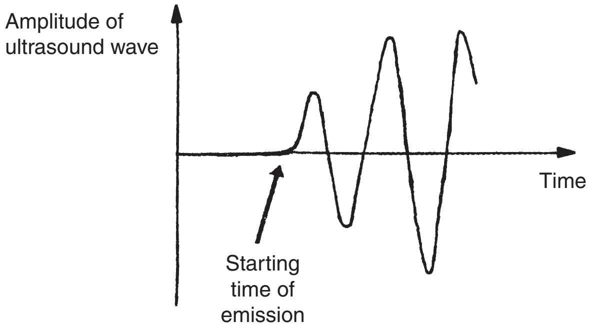

Figure 13.12
Ramp-up of ultrasonic wave after emission.

necessary to use special precautions such as making ground (earth) lines thick, using shielded cables for transmission of the signal from the ultrasonic receiver and locating the signal amplifier as close to the receiver as possible.

Another potentially serious form of noise is background ultrasound produced by manufacturing operations in the typical industrial environment that many ultrasonic range measurement systems operate. Analysis of industrial environments has shown that ultrasound at frequencies up to 100 kHz is generated by many operations and some operations generate ultrasound at higher frequencies up to 200 kHz. There is not usually any problem if ultrasonic measurement systems operate at frequencies above 200 kHz, but these often have insufficient range for the needs of the measurement situation. In these circumstances, any objects that are likely to generate energy at ultrasonic frequencies should be covered in sound-absorbing material such that interference with ultrasonic measurement systems is minimized. The placement of sound-absorbing material around the path that the measurement ultrasound wave travels along contributes further toward reducing the effect of background noise. A natural solution to the problem is also partially provided by the fact that the same processes of distance traveled and adsorption that attenuate the amplitude of ultrasound waves traveling between the transmitter and receiver in the measurement system also attenuate ultrasound noise that is generated by manufacturing operations.

Because ultrasonic energy is emitted at angles other than the direction that is normal to the face of the transmitting element, a problem arises in respect of energy that is reflected off some object in the environment around the measurement system and back into the ultrasonic receiver. This has a longer path than the direct one between the transmitter and receiver and can cause erroneous measurements in some circumstances. One solution to this is to arrange for the transmission-time counter to stop as soon as the receiver first detects the ultrasound wave. This will usually be the wave that has traveled along the direct path, and so no measurement error is caused as long as the rate at which ultrasound pulses are emitted is such that the next burst is not emitted until all reflections from the previous pulse have died down. However, in circumstances where the direct path becomes obstructed by some obstacle, the counter will only be stopped when the reflected signal is detected by the receiver, giving a potentially large measurement error.

13.10.7 Exploiting Doppler Shift in Ultrasound Transmission

The Doppler effect is evident in all types of wave motion and describes the apparent change in frequency of the wave when there is relative motion between the transmitter and receiver. If a continuous ultrasound wave with velocity v and frequency f takes t seconds to travel from a source S to a receiver R, then R will receive ft cycles of sound during time t (see Figure 13.13).

Suppose now that R moves toward S at velocity r (with S stationary). R will receive rt/λ extra cycles of sound during time t, increasing the total number of sound cycles received to $(ft + rt/\lambda)$. With $(ft + rt/\lambda)$ cycles received in t seconds, the apparent frequency f' is given by:

$f' = \frac{ft+rt/\lambda}{t} = f + r/\lambda = f + \frac{rf}{v} = \frac{f(r+v)}{v}$ (using the relation $\frac{1}{\lambda} = \frac{f}{v}$ from Eqn (13.3)).

The frequency difference Δf can be expressed as: $\Delta f = f' - f = \frac{f(v+r)}{v} - f = \frac{fr}{v}$, from which the velocity of the receiver r can be expressed as: $r = v\Delta f/f$.

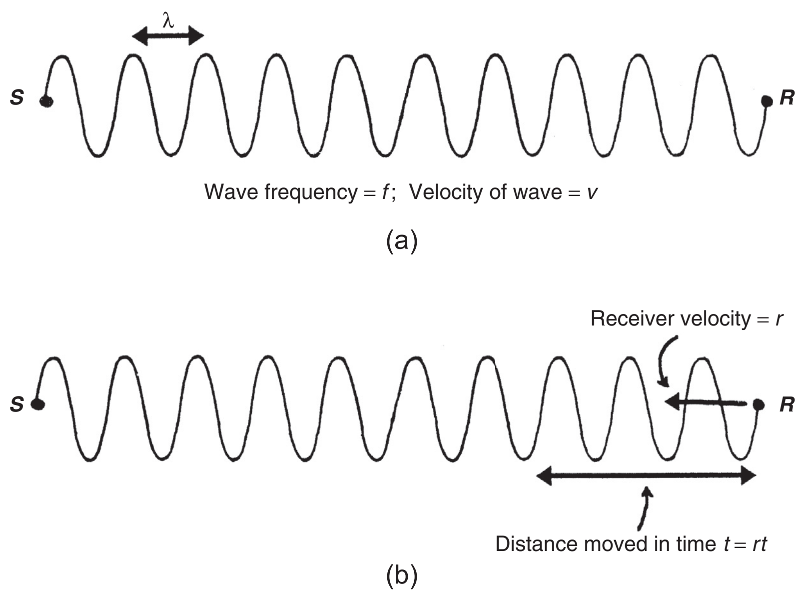

Figure 13.13
Illustration of Doppler effect. (a) Source (S) and Receiver (R) stationary; (b) Receiver (R) moving towards Sources (S).

Similarly, it can be shown that, if R moves away from S with velocity r, f' is given by:

$$f' = \frac{f(v-r)}{v} \quad \text{and} \quad \Delta f = -\frac{fr}{v}.$$

If the ultrasound source moves toward the stationary receiver at velocity s, it will move a distance st in time t and the ft cycles that are emitted during time t will be compressed into a distance $(vt-st)$.

Hence, the apparent wavelength λ' will be given by:

$$\lambda' = \frac{vt-st}{ft} = \frac{v-s}{f}.$$

Using Eqn (13.3), this can be expressed alternatively as $f' = \frac{v}{\lambda'} = \frac{vf}{v-s}$.

Similarly, with S moving away from R, it can be shown that $f' = \frac{vf}{v+s}$.

Thus, the velocity of an ultrasound receiver moving with respect to an ultrasound source can be calculated from the measured ratio between the real and apparent frequencies of the wave. This is used in devices like the Doppler shift flowmeter.

13.11 Nuclear Sensors

Nuclear sensors are uncommon measurement devices, partly because of the strict safety regulations that govern their use, and partly because they are usually expensive. Some very low level radiation sources are now available that largely overcome the safety problems, but measurements are then prone to contamination by background radiation. The principle of operation of nuclear sensors is very similar to optical sensors in that radiation is transmitted between a source and a detector through some medium in which the magnitude of transmission is attenuated according to the value of the measured variable. Cesium 137 is commonly used as a gamma ray source and a sodium iodide device is commonly used as a gamma ray detector. The latter gives a voltage output that is proportional to the radiation incident upon it. One current use of nuclear sensors is in a noninvasive technique for measuring the level of liquid in storage tanks (see Chapter 17). They are also used in mass flow rate measurement (see Chapter 16) and in medical scanning applications (Webster, 2009).

13.12 Microsensors (MEMS Sensors)

Microsensors are two- and three-dimensional micromachined structures that have smaller size, improved performance, better reliability, and lower production costs than many alternative forms of sensor. They are part of the wider class of *microelectromechanical system (MEMS) devices* that also includes microactuators. Typical sizes of microsensors range between 10 μm (0.01 mm or 10^{-5} m) up to 5 mm. The defining feature of any MEMS device is an element with some sort of mechanical functionality integrated with microelectronics. Microsensors can be regarded as miniature transducers, since they convert energy in the form of a measured mechanical signal into energy in electrical form. Individual devices vary from simple ones where the mechanical part does not move to much more complex ones involving several moving elements. Currently, devices to measure temperature, pressure, force, acceleration, rotational velocity, humidity, sound, magnetic fields, radiation, optical, biological, biomedical, and chemical parameters are either in production or at advanced stages of research.

Microsensors are usually constructed from a silicon semiconductor material, but are sometimes fabricated from other materials such as metals, plastics, polymers, glasses, and ceramics that are deposited on a silicon base. Silicon is an ideal material for sensor construction because of its excellent mechanical properties. Its tensile strength and Young's modulus is comparable to that of steel, while its density is less than that of aluminum. Sensors made from a single crystal of silicon remain elastic almost to the breaking point, and mechanical hysteresis is very small. In addition, silicon has a very low coefficient of thermal expansion and can be exposed to extremes of temperature and most gases, solvents, and acids without deterioration. This means that silicon-based sensors suffer very little fatigue and consequently have very long life (service life in terms of billions of operations are often quoted).

One downside of silicon is the relatively large expense in producing it owing to the complexity of the crystal silicon structure. This is why other materials are often used as an alternative to silicon. *Polymer-based microsensors* can be produced much more cheaply using either embossing, injection molding, or stereolithography, and these are used in applications like disposable blood testing devices. *Ceramic-based microsensors* made from various ceramic materials are also cheaper than silicon devices. *Metal-based microsensors* are made from various metals including aluminum, chromium, copper, gold, nickel, platinum, silver, titanium, and tungsten, using manufacturing techniques that include electroplating, sputtering, and evaporation processes. These are cheaper than silicon devices and, while their mechanical properties are inferior to those of silicon, they are still quite reliable.

Microengineering techniques are an essential enabling technology for microsensors, which are designed so that their electromechanical properties change in response to a change in the measured parameter. Many of the techniques used for integrated circuit (IC) manufacture are also used in sensor fabrication, common techniques being crystal growing and polishing, thin film deposition, ion implantation, wet and dry chemical and laser etching, and photolithography. However, apart from standard IC production techniques, some special techniques are also needed in addition to produce the 3D structures that are unique to some types of microsensor. The various manufacturing techniques are also used to form sensors directly in silicon crystals and films. Typical structures have forms such as thin diaphragms and cantilever beams and bridges.

While the small size of a microsensor is of particular benefit in many applications, it also leads to some problems that require special attention. For example, microsensors typically have very low capacitance. This makes the output signals very prone to noise contamination. Hence, it is usually necessary to integrate microelectronic circuits that perform signal processing in the device, which therefore becomes a *smart microsensor*. Another problem is that microsensors generally produce output signals of very low magnitude. This requires the use of special types of analog-to-digital converter that can cope with such low-amplitude input signals. One suitable technique is sigma-delta conversion. This is based on charge balancing techniques and gives better than 16 bit accuracy in less than 20 ms (Riedijk and Huijsing, 1997). Special designs can reduce conversion time down to less than 0.1 ms if necessary. The latest trend is to incorporate both analog-to-digital conversion and amplification within the microsensor device. The very latest generation of microsensors currently under development includes digital intelligence to provide linearization, calibration, and temperature compensation functions. Even smaller scale devices are also being developed, which have been given the name of nanosensors.

Microsensors are currently used most commonly for measuring pressure, acceleration, force, and chemical parameters. They are used in particularly large numbers in the automotive industry, where unit prices can be very low. Microsensors are also widely used in medical applications, particularly for blood pressure measurement.

Mechanical microsensors transform measured variables such as force, pressure, and acceleration into a displacement. The displacement is usually measured by capacitive or piezoresistive techniques, although some devices use other technologies such as resonant frequency variation, resistance change, inductance change, the piezoelectric effect, and changes in magnetic or optical coupling. The design of a cantilever beam microaccelerometer is shown in Figure 19.15. The proof mass within this is about 100 μm across and the typical deflection measured is of the order of 1 μm (10^{-3} mm).

An alternative capacitive microaccelerometer provides a calibrated, compensated, and amplified output. It has a capacitive silicon microsensor to measure displacement of the proof mass. This is integrated with a signal-processing chip and protected by a plastic enclosure. The capacitive element has a 3D structure, which gives a higher measurement sensitivity than surface-machined elements.

Microsensors to measure many other physical variables are either in production or at advanced stages of research. Microsensors measuring magnetic field are based on a number of alternative technologies such as Hall effect, magnetoresistors, magnetodiodes, and magnetotransistors. Radiation microsensors are made from silicon p-n diodes or avalanche photodiodes and can detect radiation over wavelengths from the visible spectrum to infrared. Microsensors in the form of a micro thermistor, a p-n thermodiode or a thermotransistor are used as digital thermometers. Microsensors have also enabled measurement techniques that were previously laboratory-based ones to be extended into field instruments. Examples are spectroscopic instruments and devices to measure viscosity.

As well as current research expanding the applications and functionality of microsensors, there is also work going that is looking at ways of integrating microactuators with microsensors. The aim of this next stage of research is to fabricate a microsensor, a microactuator, and controlling microelectronics onto a single silicon substrate. When this is achieved, this entire control system on a single chip will represent a very important technological breakthrough. These will have application in areas like environmental control, where microsensors measure environmental parameters and microactuators affect control action in the form of pumping, filtering, regulating, or positioning operations.

13.13 Nanosensors (NEMS Sensors)

The most recent advance in sensor miniaturization is the development of nanosensors based on nanotechnology. These are part of the wider class of *nanoelectromechanical system (NEMS) devices* that includes nanoactuators as well as nanosensors. Nanosensors vary from 1 to 100 nm in size (10^{-9} to 10^{-7} m) and are made from thin layers of either metal films or semiconductors. These are fabricated using similar techniques to MEMS sensors, but employing more advanced forms of etching, optical lithography, or electron beam lithography. They are typically used as accelerometers, biological sensors, and sensors for airborne chemicals. In time, they are expected to replace MEMS devices in many applications, since NEMS devices have advantages in terms of lower production costs and reduced power consumption, apart from their smaller size.

13.14 Summary

This chapter has revealed 12 different physical principles that are used in measurement sensors. As noted in the introduction to the chapter, the chosen order of presentation of these principles has been arbitrary and is not intended to imply anything about the relative popularity of these various principles.

The first principle covered was capacitance change, which we found was based on two capacitor plates with either a variable or fixed distance between them. We learned that sensors with a variable distance between the plates are primarily used for displacement measurement, either as displacement sensors in their own right, or to measure the displacement within certain types of pressure, sound, and acceleration sensor. The alternative type of capacitive sensor where the distance between the plates is fixed is typically used to measure moisture content, humidity values, and liquid level.

Moving on to the resistance change principle, we found that this is used in a wide range of devices for temperature measurement (resistance thermometers and thermistors), and displacement measurement (strain gauges and piezoresistive sensors). We also noted that some moisture meters work on the resistance-variation principle.

We then looked at sensors that use the magnetic phenomena of inductance, reluctance, and eddy currents. We saw that the principle of inductance change was mainly used to measure translational and rotational displacements, reluctance change was commonly used to measure rotational velocities, and the eddy current effect was typically used to measure the displacement between a probe and a very thin metal target such as the steel diaphragm of a pressure sensor.

Next we looked at the Hall effect. This measures the magnitude of a magnetic field and is commonly used in a proximity sensor. It is also employed in computer keyboard push buttons.

We then moved on to piezoelectric transducers. These generate a voltage when a force is applied to them. Alternatively, if a voltage is applied to them, an output force is produced. A common application is in ultrasonic transmitters and receivers. They are also used as displacement transducers, particularly as part of devices measuring acceleration, force, and pressure.

Our next subject of study was strain gauges. These devices exploit the physical principle of a change in resistance when the metal wire that they are made from is stretched or strained. They can detect very small displacements and are typically used within devices like diaphragm pressure sensors to measure the small displacement of the diaphragm when a pressure is applied to it. We looked into some of the science involved in strain gauge design, particularly in respect of the alternative materials used for the active element.

Moving on, we then looked at piezoresistive sensors. We saw that these could be regarded as a semiconductor strain gauge, since they consist of a semiconductor material whose resistance varies when it is compressed or stretched. They are commonly used to measure the displacement in diaphragm pressure sensors where the resistance change for a given amount of diaphragm displacement is much greater than is obtained in metal strain gauges, thus leading to better measurement accuracy. They are also used as accelerometers. Before concluding this discussion, we also observed that the term "piezoresistive sensor" is sometimes (but incorrectly) used to describe metal strain gauges as well as semiconductor ones.

In our discussion of optical sensors which followed, we observed first of all that these could involve both transmission of light through air and transmission along a fiber optic cable. Air path optical sensors exploit the transmission of light from a source to a detector across an open air path and are commonly used to measure proximity, translational motion, rotational motion, and gas concentration.

Sensors that involve the transmission of light along a fiber optic cable are commonly called fiber optic sensors. Their principle of operation is to translate the measured physical quantity into a change in either the intensity, phase, polarization, wavelength, or transmission time of the light carried along the cable. We went on to see that two kinds of fiber optic sensor can be distinguished, known as intrinsic sensors and extrinsic sensors. In intrinsic sensors, the fiber optic cable itself is the sensor, whereas in extrinsic sensors, the fiber optic cable is merely used to transmit the light to/from a conventional sensor. Our look at intrinsic sensors revealed that different forms of these are used to measure a very wide range of physical variables including proximity, displacement, pressure, pH, smoke intensity, acceleration, temperature, cryogenic leakage, oil content in water, liquid level, refractive index of a liquid, parameters in biomedical applications (oxygen concentration, carbon monoxide concentrations, blood pressure level, hormone concentration, steroid concentration), mechanical strain, magnetic field strength, electric field strength, electrical current, electrical voltage, angular position and acceleration in gyroscopes, liquid flow rate, and gas presence. By comparison, the range of physical variables measured by extrinsic sensors is much less, being limited mainly to the measurement of temperature, pressure, force, and displacement (both linear and angular).

This then led on to a discussion of ultrasonic sensors. These are commonly used to measure range, translational displacements, fluid flow rate, and liquid level. We learned that ultrasonic sensors work in one of two ways, either by measuring the change in time taken for an ultrasound wave to travel between a transmitter and receiver, or by measuring the change in phase or frequency of the transmitted wave. While both of these principles are simple in concept, we went on to see that the design and use of ultrasonic sensors suffers from a number of potential problems. First, the transmission speed can be affected by environmental factors, temperature changes being a particular problem and humidity changes to a lesser extent. The nominal operating frequency of ultrasonic elements also has to be carefully chosen according to the intended application as this affects the effective amount of spread of the transmitted energy on either side of the direction normal to the face of the transmitting element. Attenuation of the transmitted wave can cause problems. This is particularly so when ultrasonic elements are used as range sensors. This follows from the start-up nature of a transmitted ultrasonic wave, which exhibits an increasing amplitude over the first two or three cycles of the emitted energy wave. Attenuation of the wave as it travels over a distance may mean that the detector fails to detect the first or even second cycle of the transmitted wave, causing an error that is equal to one or two times the ultrasound wavelength. Noise can also cause significant problems in the operation of ultrasonic sensors, since they are easily contaminated by electromagnetic noise and are particularly affected by noise generated by manufacturing operations at a similar frequency to that of the ultrasonic measuring system. Since there is some emission of ultrasonic energy at angles other than the normal direction to the face of the ultrasonic element, stray reflections of transmissions in these nonnormal directions by structures in the environment around the ultrasonic system may interfere with measurements.

The next type of sensor discussed was nuclear sensors. We learned that these did not enjoy widespread use, with the main applications being in noninvasive measurement of liquid level, mass flow rate measurement, and in some medical scanning applications. This limited number of applications is partly due to the health dangers posed to users by the radiation source that they use and partly due to their relatively high cost. Danger to users can largely be overcome by using low-level radiation sources but this makes measurements prone to contamination by background radiation.

Finally, we looked at microsensors (part of MEMS devices), which we learned were millimeter-sized, two- and three-dimensional micromachined structures that are usually made from silicon semiconductor materials but can sometimes be made from other materials. This type of sensors have smaller size, improved performance, better reliability, and lower production costs than many alternative forms of sensor and are used to measure temperature, pressure, force, acceleration, humidity, magnetic fields, radiation, chemical parameters, and some parameters in medical applications such as blood pressure. We also briefly looked at the ongoing research into nanosensors, which are the next level of miniaturization down from microsensors and are part of the class of devices called NEMS.

13.15 Problems

13.1 Describe the general working principles of capacitive sensors and discuss some applications of them.
13.2 Discuss some applications of resistive sensors.
13.3 What types of magnetic sensors exist and what are they mainly used for? Describe the mode of operation of each.
13.4 What are Hall effect sensors? How do they work and what are they used for?
13.5 How does a piezoelectric transducer work and what materials are typically used in their construction? Discuss some common applications of this type of device.
13.6 What is a strain gauge and how does it work? What are the problems in making and using a traditional metal-wire strain gauge and how have these problems been overcome in new types of strain gauge?
13.7 Discuss some applications of strain gauges.

13.8 What are piezoresistive sensors and what are they typically used for?

13.9 What are the principal advantages of an optical sensor? Discuss the mode of operation of the two main types of optical sensor.

13.10 What are air path optical sensors? Discuss their mode of operation, including details of light sources and light detectors used.

13.11 How do fiber optic sensors work. Discuss their use in intrinsic and extrinsic sensors.

13.12 Explain the basic principles of operation of ultrasonic sensors and discuss what they are typically used for?

13.13 What factors govern the transmission speed and directionality of ultrasonic waves?

13.14 Discuss the use of ultrasonic sensors in range-measuring systems, mentioning the effect of attenuation of the wave as it travels. How can the measurement resolution and accuracy be optimized?

13.15 Discuss the effects of extraneous noise in ultrasonic measurement systems. How can these effects be reduced?

13.16 Discuss the phenomenon of Doppler shift in ultrasound transmission and explain how this can be used in sensors.

13.17 Briefly explain the mode of operation of nuclear sensors. What applications do nuclear sensors have? Why are they not in common use in these applications?

13.18 What are microsensors and what advantages do they have compared to conventional sensors? How are they made and what applications are they used in?

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