# 4
# DISPLACEMENT

## 4.1 INTRODUCTION

Displacement is the vector representing a change in position of a body or a point with respect to a reference. It may be linear or rotational motion, expressed in absolute or relative terms. Many of the modern scientific and industrial observations need a very accurate measurement of this parameter. Being a fundamental quantity, the basic sensing device is widely adapted with suitable linkages for the measurement of many derived quantities, such as force, stress, pressure, velocity, and acceleration. The magnitude of measurement ranges from a few microns to a few centimetres in the case of linear displacement and a few seconds to 360° in the case of angular displacement.

A majority of displacement transducers sense the static or dynamic displacement by means of a sensing shaft or similar links mechanically coupled to the point or body whose motion is measured. Such attachments of both linear and angular transducers are usually of simple mechanical configurations, but the coupling must be primarily designed to avoid any slippage after it is fastened and thereby keep the back-lash minimum. For linear-displacement measurements, the common types employed are the threaded end, lug, clevis, and bearing couplings. Spring-loaded shafts may also be used for certain applications. A number of specialized types of displacement transducers operate without use of a mechanical linkage between the transducer and the object whose displacement is to be measured, as in the case of some of the electromagnetic, capacitive, and optical transducers.

## 4.2 PRINCIPLES OF TRANSDUCTION

Displacement transducers can be classified primarily on the basis of the transduction principle employed for the measurement. In this chapter only the electromechanical transducers which convert displacement quantities into electrical voltages/currents are dealt with.

The major electrical transduction principles used are:

(i) Variable resistance—potentiometric/strain gauge
(ii) Variable inductance/linear variable differential transformer/variable reluctance
(iii) Variable capacitance
(iv) Synchros and resolvers.

A number of additional types are also designed, depending upon the convenience and measurement accuracy required, such as digital output transducers, electro-optical devices, and the radioactive devices. In practice, potentiometric- and inductive-type devices are most widely used in scientific and engineering applications. The performance characteristics of a few selected variety displacement transducers are shown in Table 4.1

**Table 4.1** Characteristics of Linear Displacement Transducers

| Transduction Principle | Range mm | Linearity % F.S. | Repeatability (microns) | Temperature Range (°C) | Resolution (microns) | Frequency Response (Hz) | Remarks |
|---|---|---|---|---|---|---|---|
| 1. Resistive wire-wound potentiometer | 100 | 0.25 | 50 | –10 to 75 | 50 | 5 | Long ranges, economical, high output, and minimum electronics |
| Conductive strip potentiometer | 100 | 0.5 | 5 | –10 to 75 | 10 | 10 | Poor resolution and high noise |
| Cantilever with strain gauges | 10 | 0.5 | 50 | –10 to 70 | 10 | 100 | Versatile, small size, low range, and large reaction forces |
| 2. Inductive/variable reluctance | 5 | 0.5 | 0.5 | –20 to 75 | 2 | 100 | Small size, high resolution, non-contact type, and low range |
| Linear variable differential transformer | 50 | 0.1 | 0.5 | –10 to 75 | 1 | 1000 | Good linearity, high resolution, but interference due to magnetic field |
| Eddy current (proximity) | 10 | 0.75 | 5 | –20 to 80 | 2 | 5000 | Non-contact type, and high output |
| 3. Capacitive | | | | | | | Easy mechanical design, high temperature operation, error due to stray capacitance |
| (a) Variable area | 50 | 0.1 | 0.5 | – 40 to 200 | 0.1 | 50 | |
| (b) Variable gap | 5 | 0.5 | 2 | –10 to 500 | 0.1 | 2000 | |
| 4. Digital transducer | 10 to 500 | 0.1 | 0.5 | –0 to 55 | 0.5 | 100 | Long range, digital output, high accuracy and resolution, expensive and bulky |

### 4.2.1 Variable Resistance Device

Displacement transducers using potentiometric variable resistance transduction elements are invariably shaft-coupled devices. The sensing element is basically a resistance-potentiometer with a movable wiper contact attached to an insulated plunger type shaft, mechanically linking the point under measurement. The contact motion can be translation, rotation, or a combination of the two, thus allowing measurements of rotary or translatory displacements. They are relatively simple in construction, in the sense that a sliding contact (wiper) is made to move linearly over a resistance element which may be in the form of a wire or a conductive plastic film. The resistivity and temperature coefficient of the resistance element should be of such a value that the device operates with appreciable constant sensitivity over a wide temperature range. The constructional features of linear and rotary potentiometers are shown in Fig. 4.1 The three major elements critical in a potentiometric device are the winding wire, winding former, and wiper as shown in Figs 4.1 (a) and (b).

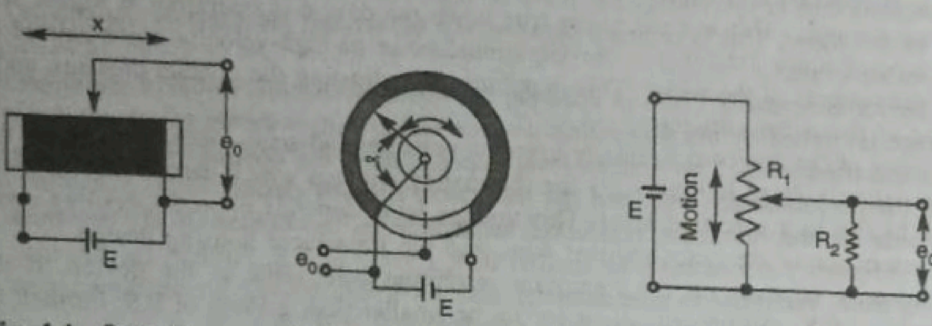


**Fig. 4.1** Potentiometric displacement transducer. (a) linear motion; (b) angular motion; (c) circuit arrangement

The winding wire is a precision drawn resistance wire with a diameter of about 25 to 50 microns and is wound over a cylindrical or a flat mandrel of ceramic, glass, or anodized aluminium. The wire is annealed in a reducing atmosphere to avoid any surface oxidation. Resistivity may vary normally from 0.4 μΩ-m to 1.3 μΩ-m, and temperature coefficient may vary from 0.002%/°C to 0.01%/°C. The wire should be strong, ductile, and protected from surface corrosion by enamelling or oxidation. The dimensional tolerance should be less than 1%, and the resistance stability with time should be of a very high order. The materials commonly employed are the alloys of copper-nickel, nickel-chromium, and silver-palladium. The winding can be linear, toroidal, or helical, and should possess uniform spacing and constant tension. The outer surface, except for the linear track of the wiper, is covered with a suitable insulating material to protect against dust and abrasion.

The wipers are spring elements made from tempered phosphor-bronze, beryllium-copper, or other precious metal alloys and are suitably shaped to move over the resistance element with minimum friction. The wiper contact force and contact resistance are important factors in the overall accuracy of the device. In some cases conductive lubricants are also used to reduce the friction. Leaf spring and dual wipers are designed for better contact and ability to withstand high shocks and vibration.

The main requirements for winding formers are good dimensional stability and surface insulation. Some of the recommended materials are ceramic, steatite, anodized aluminium, and moulded epoxies.

The whole transduction element described above can be employed for linear as well as angular displacement. The linear range depends very much on the mechanical design. The resistance value and the current-carrying capacity are chosen to suit the desired application; normal values are range 2 to 10 cm F.S., resistance 100 to 50,000 ohms, and current capacity 0.5 to 5 mA. The resolution of the device depends upon the wiper width, diameter of the resistance wire, and spacing between the windings. An optimum choice is sought for the highest precision and resolution. In the case of the wire wound element, the wiper wire diameter to spacing ratio is normally 10, and the resolution achievable is 0.05% to 0.1%. A linearity of the order of 0.1% can be achieved easily, as wires of uniform diameter and specific resistance are available. The plastic-film type is ideal for infinite resolution purposes, even though it is difficult to get a resolution better than 5 microns in practice.

Electrical noise is another factor normally exhibited by these devices and they are random in nature. Further, they depend on the current and speed of motion of the wiper. Wire-wound devices are relatively free from Johnson noise. But the contact noise caused by variation in contact resistance when the wiper moves along the potentiometer track is not negligible in many cases. The noise level increases with wear and tear and also with the contamination or oxidation of the track and the wiper surfaces. Sometimes, thermoelectric effects due to dissimilar materials used for the wiper and wire can also generate a voltage acting as a noise source. This is particularly true when the device is operating at higher temperatures. Yet another type of noise exhibited is the vibrational noise or high-velocity noise caused by jumping or bouncing movements of the wiper. This is reduced by adjusting the contact pressure and oscillatory characteristics of the wiper structure.

The sensitivity of the device is normally given as volts per full-scale mechanical travel of the wiper. The input excitation voltage is limited by the dissipating wattage which causes the temperature of the winding wire to rise to a specified level. This voltage level depends upon the cooling conditions, the thermal characteristics of the potentiometer wire, and the transducer housing design.

Inherent linearity depends on the minimum resolution achievable in the device. If the apparent resolution is $n$% of F.S., the linearity error cannot be smaller than $\pm$ ½$n$% of F.S. Further, the linearity is a function of the winding pitch, variations in wire diameter, and any irregularity in former dimensions and wiper movements. The normal value achievable for a standard unit is 0.1%

The resistance measurement can be carried out with a simple circuit, as shown in Fig 4.1(c). The circuit linearity is determined by the ratio of the total potentiometer resistance $R_1$ to the load resistance $R_2$ as indicated in the figure. A better scheme for measurement is the Wheatstone's bridge network with a suitable detector system (the bridge is analysed in detail in Chapter 5).

The major disadvantages of the potentiometer-type displacement transducer are poor dynamic response, susceptibility to vibration and shock, poor resolution, and presence of noise in signal.

Displacement transducers for very short stroke lengths can be designed with high precision using a bonded/unbonded strain-gauge type sensor. The motion to be measured is transferred to an elastic element, such as a cantilever beam, and the stresses developed on application of displacement is related to the motion. This principle is extended very much in the design of force, pressure, and acceleration transducers.

### 4.2.2 Variable Inductance Transducer

A simple and more popular type of displacement sensor is the variable-inductance type wherein the variation of inductance as a function of displacement is achieved either by variation in mutual inductances or self inductances. Devices operating on these principles are more widely known as linear variable differential transformers and variable reluctance sensors respectively.

***(a) Linear Variable Differential Transformer (LVDT)*** Linear variable differential transformer type of transducers find a number of applications in both measurement and control systems. The extremely fine resolution, high accuracy, and good stability make the device particularly suitable as a short-stroke, position-measuring device. Since a number of physical quantities, such as pressure, load, and acceleration can be measured in terms of mechanical deflection. LVDT forms the basic sensing element in all such measurements. The LVDT device is widely used as the basic element in extensometers, electronic comparators, thickness-measuring units, and level indicators. Some of the other important applications are in numerically-controlled machines and creep-testing machines.

The basic construction of the differential transformer is shown in Fig. 4.2(a) at three different core positions.

The linear variable differential transformer consists of a primary coil and two identical secondary coils, axially-spaced and wound on a cylindrical-coil former, with a rod-shaped magnetic core positioned centrally inside the coil assembly providing a preferred path for the magnetic flux linking the coils. The displacement to be measured is transferred to the magnetic core through suitable linkages.

When the primary coil is energized with an ac carrier wave signal, voltages are induced in each secondary section, the exact value depending upon the position of the magnetic core with respect to the centre of the coil assembly. If the core is symmetrically placed (electrically) with respect to the two secondary coils, equal voltages are induced in the two coils. When these two outputs are connected in phase opposition as shown in Fig. 4.2(b), the magnitude of the resultant voltage tends to a zero value. Such a balance point is termed 'the null position'. In practice, a small residual voltage is always present at a null position due to the presence of harmonics in the excitation signal and stray capacitance coupling between the primary and secondary windings. When the core is now displaced from the null position the induced voltage in the secondary towards which the core has moved increases while that in the other secondary decreases. This results in a differential voltage output from the transformer.

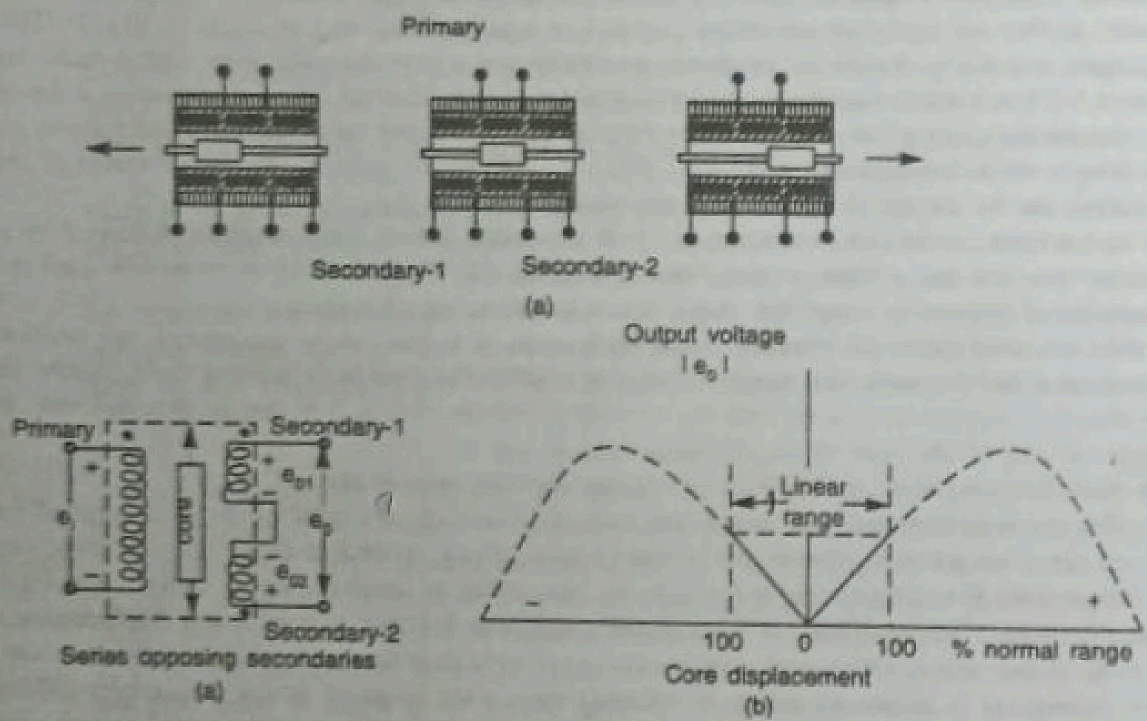


**Fig. 4.2** Linear variable differential transformer: (a) basic construction; (b) connection of secondary windings; (c) transfer characteristics

The signal output $e_o$ in relation to the other characteristics of the coil is given by[2]

$$e_o = \frac{16\pi^3 f I_p n_p n_s}{10^9 \ln\left(\frac{r_o}{r_i}\right)} \frac{2bx}{3w}\left(1 - \frac{x^2}{2b^2}\right) \tag{4.1}$$

where $f$ = excitation signal frequency, $I_p$ = primary current, $n_p$ = number of turns in primary, $n_s$ = number of turns in secondary, $b$ = width of the primary coil, $w$ = width of the secondary coil, $x$ = core displacement, $r_o$ = outer radius of the coil, and $r_i$ = inner radius of the coil.

With proper design of coils, the magnitude of the output signal is made to vary linearly with the mechanical displacement of the core on both sides with respect to the null position, as shown in Fig. 4.2(c). While the magnitude of the output voltages are ideally the same for equal core displacements on either side of the null, the phase difference between the output and input voltages changes by 180° when the core moves through the null position. In actual measurement, this phase change-over is measured with a phase-sensitive detector.

The sensitivity is proportional to the frequency $f$ and the primary current $I_p$, and for best linearity $x << b$. However, larger $I_p$ produces core saturation and an increase in the temperature of the coil, and hence results in larger harmonics at null position, making adjustment difficult. An increase in frequency produces a greater effect of stray capacitance, and in turn a large null voltage. In practice, the design is optimized for the lowest null voltage, highest linearity, and appropriate size.

The coils are wound on phenolic or ceramic formers to improve the dimensional stability. The coil former material should be strong and mechanically stable to guard against temperature effects and should be able to withstand elevated temperature and thermal shock.

The coils are wound with an enamelled copper wire possessing an insulation suitable for the ambient temperature specified. The transformer is then enclosed in ferromagnetic cases, providing full electrostatic and electromagnetic shielding. The moving core is made of ferromagnetic material of high permeability, selected for optimum performance in general use and heat treated to provide the best magnetic properties. The normal excitation voltage is 1.0 V at a carrier frequency of 2 kHz to 10 kHz. The carrier frequency is suitably chosen for optimum sensitivity and proper demodulation. The dynamic response of the LVDT is limited mainly by the excitation frequency; faithful linear characteristics are obtained for frequencies up to 0.1 times the carrier frequency. The normal ranges are ± 10 microns to ±10 mm, operating over a temperature range of $-40°$ to $+100°$ C. In general, the linear range is primarily dependent on the length of the primary and secondary coils.

The instrumentation can be carried out with a suitable carrier wave amplifer, followed by a phase sensitive detector and a filter, as described in Chapter 12. Phase detector is invariably used in all the measurement systems to avoid the ambiguity in the direction of motion.

With the availability of miniature integrated chips, it is feasible to incorporate the oscillator, the demodulator and the associated electronic circuitry within the transducer housing itself, thereby enabling the device to operate as a dc-dc system. An output voltage of 0 to 5 V can be obtained with an input supply of ± 15 V dc.

The main advantages of the LVDT type of displacement sensors are:

(i) *Mechanical:* Simplicity of design and ease of fabrication and installation, wide range of displacement; frictionless movement of core and hence infinite resolution; rugged construction; negligible operating force (core weight being low), and ability to operate even at higher temperatures.

(ii) *Electrical:* Output voltage is a linear and continuous function of mechanical displacement (linearity better than 0.25%), high sensitivity (2 mV/volt/10 microns at 4 kHz excitation); low output impedance (100 ohms); ability to operate over a wide range of carrier frequencies (50 Hz to 20 kHz); infinite resolution in output (theoretically limiting factors being signal to noise ratio and input stability conditions); and very low cross sensitivity.

***(b) Angular Displacement Measurement*** A rotary variable differential transformer is a very convenient device for the measurement of angular displacement. The device operates on the same principle as LVDT explained earlier, where the output voltage varies linearly with the angular position of the shaft. A typical unit is illustrated in Fig. 4.3.

A cardioid-shaped cam (rotor) of a magnetic material is used as the core. The input shaft fastened to the core is mounted at the centre of the coil former on which the primary and secondary are wound symmetrically. The cardioid shape of the rotor is so chosen as to produce a highly linear output over a specified angle of rotation. The shaft is mounted with miniature precision ball bearings to minimize friction and mechanical hysteresis. The main advantages of the unit are infinite resolution and linear operation (better than ± 0.5% of the full range). The signal conditioner employed here is the same as that for LVDT type transducers.

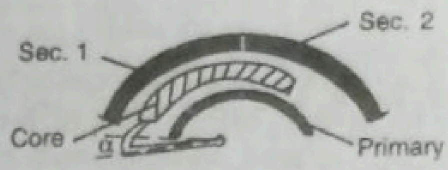

Fig. 4.3 Rotary variable differential transformer

***(c) Variable Reluctance Transducer*** The variable reluctance type displacement sensor is very useful for certain laboratory measurements of stress, thickness, vibration, and shock. In one of the configurations, two coils $L_1$ and $L_2$ are wound continuously over a cylindrical bobbin with a ferromagnetic core moving within it. Any variation in the position of the core will change the self-inductances of the coils $L_1$ and $L_2$, as illustrated in Fig. 4.4. In another type, an E-shaped magnetic core having two windings at the end limbs is used with an armature mounted suitably covering the pole faces, with an appropriate air gap. In either case, it can be shown that the fractional change $\Delta L$ in the inductance $L$ is approximately related to the fractional change $\Delta x$ in position $x$ of the core as $\frac{\Delta L}{L} = -\frac{\Delta x}{x}$ for small displacements.

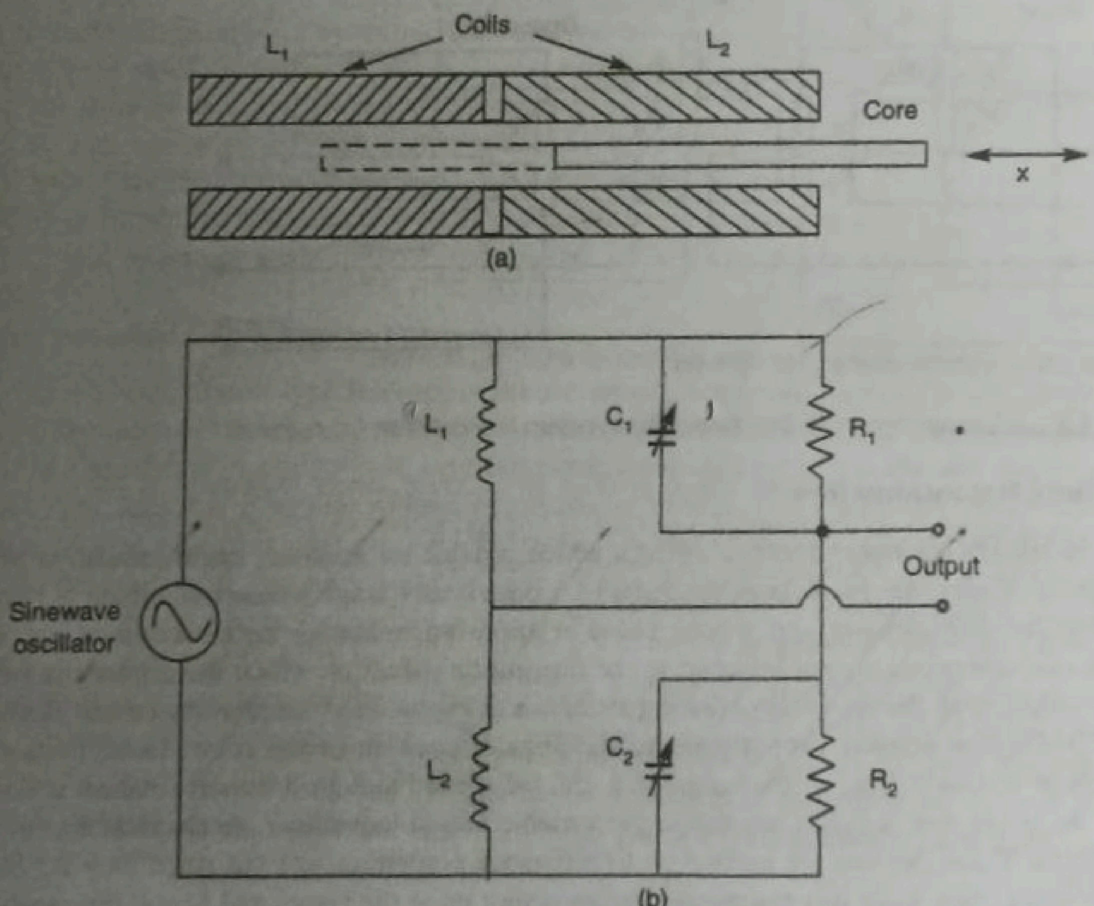

Fig. 4.4 Variable reluctance displacement transducer: (a) coil assembly; (b) detector circuit.

Measurements are carried out with a Wheatstone's bridge network as shown in Fig. 4.4(b) wherein the coils $L_1$ and $L_2$ form half of the bridge and the other two arms are completed with two fixed resistors $R_1$ and $R_2$ with capacitors $C_1$ and $C_2$ in parallel to achieve both amplitude and phase balance. The main advantages of the device are its high sensitivity and good linearity of 0.5 to 1% even for long stroke lengths of 50 cm (overall length should be double that of a stroke length). The device can be operated under severe environmental conditions, with encapsulation of the coils in an epoxy resin and hermetically-sealed bobbin. With appropriate modification, it can be employed for velocity and acceleration measurements also.

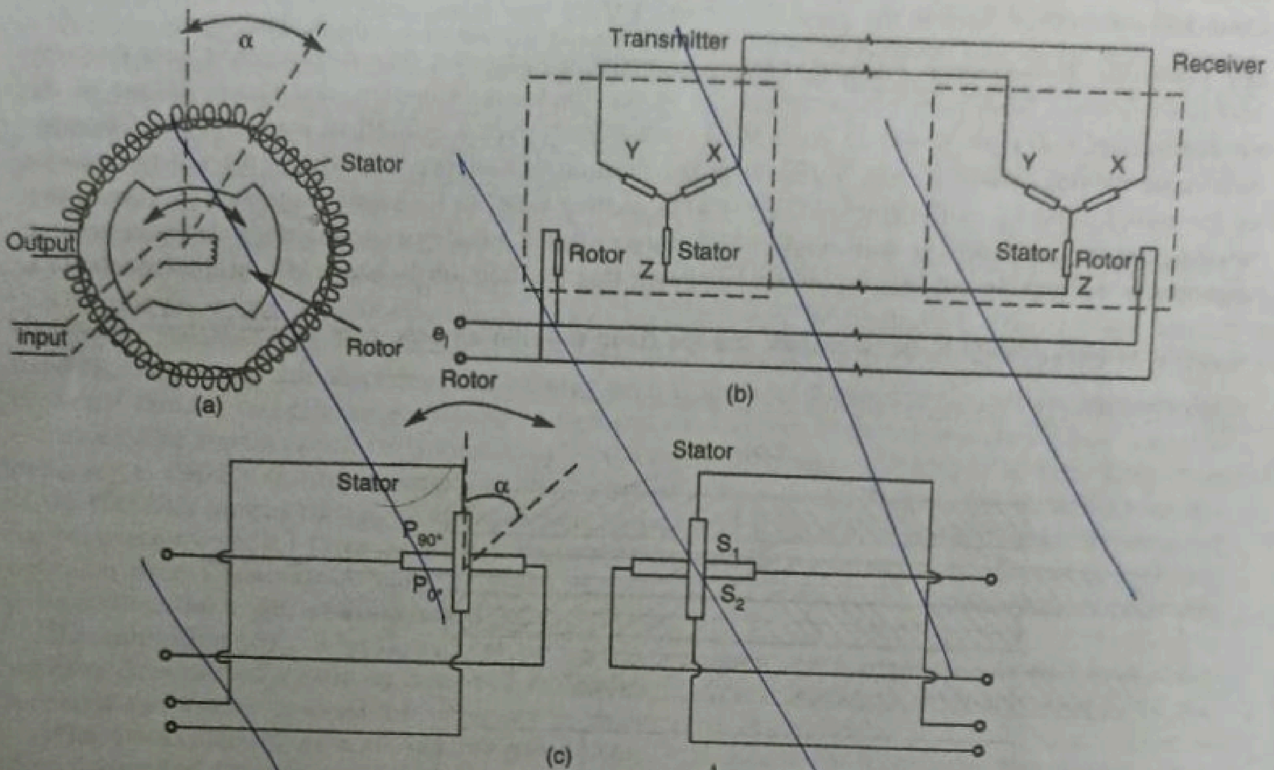


Fig. 4.5 (a) Induction potentiometer; (b) synchro transmitter; (c) resolver

### 4.2.3 Induction Potentiometers

Induction potentiometers are linear synchro devices which provide an accurate, linear indication of the shaft rotation about a reference position in the form of a polarized voltage whose magnitude is proportional to the angular displacement and whose phase relationship indicates the direction of the shaft rotation. The device comprises a rotor attached to the transmitting shaft on which the primary is wound and its stator is wound with the secondary winding as shown in Fig. 4.5(a). The windings are so designed that the output voltage is directly proportional to the angular position of the rotor. Good linearity is feasible for angular displacements in the range of ± 45° only, even though the shaft rotation is continuous. Some of the errors that can arise are due to the variable output impedance, mechanical asymmetry, and thermal effects. These devices are analogous to resistance potentiometers but since they are induction-type components, they have less restraining forces acting upon the rotors and hence are capable of providing higher resolution.

### 4.2.4 Synchros and Resolvers

Synchros and resolvers are basically a class of ac electromechanical, variable-coupling transformer devices primarily employed for angular data transmission and computing systems. The angular shaft position data is transmitted from one location to another through converted electrical signals.

The basic electromagnetic structure of a synchro consists of a wound rotor and a wound stator, concentrically arranged to give adjustable mutual coupling between the windings of the two members. The rotor is wound with a single-phase concentrated winding and the stator is wound with three-phase distributed windings connected in a Y-configuration. The rotor is excited with an ac signal, and by the transformer action between the rotor and stator windings, voltages are induced in the stator coils. The magnitudes of these voltages depend upon the angular position of the rotor with respect to the stator. The output voltage varies sinusoidally, depending upon the position of the rotor with respect to the stator. In a typical practical set-up, a pair of synchros are used: one acts as a transmitter and the other as a receiver, as shown in Fig. 4.5(b).

An inductive resolver is essentially a variable transformer with a rotary electromagnetic coupling between the primary and secondary windings. In a typical angle-positioning resolver, two windings are provided at right angles to one another for both the stator and rotor. The windings are located in such a manner that the output voltage has an amplitude proportional to the sine or cosine of the input shaft position of the rotor with respect to the stator. Depending upon the designer's particular application, either the rotor or stator may be used as the primary. The electrical connections of a resolver are shown in Fig. 4.5(c).

The main advantages of synchros and resolvers are:

(i) Infinite resolution
(ii) No wear of rotation, except at slip rings
(iii) System operating at much higher speeds
(iv) Relatively insensitive characteristics to stray cable capacitances
(v) High reliability and accuracy (0.01% feasible)
(vi) Useful operating angle of 360° and capable of continuous rotations.

### 4.2.5 Variable Capacitance Transducer

The variable capacitance type transducer finds considerable usage in specific and limited areas in the field of displacement measurement. They are ideally suited as non-contact type dynamic sensors, especially, in the studies of vibration in very light structures such as thin walls and diaphragms. The non-contact type sensor is desirable when a transducer is needed to measure the mechanical displacement without causing any additional mechanical loading on the vibrating object. Some of the advantages of this device are that it has high stability, good linearity, compactness, and good temperature range. Further, its performance in the contact-type version is superior to other comparable transducers in large displacement range of 0 to 25 cm.

The most common form of the variable capacitor used for displacement measurement is a parallel-plate capacitor with a variable gap. The capacitance variation in a parallel-plate capacitor can be achieved by changing the gap width between the plates $d$, the common area of the plates $A$, or the dielectric constant $k$, as shown in Fig. 4.6.

The capacitance $C$ of such a parallel-plate capacitor is given by

$$C = \frac{kA}{d} \tag{4.2}$$

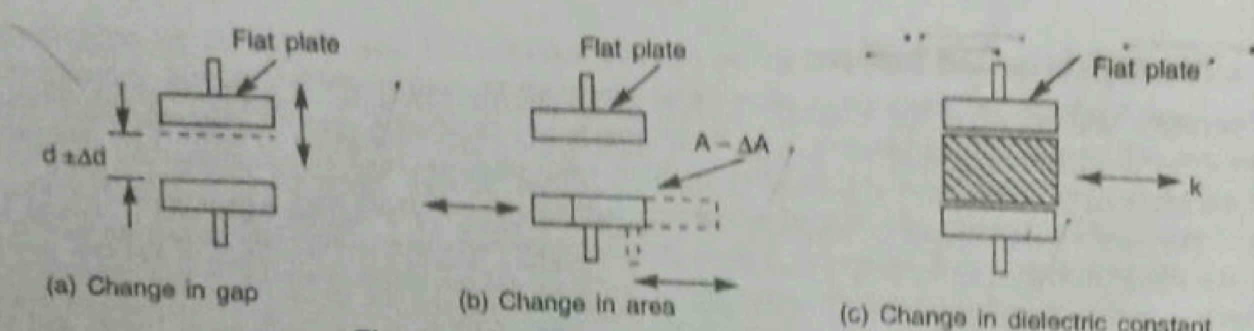


**Fig. 4.6** Variable capacitance devices

In a typical device one plate of the transducer is kept fixed and the other plate is moved or deflected depending upon the displacement measurement. The variable dielectric system is employed in the case of level measurements in liquid columns, as in the fuel gauge system of an aircraft or level indicator in a chemical plant. The resultant change in capacitance in all the above cases can be converted to an useful electrical signal by means of a variety of circuitry.

For small changes $\Delta d$ in position with respect to an initial value, the capacitance variation $\Delta C$ can be written as

$$\frac{\Delta C}{C} = \frac{-\Delta d}{d} \tag{4.3}$$

where higher-order terms are neglected.

Similarly, if $\Delta A$ is the change in area and $\Delta k$ is the change in the dielectric constant, then

$$\frac{\Delta C}{C} = \frac{\Delta A}{A} \tag{4.4}$$

and

$$\frac{\Delta C}{C} = \frac{\Delta k}{k} \tag{4.5}$$

Equations (4.4) and (4.5) represent exact relationship, indicating that the variable area and variable dielectric constant configurations produce a linear relationship without restrictions on the range.

A linear variable capacitance device in a practical application comprises a cylinder moving concentrically inside two other identical cylinders with a constant air gap. With the movement of the central cylinder, the capacitance area of one section increases while the other correspondingly decreases. The resultant change in capacitance is directly proportional to the displacement of the inner cylinder. The main advantages of the device are good stability, and a linearity better than ± 0.2% over a 25-cm range.

A simple instrumentation system for single-ended measurements using an operational amplifer is shown in Fig. 4.7. This circuit arrangement gives a linear output in cases where (a) $C_2$ is a fixed capacitance and $C_1$ is the transducer capacitance operating on the principle of capacitance variations due to area change or dielectric constant change, as can be seen from the relationship,

$$e_o = -\frac{C_1}{C_2} \cdot e_i \tag{4.6}$$

$$= -\frac{1}{C_2} \frac{kA}{d} \cdot e_i \tag{4.7}$$

$$e_o \propto k \text{ or } A \tag{4.8}$$

(b) $C_1$ is a fixed capacitor and $C_2$ is the transducer capacitance, operating on the principle of variation in gap, giving rise to

$$e_o = -\frac{C_1}{C_2} \cdot e_i$$

$$= -\frac{C_1 d}{kA} \cdot e_i \tag{4.9}$$

$$e_o \propto d \tag{4.10}$$

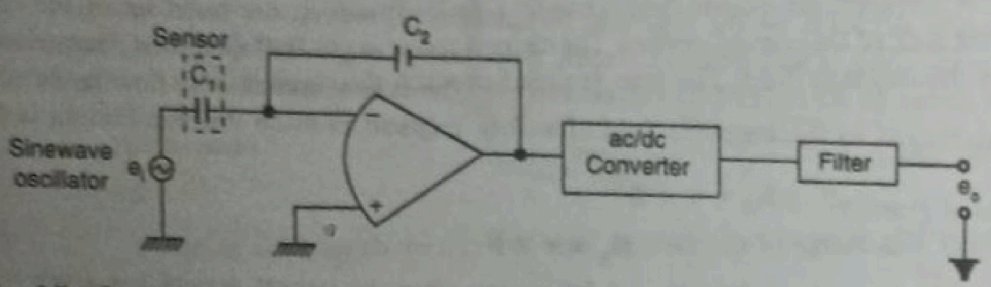


**Fig. 4.7** Operational amplifier circuit configuration for capacitance type displacement transducers

For higher accuracy a closed loop ac servo bridge system is normally used as illustrated in Fig. 4.8. Any out-of-balance of the bridge due to the change in transducer capacitance is amplified to actuate a servomotor. The motor in turn positions a reference capacitance, till the bridge output becomes zero. The output is then read in terms of the position of the motor shaft with a high accuracy. Capacitance-type sensors find wide use in gauging and inspection systems in metrology and in checking dimensions of gauges in grinding operations and roll spacing in strip-rolling mills. Very low drift and high accuracy over long ranges allow very precise control over the final product. The device can be used as an extensometer in the measurement of creep and tensile properties of materials over long periods. Capacitance strain gauges, fabricated with ceramic and nimonic materials, can be profitably employed for displacement measurements up to 600° C. With suitable design features, the device can be adopted for the measurement of pressure and force in the instrumentation of aircraft, other vehicles, and process control.

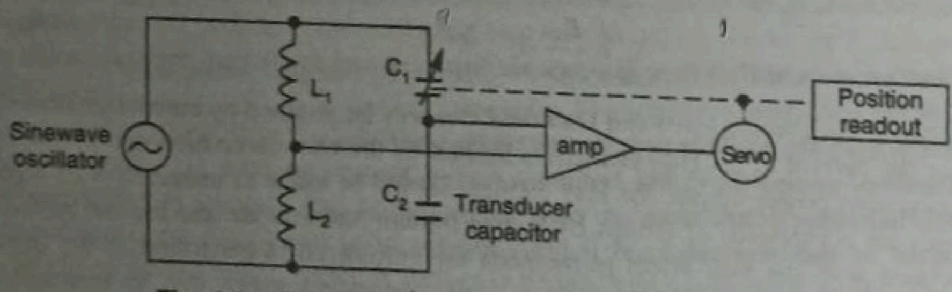


**Fig. 4.8** AC servo bridge arrangement for variable capacitance devices

### 4.2.6 Hall Effect Devices

One of the numerous applications of the Hall effect is in position measurements, particularly for measuring angular displacements of shafts.

The Hall effect occurs when a transverse magnetic field is applied to a current-carrying conductor.[3] It results in an electric field perpendicular to the directions of both the magnetic field and current with a magnitude proportional to the product of the magnetic field strength and current. The schematic arrangement of the conductor, the magnetic field, and current flow are shown in Fig. 4.9(a).

An electron of charge $e$ (stream of such electrons being the net current) travelling in a magnetic field **B** with a velocity **v** experiences a Lorentz force **F** given by

$$\mathbf{F} = e\,(\mathbf{v} \times \mathbf{B}) \tag{4.11}$$

The current flow through the conductor is constrained by the boundaries of the solid, and the electrons are initially deflected by the magnetic flux density. However, the build up of the charges toward one side of the solid, in turn create an electric field (known as the Hall field) that counterbalances the Lorentz force acting on the bulk of the current carriers. The current continues to flow in the original direction as if unaffected by the magnetic field. The time required to reach this equilibrium is of the order of $10^{-14}$ s.

The electric field is given by

$$\mathbf{E}_H = \mathbf{v} \times \mathbf{B} \tag{4.12}$$

If $\rho$ and $e$ represent the density and charge of the carriers, then the current density **i** is given by

$$\mathbf{i} = \rho\,\mathbf{v} \tag{4.13}$$

The Hall field represented by single electron velocity is therefore

$$\mathbf{E}_H = \frac{1}{\rho}\,\mathbf{i} \times \mathbf{B} \tag{4.14}$$

The factor $\frac{1}{\rho}$ is termed as the 'Hall coefficient', $R_H$, which is inversely proportional to the carrier density in the solid. Thus, the Hall effect is much more pronounced in semiconductors than in metals. For practical applications, it is advantageous, if the effect is expressed in terms of the electric potential rather than the electric field.

From Fig. 4.9(a), it can be seen that $V_H = wE_H$, and $I = iwd$; therefore, the Hall potential is given by

$$V_H = \frac{R_H}{d}\,IB \tag{4.15}$$

The equilibrium between the Lorentz force and Hall field can only be attained by current carriers with a single velocity. Since the current in the Hall element is limited by the heat dissipation and permissible temperature rise for maximum power output, the Hall element should be made of materials with highest mobility. Such materials are compounds of groups III-V, like Indium Antimonide and Indium Arsenide. Some problems associated with the Hall-effect phenomena are current noise generated in the device, residual voltages due to misalignment of the terminals, and magnetoresistance due to non-uniform velocities of the carriers.

A typical transducer arrangement applying the Hall-effect phenomena for producing an output which is directly proportional to small rotary shaft displacements is shown in Fig. 4.9(b). The Hall probe is rigidly suspended between the poles of a permanent magnet fixed to the shaft as shown in the figure; the probe remains stationary as the shaft (with the magnet mounted) rotates. With a constant control

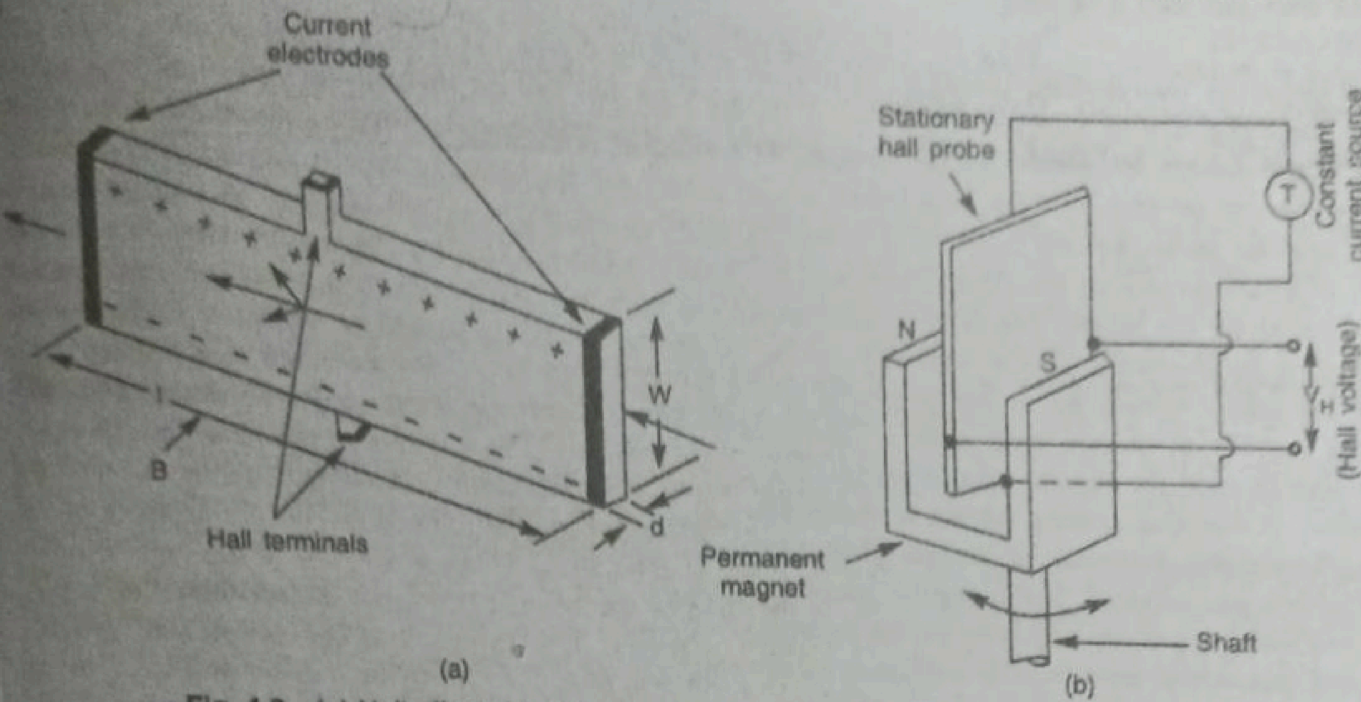


**Fig. 4.9** (a) Hall effect principle; (b) Hall effect angular displacement transducer

current supplied to the electrical contacts at the end of the probe, the voltage generated (Hall voltage) across the probe is directly proportional to the sine of the angular displacement of the shaft. Hence, the linear scale between the rotation and output voltage can be obtained up to ± 6° of the rotation.

The main advantage of such transducers is that they are non-contact devices with high resolution and small size. Some of the other applications are in measurements of velocity, rpm, sorting, limit sensing, and non-contact current and magnetic field measurements.[4]

### 4.2.7 Proximity Devices

Although not normally considered as transducers, proximity devices are in fact non-contact displacement transducers having a discrete increment in the output at one point within the travel range. Such devices are developed employing electromagnetic, inductive, reluctance, or capacitance principles. In a typical electromagnetic proximity device, the output increases above a set value when approached by a ferro-magnetic material body at a rate sufficient to cause an output producing a change in the magnetic flux. The range depends very much on the size of the transducer, pole-face area, and the transduction principle employed.

A popular type of proximity device, commonly used in machine shops is the non-contact pneumatic cum electronic "air gauging" sensor, which measures the gap clearance precisely in comparison to a calibrated setting master. The device is basically a probe that senses the variations in the overall dimensions of the component under measurement. The linear movement of the plunger is converted to an electrical output signal which is further processed and displayed digitally. The sensor has a range of 0 – 1 mm, with a least count of 0.5 micron and the main advantages are compactness, high resolution and fast multi-gauging facility with access to computer compatible instrumentation for data analysis.

## 4.3 DIGITAL TRANSDUCERS

With the advent of digital data-handling systems for any measurement, devices by which mechanical displacement can be transduced directly into a digital output, by a suitable electromechanical or electro-optical arrangement, without any intermediate analog to digital conversion operation, have come into importance and utility. These digital transducers can be either of the incremental type or of the absolute type. Interference and Moire pattern techniques are also employed for higher resolutions.

The incremental-type devices are employed for both linear as well as angular displacement measurements. The device for angular measurements consists of a sensing shaft attached to a disc which is divided into a number of equal sectors on the circumference. The linear version operates in a similar manner with equal sectors along the length. The sensing mechanism can be a direct electrical contact with a wiper or brush or a photo-electric device with slots acting as optical windows. Each time an incremental motion of the sensor occurs, pulses are generated which are measured in a counter.

A gear with a large number of shaped teeth with a direct electrical contact or electromagnetic induction pick-up can also be used for angular measurements. The counting of the pulse train is again carried out with a counter. A direction sensing feature is incorporated to sense the direction of motion, positive/negative or clockwise/anti-clockwise. In the case of angular transducers, the performance of the electromagnetic transduction gets affected, if the angular speed is either too low or too high. Similar devices can be developed with the pick-up operating on the variable reluctance or capacitance principle.

The absolute digital displacement transducer is similar in construction to the incremental type described above, except that a unique coded information is obtained identifying a given position. This is achieved with a linear translational encoder or a rotary shaft position encoder as shown in Fig. 4.10.

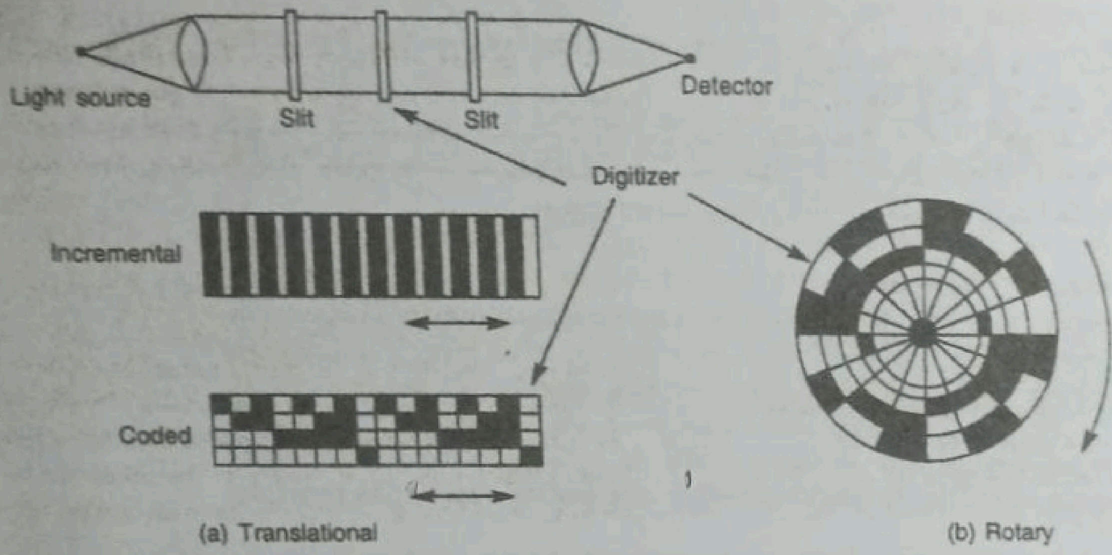


**Fig. 4.10** Details of a digital encoder for linear and angular displacement measurement

The principle of encoder is based on the on-off switching of a multiple track (each track representing a bit), each track divided into conducting or insulating sections with the smallest increment suitably chosen for the highest possible resolution. As the device moves under the brushes or optical windows, the respective circuits are switched 'on' and 'off' and the code is either displayed in decimal format with a suitable translator or fed directly to a processor.

A variety of codes are used in encoders for proper identification. The choice depends on such factors as the available computing circuitry, nature of the display required, total number of counts and degree of reliability. The most compact code is the natural binary code with the bits in terms of $2^0$, $2^1$, $2^2$ and $2^3$. A binary decimal code is a combination of the binary system and the Arabic decimal system used as 8421 BCD system. Each digit in Arabic is repeated by a binary code

$$8473 = 1000 \quad 0100 \quad 0111 \quad 0011$$

The main disadvantage of the binary and 8421 coding systems is that two or more bits have to change simultaneously during a single position change. This is overcome by a binary coded decimal (BCD) system, such as the "gray code", wherein only one-bit change takes place in the transition between any two consecutive numbers. Another modification based on the cyclic decimal system is the Datex Code, patented by Giannini Corporation, USA. By this there is only one decimal digit shift for each number sequence from 0 to any other number in the Arabic structure.

### 4.4 ~~LEVEL MEASUREMENTS~~

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Liquid-level measurements are widely employed to monitor as well as measure quantitatively the liquid content in vessels, reservoirs and tanks, or the liquid column height in open-channel streams and a variety of other similar cases in industrial processes. The type of device employed depends very much upon the accuracy, repeatability, range and instrumentation needed. The environmental conditions, to which the level sensors are exposed to, are also critical in many cases.

The simplest method of level measurement utilizes a float or displacer as the primary element. The principle is based upon the buoyancy effect and any change in the apparent mass density affects the accuracy. The float is mechanically coupled to a suitable displacement sensor, such as a simple potentiometer or linear variable differential transformer for continuous indication and recording.

In many cases, other techniques, such as measuring the differential pressure formed by the hydraulic head of the liquid column, are preferred for high accuracy and greater resolution. The actual height of the fluid is computed, knowing the density of the liquid and making corrections for the temperature and density variations. The sensor used for the measurement is the differential pressure cell, using special corrosion-resistant materials for the diaphragms. In the "bubbler" technique of measurement, a pipe is inserted into the tank within a few centimetres of the bottom and air or some other fluid is pumped through the pipe. When it bubbles, the air pressure in the pipe is equal to the hydraulic head of the liquid and this can be measured with a standard differential pressure sensor. The liquid level is then computed knowing the specific gravity of the liquid.

Two of the most common type of level sensors having wide application are the capacitance sensor and ultrasonic transducer. The capacitance device essentially consists of a concentric type electrical probe inserted into the tank, and the liquid acts as the dielectric of the capacitance formed. The probe capacitance $C$ varies as the level varies and this change in $C$ can be measured precisely with an ac bridge system or as a change in the frequency when coupled with a tank circuit of a high-frequency oscillator. As any change in temperature can affect the dielectric constant, suitable corrections are made to minimize the error in measurement. The main disadvantage is that the system is not applicable for conducting liquids. Such sensors are widely used to measure the level in fuel tanks of aircrafts and industrial plants. Ultrasonic devices can be readily used for gas-liquid, liquid-liquid or gas-solid interfaces. The principle of measurement is the same as that of the ultrasonic flow meters described in Chapter 8. A variety of configurations are employed in actual practice either as an on-off damped sensor or on-off transmitter, or as a continuous monitoring device. In the continuous type, the propagation time of an ultrasonic beam from a transmitting device to a receiver through the fluid is measured accurately and the level is interpolated. The accuracy is adversely affected by any change in the density of the liquid.

The liquid level in a container can be inferred by weighing the vessel with its contents and computing the level, knowing the density of the liquid. Using suitable electronic circuits, the base weight of the