6.18 INTRODUCTION TO TRANSDUCER

A transducer is a device that converts energy from one form to another form. This energy may be electrical, mechanical, chemical, optical or thermal. Transducers may be classified according to their applications, methods of energy conversion, nature of the output signal, and so on. All these classifications usually result in overlapping areas. A sharp distinction among the types of transducers is difficult. A transducer that gives electrical energy as the output is known as an *electrical transducer*. The output electrical signal could be voltage, current, or frequency, and the production of these signals is based upon resistive, capacitive, inductive effects, etc. For measuring non-electrical quantities, a detector is used, which usually converts the physical quantity into a displacement that activates the electrical transducer. The *displacement transducers*, namely, capacitive, potentiometric, photoelectric (phototube) and piezoelectric, use the principle of converting a mechanical force into displacement and then into electrical parameters. Here, the mechanical elements used for converting this applied force into displacement are called force-summing devices.

6.19 CLASSIFICATION OF TRANSDUCERS

The transducers are classified:

- **On the basis of transduction form:**

  Based on how the input quantity or measurand is converted, it is further classified as

  - Resistive transducer
  - Capacitive transducer
  - Inductive transducer

  Example: piezoelectric, thermoelectric, magneto restrictive and so on.

- **Primary and secondary transducers**
  Element which makes direct contact to the measurand or the physical quantity is called a primary transducer and the transducers which convert the output of primary transducer to electrical output are called secondary transducers.
  Example: In Bourdon-tube pressure-gauge device, the primary transducer is the Bourdon tube and secondary transducer is an LVDT (Linear variable differential transformer)
- **Passive and active transducers**
  Active transducers, also known as self-generating type, develop their own voltage or current as the output signal. The energy required for production of this output signal is obtained from the physical phenomenon being measured. *Passive transducers*, also known as externally powered transducers, derive the power required for energy conversion from an external power source. However, they may also absorb some energy from the physical phenomenon under study. A few examples of active and passive transducers are given in Table 6.4.

Table 6.4 *Active and Passive transducers*

Active Transducers	Passive Transducers
Thermocouple	**Resistance**
Piezoelectric transducer	Potentiometric device
Photovoltaic (Photojunction) cell	Resistance strain gauge
Moving-coil generator	Resistance thermometer
Photoelectric (Photoemission) cell	Thermistor
	Photoconductive cell
	Inductance
	Linear Variable Differential Transformer (LVDT)
	Capacitance
	Voltage and current
	Devices using Hall effect
	Photoemissive cell
	Photomultiplier tube

Opto-electronic transducers, such as photoconductive cells, photovoltaic cells, solar cells, phototubes, and photomultiplier tubes use the principle of converting light energy into electrical energy.

(a) **Analogue and digital transducer**
Transducers that convert the input quantity into an analogue output are known as analogue transducers. Example: Strain gauge, LVDT, thermocouple, thermistor.
Transducers that convert the input quantity into an electrical output in the form of pulses are known as digital transducers.

(b) **Transducer and inverse transducer**
A device that converts a non-electrical quantity into an electrical quantity is known as a transducer and the device that converts an electrical quantity to a non-electrical quantity is known as an inverse transducer.

Some of the basic requirements of a transducer are given as follows: **[AU Nov/Dec, 2011]**

- ***Linearity:*** The input–output characteristics of the transducer should be linear.

- ***Ruggedness:*** The transducer should withstand overloads, with measures for overload protection.
- ***Repeatability:*** The transducer should produce identical output signals when the same input signal is applied at different times under the same environmental conditions.
- ***High stability and reliability:*** The output from the transducer should not be affected by temperature, vibration, and other environmental variations, and there should be minimum errors in measurements.
- ***Good dynamic response:*** In industrial, aerospace, and biological applications, the input to the transducer will not be static but dynamic in nature, i.e., the input will vary with time. The transducer should respond to the changes in input as quickly as possible.
- ***Convenient instrumentation:*** The transducer should produce a sufficiently high analogue output signal with high signal-to-noise ratio, so that the output can be measured either directly or after suitable amplification.
- ***Good mechanical characteristics:*** The transducer, under working conditions, will be subjected to various mechanical strains. Such external forces should not introduce any deformity and affect the performance of the transducer.

Of the many effects that are used in transducers, the principal effects used are variation of resistance, inductance, capacitance, piezoelectric effect and thermal effects which are described in the following sections.

6.20 Resistive Transducer

[AU Nov/Dec, 2011]

A transducer that converts the change in resistance of the material into an electrical signal with respect to environmental conditions is known as a resistive transducer. This transducer can be used to change resistance in both AC and DC devices. The resistive transducer is used for measuring physical quantities like temperature, displacement, vibration and so on. In general, the resistance of the material is given by

$$R = \frac{\rho l}{A}$$

where R is the resistance in ohms, A is the cross-sectional area of the conductor in metre square, L is the length of the conductor in metres and ρ is the resistivity of the conductor in materials in ohm metre.

The classification of resistive transducers is based on the variation of any one of the quantities i.e., length, area or resistivity of the material. The different types of resistance transducers are:

- Potentiometric transducer
- Strain gauges
- Resistance thermometers
- Thermistors

6.20.1 Potentiometric Transducer

[AU Nov/Dec, 2012]

The basic circuit of a potentiometric transducer is shown in Figure 6.42. A potentiometric transducer consists of a resistance element that is contacted by a movable slider. A force-summing member is used to move the slider, thereby changing the resistance and hence the

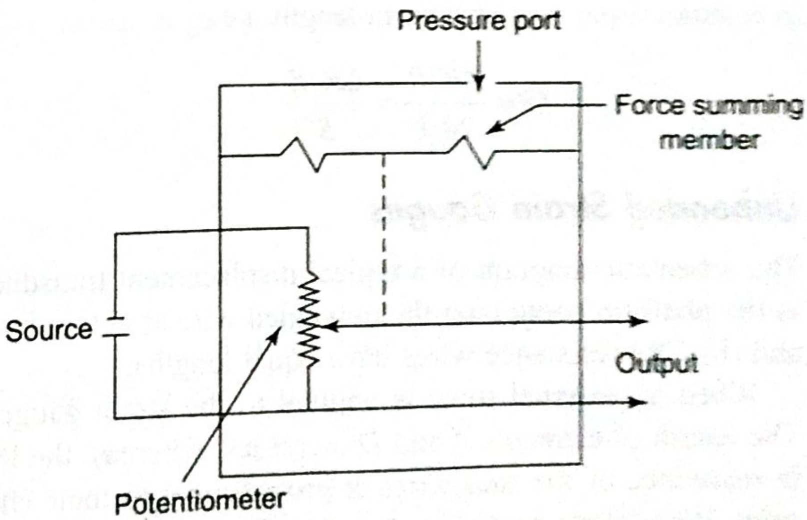


Figure 6.42 Potentiometric Transducers

output voltage changes correspondingly. The same principle can be used to vary the resistance in a bridge circuit. This transducer has high electric efficiency and provides a sufficient output to permit control operations without further amplification.

The advantages, disadvantages and applications of potentiometric transducer are discussed below:

Advantages

1. It is cheap, simple to operate and has a high resolution.
2. It is very useful in applications where there are no severe requirements.
3. It helps in measuring large amplitudes or displacement.
4. Since it has a high electrical efficiency, it is used in control applications.

Disadvantages

1. It requires a large force to move its contacts.
2. Sliding contacts can get contaminated, worn out, and there is a possibility of misalignment and generation of noise.
3. Life-time of this transducer is limited.

Applications

This transducer is used in:

1. A voltage divider to obtain an adjustable output voltage.
2. Audio-control devices for frequency attenuation, to adjust loudness and so on.
3. Televisions to control brightness, contrast and colour response.
4. Measuring the displacement

6.20.2 Electrical Strain Gauges [AU Nov/Dec, 2014]

If a metal conductor is stretched or compressed, its resistance changes because of dimensional changes (length and cross-sectional area) and resistivity change. If a wire is under tension and increases its length from l to $l + \Delta l$, i.e., the strain $S = \frac{\Delta l}{l}$, then its resistance increases from R to $R + \Delta R$.

The sensitivity of a strain gauge is described in terms of gauge factor G and is defined as the unit change in resistance per unit change in length, i.e.,

$$G = \frac{\Delta R/R}{\Delta l/l} = \frac{\Delta R/R}{S}$$

Unbonded Strain Gauges

The schematic diagram of a typical displacement transducer wherein the measuring forces are transmitted to the platform containing the unbonded wire structure by means of a force rod is shown in Figure 6.43 (a) and (b). The resistance wires have equal lengths.

When an external force is applied to the strain gauge, the armature moves in the direction indicated. The length of elements A and D increases, whereas, the length of elements B and C decreases. The change in resistance of the four wires is proportional to their change in length and this change can be measured using Wheatstone bridge as shown in Figure 6.43(c).

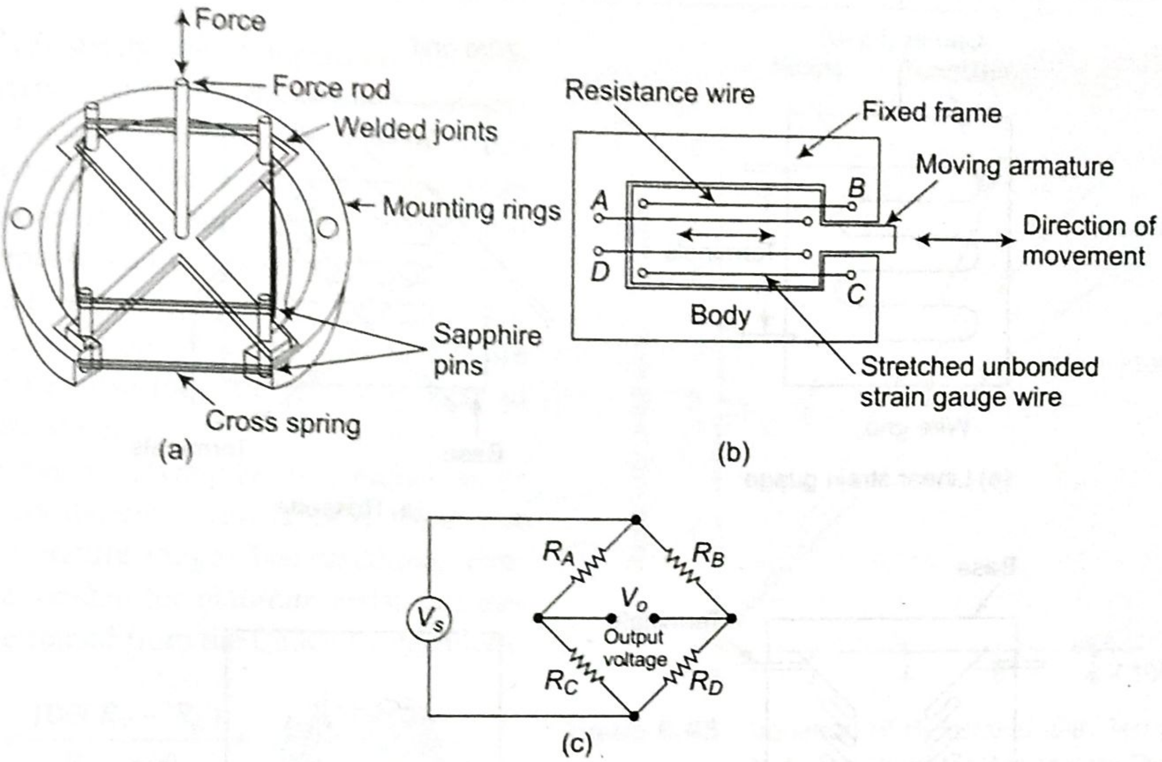


Figure 6.43 Unbonded Strain Gauge

Thus, the external force causes variation in resistance of the wires, unbalancing the bridge and causing an output voltage V_a proportional to the pressure. The bridge is balanced if

$$\frac{R_A}{R_C} = \frac{R_B}{R_D}$$

Bonded Strain Gauge

A bonded-wire strain gauge consists of a grid of fine resistance wire of a diameter of about 25 mm. The wire is cemented to a base. The base may be a thin sheet of paper or a very thin Bakelite sheet. The wire is covered with a thin sheet of material so that it is not damaged mechanically. The base is bonded to the structure under study with an adhesive material. It acts as a bonding material. It permits a good transfer of strain from base to wires. The commonly used types of bonded strain gauges are shown in Figure 6.44. The advantages, disadvantages and applications of strain gauges are given below:

Advantages

1. No moving part exists in the system.
2. Device is small and inexpensive.
3. It has faster response time.

Disadvantages

1. Non-linear characteristics exist in the transducer.
2. Transducer needs to be calibrated.
3. Very sensitive to environmental condition.
4. Has very long term-drift.

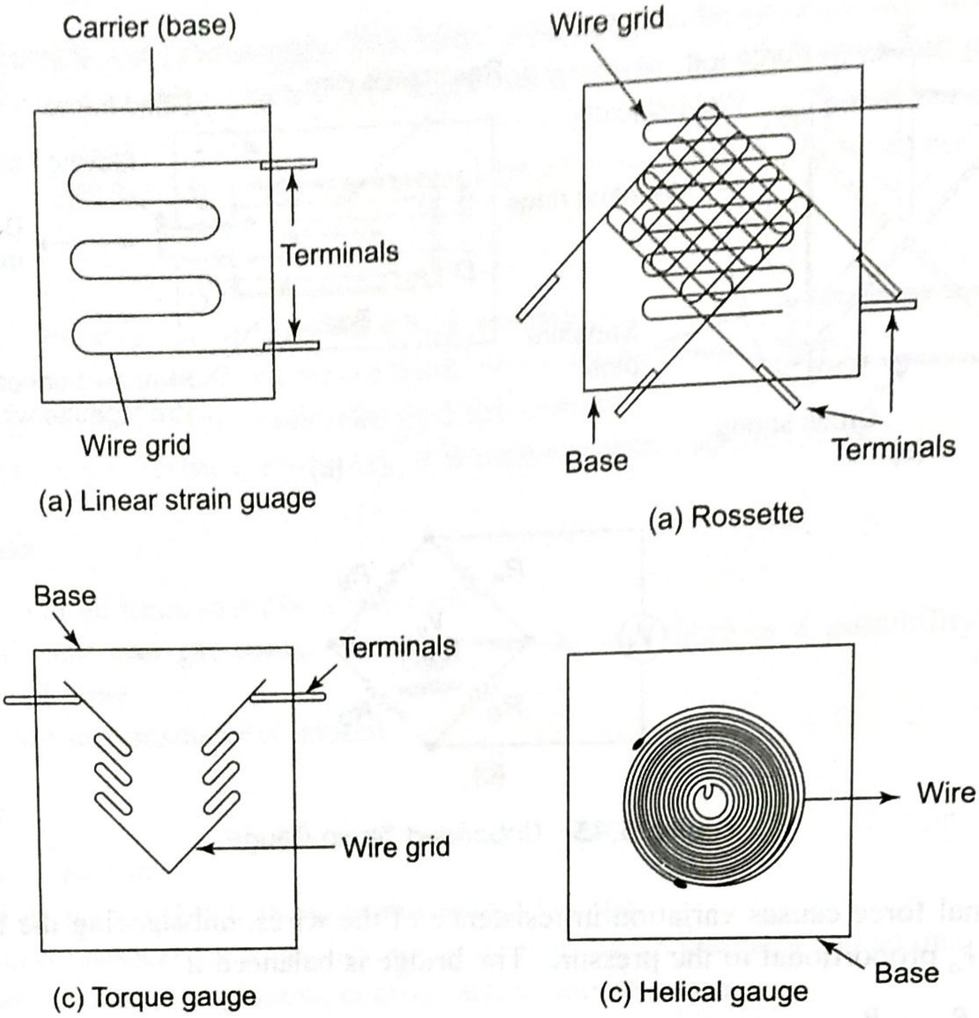


Figure 6.44 Bonded Strain Gauges

Applications

1. Used in measuring normal strains in any desired direction.
2. Can be used in measuring shear strain using some special arrangements.
3. Possible to read the reading remotely.
4. Can be used in measuring static and dynamic strains.
5. Can be used in measuring vibration, torque, bending, deflection, compression and tension.

6.20.3 Resistance Thermometer

[AU Nov/Dec, 2011]

The resistance of most electrical conductors varies with temperature, according to the relation

$$R = R_0(1 + aT + bT^2 + \ldots)$$

where R_0 is the resistance at temperature T_0 (at 0°C), R is the resistance at T, and a and b are constants.

Over a small temperature range, depending on the material, the above equation reduces to

$$R = R_0(1 + \alpha T)$$

where α is the temperature coefficient of resistance.

Important properties of materials used for resistance thermometers are: (i) high temperature-coefficient of resistance, (ii) stable properties so that the resistance characteristic does not drift with repeated heating and cooling or mechanical strain, and (iii) a high resistivity to permit the construction of small sensors. The variation of resistivity with temperature of some of the materials used for resistance thermometers is shown in Figure 6.45. From the Figure, it can be seen that tungsten has a suitable temperature coefficient of resistance but is brittle and difficult to form. Copper has a low resistivity and is generally confined to applications where the sensor size is not restricted. Both platinum and nickel are widely used because they are relatively easy to obtain in pure state.

Platinum has an advantage over nickel, as its temperature coefficient of resistance is linear over a larger temperature range. The resistance–temperature relationship for platinum resistance elements is determined from the Callendar equations:

$$T = \frac{100(R_T - R_0)}{R_{100} - R_0} + d\left(\frac{T}{100} - 1\right)\frac{T}{100}$$

where R_T is the resistance at temperature T, R_0 is the resistance at 0°C, R_{100} is the resistance at 100°C and d is the Callendar constant, which is approximately 1.5.

The construction of an industrial platinum resistance thermometer is shown in Figure 6.46.

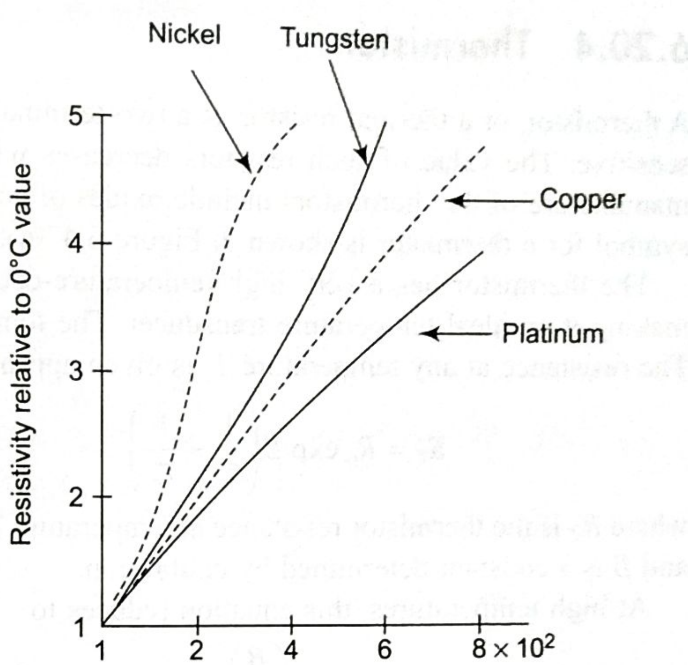


Figure 6.45 Variation of Resistivity with Temperature of Materials Used for Resistance Thermometer

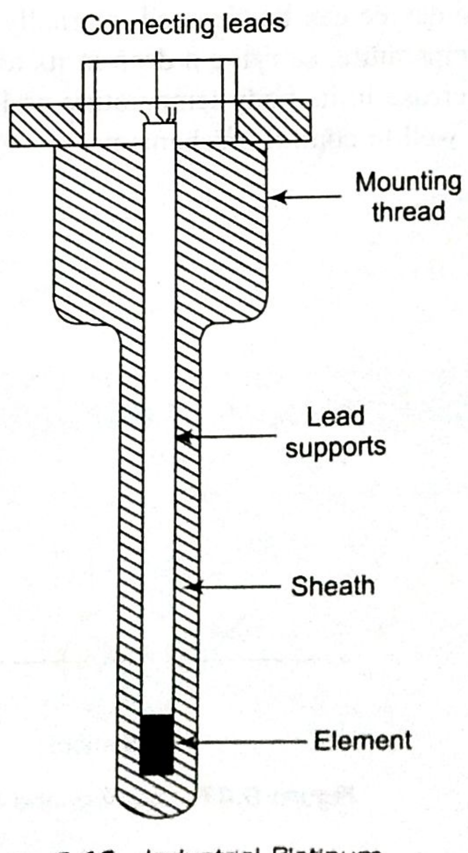


Figure 6.46 Industrial Platinum Resistance Thermometer

Advantages, Disadvantages and Applications of Resistance Thermometer

Advantages

1. Accurate measurement of quantity is possible.
2. Direct operation of indicators and recorders is possible.
3. Easily to install and replace.
4. Possible to measure differential temperature.
5. Wide range of temperature can be measured i.e., from -20° C to + 650° C.
6. Smaller in size and is suitable for remote indication.

Disadvantages

1. External power source is necessary for its operation.
2. Comparatively expensive when compared to other transducers.
3. Self-heating problem exists in the transducer.

Applications

Commonly used in aerospace, analytical equipment, food-service equipment, and semiconductor equipment.

6.20.4 Thermistor

[AU Nov/Dec, 2014]

A thermistor, or a thermal resistor, is a two-terminal semiconductor device whose resistance is temperature sensitive. The value of such resistors decreases with increase in temperature. Materials employed in the manufacture of the thermistors include oxides of cobalt, nickel, copper, iron, uranium and manganese. The symbol for a thermistor is shown in Figure 6.47(a).

The thermistor has a very high temperature-coefficient of resistance, of the order of 3 to 5% per °C, making it an ideal temperature transducer. The temperature coefficient of resistance is normally negative. The resistance at any temperature T, is given approximately by

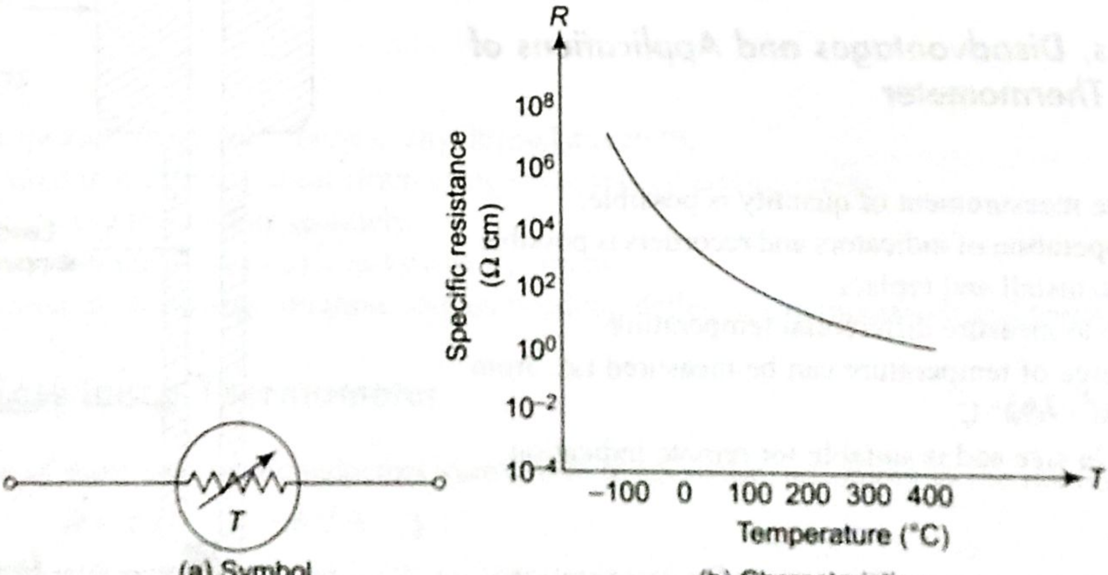
$$R_T = R_0 \exp \beta\left(\frac{1}{T} - \frac{1}{T_0}\right)$$

where R_T is the thermistor resistance at temperature $T(K)$, R_0 is the thermistor resistance at temperature $T_0(K)$ and β is a constant determined by calibration.

At high temperatures, this equation reduces to

$$R_T = R_0 \exp\left(\frac{\beta}{T}\right)$$

The resistance–temperature characteristic is shown in Figure 6.47 (b). The curve is non-linear and the drop in resistance from 5000 Ω to 10 Ω occurs for an increase in temperature from 20°C to 100°C. The temperature of the device can be changed internally or externally. An increase in current through the device will raise its temperature, carrying a drop in its terminal resistance. Any externally applied heat source will result in an increase in its body temperature and drop in resistance. This type of action (internal or external) lends itself well to control mechanisms.



(a) Symbol (b) Characteristics

Figure 6.47 Symbol and Resistance–Temperature Characteristics of a Thermistor

Three useful parameters used in characterising thermistors are: time constant, dissipation constant, and resistance ratio. The time constant is the time taken for a thermistor to change its resistance by 63% of its initial value, for zero power dissipation. Typical values of time-constant range from 1–50 s.

The dissipation constant is the power necessary to increase the temperature of a thermistor by 1°C. Typical values of dissipation constant range from 1 mW/°C to 10 mW/°C.

Resistance ratio is the ratio of the resistance at 25°C to that at 125°C. Its range is approximately 3–60.

Advantages, Disadvantages and Applications of Thermistor

Advantages

1. Compact, low cost and longer life-time.
2. Has good stability of the system.
3. Has faster response i.e., from seconds to minutes.
4. More sensitive when compared to other temperature sensors.
5. Compatible with many devices.
6. Easy to interface with the external circuits.

Disadvantages

1. Requires shielding.
2. Requires an input power to activate.
3. Low excitation current is required to avoid self-heating.
4. Not suitable for large temperature range.
5. Non-linear resistance temperature characteristics.

Applications

Thermistor are used in:

1. Measurement of temperature.
2. Controlling of temperature.
3. Temperature compensation.
4. Measuring voltage and power at high frequencies, thermal conductivity, level, flow and pressure of liquids and composition of gases.
5. Measuring vacuum and to provide time-delay.

Comparison between RTD and Thermistor

The comparison between RTD and thermistor is given in Table 6.5.

Table 6.5 *Comparison between RTD and thermistor*

RTD	THERMISTOR
It is made up of metals.	Thermistor is made up of semiconductor materials.
Since metals have a positive temperature coefficient (PTC) of resistance, its resistance is directly proportional to temperature	Since semiconductor materials have a negative temperature coefficient (NTC) of resistance, its resistance is inversely proportional to temperature.
Has linear resistance temperature characteristics	Has non-linear resistance temperature characteristics
Less sensitive to temperature.	Highly sensitive to temperature.
Has wide operating range i.e., –200°C to 650°C	Has a narrow operating range i.e., –100°C to 300°C
Larger in size.	Smaller in size.
Costlier when compared to a thermistor.	Cheaper when compared to RTD
Has low self-resistance.	Has high self-resistance.
Provides high degree of accuracy and long-term stability.	Provides an accuracy of ± 0.01°C.
Used in laboratory and industrial applications.	Used in dynamic temperature measurement.

6.21 Inductive Transducer

[AU Nov/Dec, 2011]

When a force is applied to a ferromagnetic armature, the air gap, as shown in Figure 6.48, gets changed, thereby varying the reluctance of the magnetic circuit i.e., the inductance of the magnetic circuit gets changed. Thus, the applied force is measured by the change of inductance in a single coil. The inductive transducer enables static and dynamic measurements.

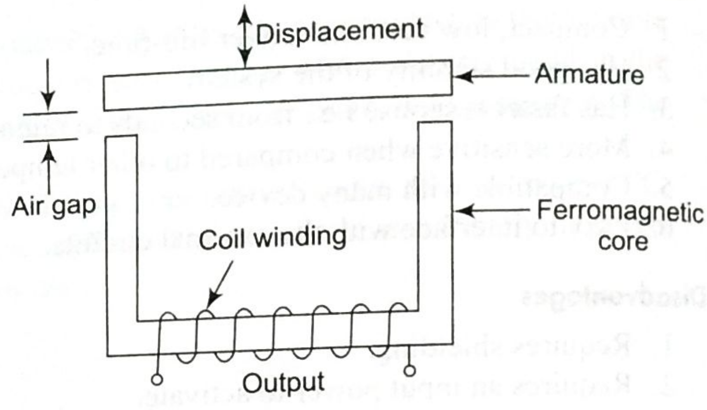


Figure 6.48 Inductive Transducers

6.21.1 Linear Variable Differential Transformer (LVDT)

[AU April/May, 2015]

The most widely used inductive transducer is the Linear Variable Differential Transformer (LVDT), as shown in Figure 6.49(a). It consists of a primary coil and two exactly similar secondary coils with a rod-shaped magnetic core positioned centrally, inside the coil. An alternating current is fed into the primary, and voltages V_{o1} and V_{o2} are induced in the secondary coils. As these coils are connected in series opposition, the output voltage is $V_o = V_{o1} \approx V_{o2}$. If the core is placed ideally in the central position (null position or reference position), $V_{o1} = V_{o2}$ and hence, the output voltage $V_o = 0$. In practice, due to incomplete balance, a residual voltage usually remains with the core in this position. As shown in Figure 6.49 (a), when the core is displaced from the null position, the induced voltage in the secondary towards which the core has moved increases, while in the other the secondary voltage decreases. This results in a differential voltage output from the transformer.

The output voltage produced by the displacement of the core is linear over a considerable range, as shown in Figure 6.49(b) but flattens out at both ends, and the voltage phase changes by 180°, as the core moves through the centre position.

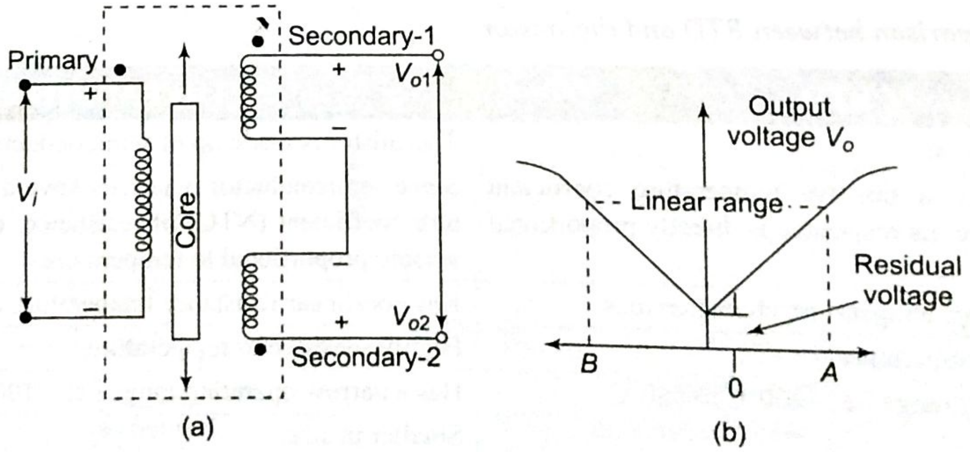


Figure 6.49 Linear Variable Differential Transformer (a) Schematic Diagram (b) Characteristics

LVDT provides continuous resolution and shows low hysteresis and hence, repeatability is excellent under all conditions. As there are no sliding contacts, there is less friction and less noise. It is sensitive to vibrations and temperature. The receiving instrument must be selected to operate on AC signals or a demodulator network must be used if a DC output is required.

Advantages, Disadvantages and Applications of LVDT

Advantages

1. It is used in wide range of applications
2. Presence of a linear relationship in the instrument
3. High sensitivity and output
4. High resolution, high sensitivity and good repeatability
5. Consumes less power
6. Produces low hysteresis
7. Low frictional losses

Disadvantages

1. Requires large displacement to get considerable differential output.
2. Very sensitive to stray magnetic field and hence requires shielding.
3. Temperature and vibrations affect output of the transducer.
4. The dynamic response is being controlled mechanically.

Applications

1. Used to measure displacement with ranging from a few mm to cm.
2. Can be used as primary and secondary transducers.
3. Used in combination with Bourdon tube to measure pressure.
4. Mostly used in servomechanisms and other industrial applications.

6.21.2 Rotary Variable Differential Transformer (RVDT) [AU Nov/Dec, 2014]

Rotary Variable Differential Transformer or RVDT is an inductive transducer, which senses the angular displacement of the conductor and gives a linear output proportional to it i.e., it provides a variable AC output voltage proportional to the angular displacement of the input shaft. It is similar to LVDT, except that its core is in cam shape and moves between the windings by means of a shaft. The output signal of RVDT is linear within a specified range over the angular displacement when it is energised using a fixed AC source. The schematic diagram of RVDT is shown in Figure 6.50.

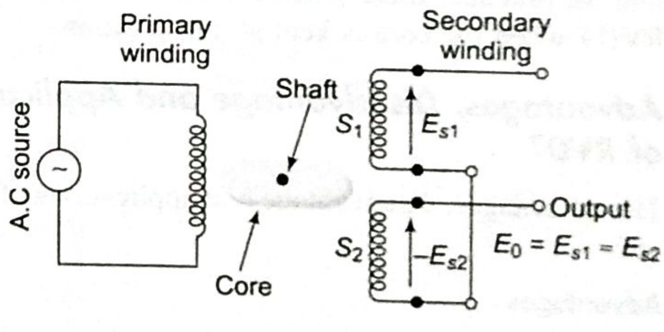


Figure 6.50 Schematic Diagram of RVDT

The RVDT consists of one primary winding and two secondary windings. The emf induced in the two secondary windings is a function of rotary displacement of the core around the shaft and both the secondary windings are placed in such a way that the emf induced is 180^0 out of phase with each other.

Working

The working of RVDT is similar to the operation of LVDT. According to the angular movement of the shaft, three differential conditions are formed.

Condition 1

When shaft is at null position, as shown in Figure 6.50, the emf induced in both the secondary windings are equal but opposite in phase. Therefore, the differential output taken from the secondary windings is zero and is explained mathematically using the following equation:

$$E_{s1} = E_{s2}$$

Where E_{s1} is the emf induced in the first secondary winding and E_{s2} is the emf induced in the other secondary winding.

Therefore, the resultant output voltage is given by $E_0 = E_{s1} - E_{s2} = 0$.

Condition 2

When the shaft starts rotating in the clockwise direction, more portion of the core comes in contact with secondary winding S_1 when compared to S_2. Hence, the emf induced across the secondary winding S_1 is more than the emf induced across the secondary winding S_2 i.e.,$E_{s1} > E_{s2}$. Therefore, the differential output drawn from these windings is positive.

i.e., $E_0 = E_{s1} - E_{s2} =$ positive

Condition 3

When the shaft starts rotating in the anti-clockwise direction, more portion of the core comes in contact with secondary winding S_2, when compared to S_2. Hence, the emf induced across the secondary winding S_2 is more than the emf induced across the secondary winding S_1 i.e., $E_{s1} < E_{s2}$. Therefore, the differential output drawn from these windings is negative

i.e., $E_0 = E_{s1} - E_{s2} =$ negative

The curve between the magnitude of differential output voltage and angular displacement is shown in Figure 6.51. The curve is linear for small angular displacements and beyond this range, it starts to deviate from the straight line. In practice, there will be some residual voltage in RVDT when the core is kept at null position.

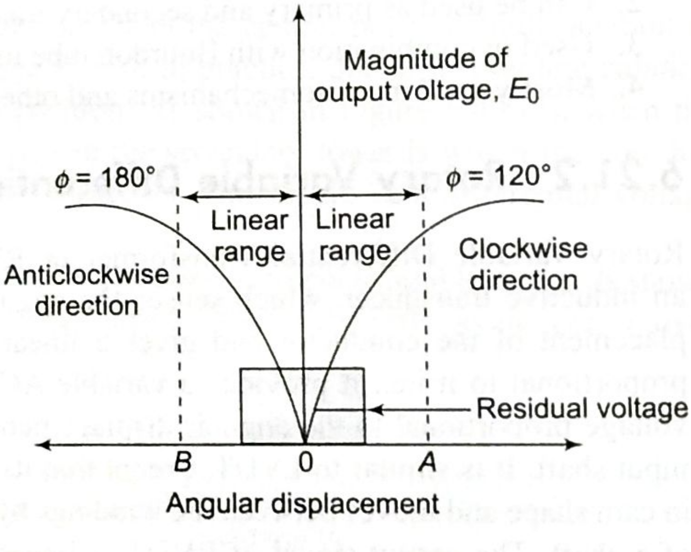


Figure 6.51 Input–Output Curve of RVDT

Advantages, Disadvantage and Applications of RVDT

The advantages, disadvantage and applications of RVDT are:

Advantages

1. Low cost due to popularity in application.
2. Solid and robust construction, which helps in operating it at different environmental conditions.
3. High accuracy and reliability can be achieved, as there is no frictional resistance.
4. Hysteresis is negligible.

Disadvantage

The RVDT provides linear output only for certain range of angular displacement.

Applications

The RVDT is used in:

1. Flight control actuation / navigation
2. Fuel-control valves
3. Cockpit controls
4. Signal conditioning as RVDT conditioner
5. Actuator feedback

6.22 CAPACITIVE TRANSDUCER

[AU Nov/Dec, 2014]

The capacitance of a parallel-plate capacitor is given by

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

where A is the area of each plate in m^2, d is the distance between parallel plates in m, ε_0 is the dielectric constant (permittivity) of free space in F/m and ε_r is the relative dielectric constant (permittivity).

The capacitance is directly proportional to the area of the plate (A) and inversely proportional to the distance between the parallel plates (d). Obviously, any variation in A or d causes a corresponding variation in the capacitance. This principle of variation in d is used in the capacitive transducer, as shown in Figure 6.52.

When a force is applied to a diaphragm, which acts as one plate of a capacitor, the distance between the diaphragm and the static plate is changed. The resulting change in capacitance can be measured with an AC bridge or an oscillator circuit in which an electric counter can measure the change in frequency and which is a measure of the magnitude of the applied force. In a capacitor microphone, the same principle is used, where the sound pressure varies the capacitance between the fixed plate and a movable diaphragm. The capacitive transducer can measure static and dynamic changes. The drawback of this transducer is its sensitivity to temperature variations.

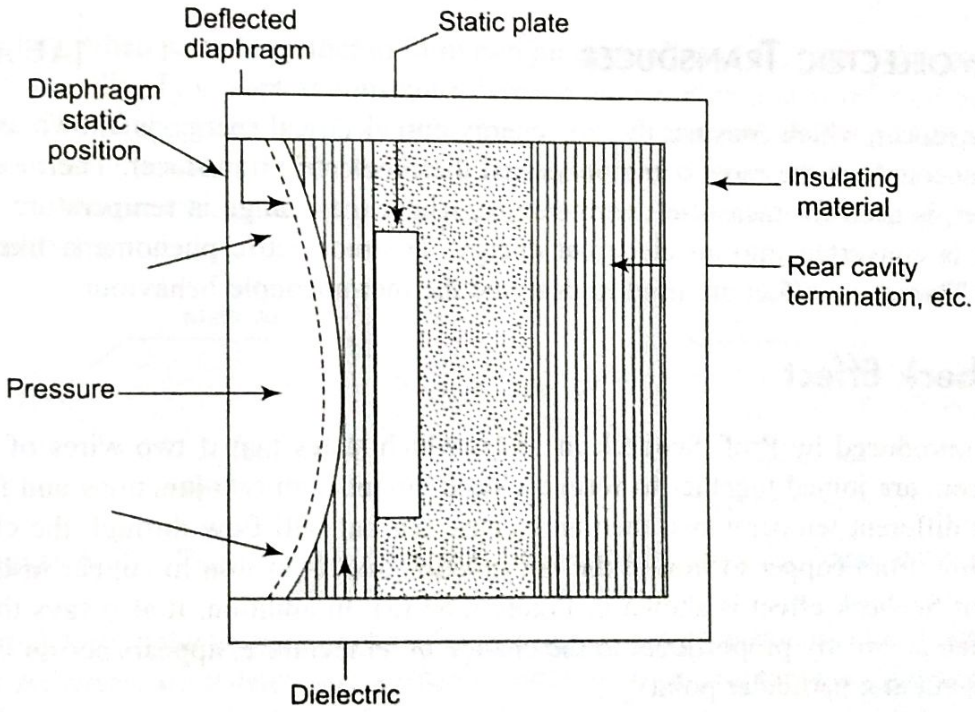


Figure 6.52 Capacitive Transducer

6.22.1 Advantages, Disadvantages and Applications of Capacitive Transducer

Advantages

1. Requires external force for operation, which makes it useful for small systems.
2. Highly sensitive and has good resolution.

3. Good frequency response.
4. Requires small power for its operation.
5. High input impedance decreases the loading effect.
6. It requires an external force for operation and hence very useful for small systems.

Disadvantages

1. Requires insulation.
2. Requires earthing to avoid stray magnetic field.
3. Sensitive to temperature changes, dust particles and moisture.
4. Presence of non-linear characteristics
5. Associates complex instrumentation circuitry.

Applications

1. Helps in measuring linear and angular displacement.
2. Used to measure force and pressure
3. Used as pressure transducer where change in dielectric constant occurs.
4. Measurement of humidity in the gases, volume, density and so on.

6.23 THERMOELECTRIC TRANSDUCER [AU April/May, 2011]

A temperature transducer, which converts thermal energy into electrical energy, is known as a thermoelectric transducer. Thermocouple is the most commonly used thermoelectric transducer. Thermocouple, a type of primary transducer, is used for measuring temperature, where the change in temperature arising from two dissimilar metals is converted into an electrical energy. Thermoelectric phenomena like Seebeck effect, Peltier effect and Thompson effect are used to describe the thermocouple behaviour.

6.23.1 Seebeck Effect

This effect was introduced by Prof. Seebeck in 1821, which states that if two wires of different metals, like copper and iron, are joined together to form a closed circuit with two junctions and if those junctions are maintained at different temperatures, then an electric current will flow through the closed circuit i.e., the current will flow from copper to iron in the hot junction and from iron to copper in the cold junction. The explanation of Seebeck effect is shown in Figure 6.53 (a). In addition, it also says that an emf called Seebeck emf, which is directly proportional to the change in temperature, appears across the open circuit if the copper wire is cut at a particular point.

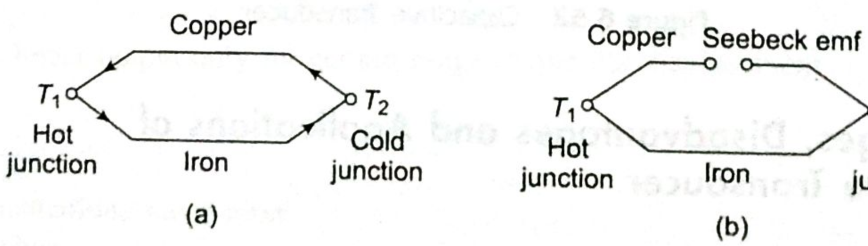


Figure 6.53 Seebeck Effect (a) Flow of Current (b) Emf

6.23.2 Peltier Effect

Professor Peltier introduced this effect, which is a reverse of Seebeck effect, in 1824. It states that if two wires of dissimilar metals form two junctions when an external voltage source is connected, as shown in Figure 6.54, then the current starts flowing through both the junctions. It also states that the heat is absorbed at a junction where the current is flowing from copper to iron, making the junction T_1 hot, and heat is liberated at a junction where the current is flowing from iron to copper, making the junction T_2 cold.

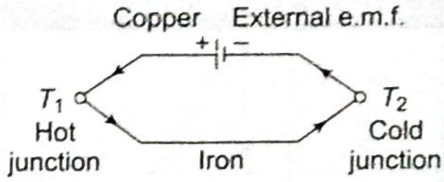


Figure 6.54 Peltier effect

6.23.3 Thompson Effect

It is a reversible heat flow effect, which was introduced by Professor Thompson. It states that when a current flows through the copper conductor with a thermal gradient along its length, then heat is released at a junction where the current and heat flow are in the same direction and heat is absorbed at a junction where different directions exist for current and heat flow.

6.23.4 Construction of a Thermocouple

Two dissimilar metals, when joined together to form two junctions T_1 and T_2, form a thermocouple, as shown in Figure 6.55 (a). Usually, T_2 is kept at constant reference temperature and is referred as cold junction or reference junction. The temperature which is to be measured is subjected to T_1 and hence it is referred as hot junction or measuring junction. When there is a temperature difference between T_1 and T_2, an emf that is proportional to the temperature gradient gets generated and can be measured using any meter or recorder, as shown Figure 6.55 (b).

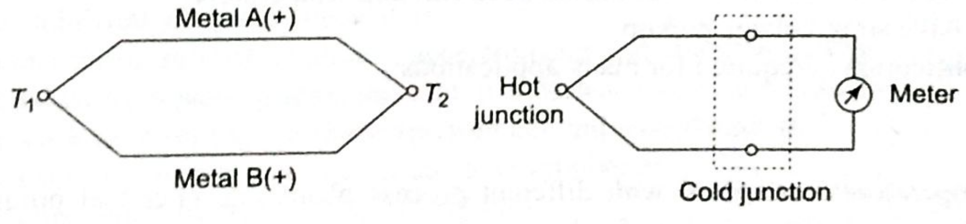


Figure 6.55 Thermocouple Circuit (a) Schematic Diagram (b) Practical Circuit

Generally, the junction in the thermocouple is formed in two ways: twisted weld and butt weld. In twisted weld, two large sized wires are twisted and welded together with several turns to give mechanical strength, while in butt weld, two comparatively small wires are fused together into a round bend. The normal sizes of metals are: 0.5 mm diameter for noble metals and 1.5 to 3 mm diameter for base metals.

6.23.5 Types of Thermocouples

Based on the materials used in the thermocouple and the range of temperature it can measure, the different types of thermocouples are listed in Table 6.6.

Table 6.6 *Types of Thermocouples*

Type of Thermocouples	Material Used	Temperature Range
T	Copper - constantan	–250°C to 400°C
J	Iron - constantan	–200°C to 850°C
K	Chromel - Alumel	–200°C to 110°C
E	Chromel - Constantan	–200°C to 850°C
S	Platinum - Platinum rhodium	0°C to 1400°C
—	Tungsten - molybdenum	0°C to 2700°C
—	Tungsten-Rhenium	0°C to 2600°C

Advantages, Disadvantages and Applications of Thermocouples

Advantages

1. Rugged construction
2. Covers wide range of temperature: –270°C to 2700°C
3. Most suitable for temperature measurement in industrial furnaces
4. Cheaper in cost
5. Easy to check the calibration
6. Offers good reproducibility
7. High response speed and good accuracy

Disadvantages

1. To have high accuracy, it is necessary to have cold junction compensation.
2. Non-linear characteristics exist between induced emf and temperature.
3. Possible to have stray voltage pickup.
4. Signal amplification is required for many applications.

Applications

1. Testing temperatures associated with different process plants e.g. chemical production, petroleum refineries, heating appliance safety, food industries, steel, iron and aluminium industries, plastics and resin industries.
2. Suitable for low temperature and cryogenic applications.
3. Temperature profiling in ovens, furnaces and kilns.
4. Temperature measurement of gas turbine and engine exhausts.

6.24 Piezoelectric Transducer [AU May/June, 2011]

If the dimensions of asymmetrical crystalline materials, such as quartz, Rochelle salt and barium titanite, are changed by the application of a mechanical force, the crystal produces an emf. This property is used in piezoelectric transducers. The basic circuit of a piezoelectric transducer is shown in Figure 6.56. Here, a crystal is placed between a solid base and the force-summing member. An externally applied force gives pressure to the top of the crystal. Hence, it produces an emf across the crystal, which is proportional to the magnitude of the applied pressure. As this transducer has a very good high-frequency response, it is used in high-frequency accelerometers. As it needs no external power source, it is called a self-generating transducer. The main drawbacks are that it cannot measure static conditions and the output voltage is affected by temperature variations of the crystal.

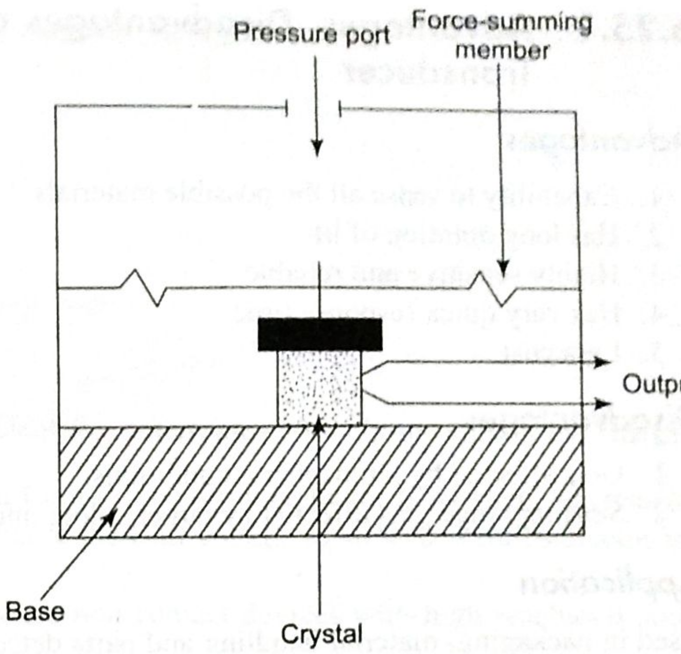


Figure 6.56 Piezoelectric Transducer

6.24.1 Advantages, Disadvantages and Applications of Piezoelectric Transducer

Advantages

1. Available in desired shape
2. Has rugged construction and it is smaller in size
3. Has good frequency response and negligible phase-shift

Disadvantages

1. Used in dynamic measurement only
2. Highly sensitive to temperature
3. Since some crystals are water-soluble, it might get dissolved in highly humid environment

Applications

1. Helps in stabilising electronic oscillators
2. Used in measuring surface roughness, accelerometer and vibration pickup
3. Used in industrial cleansing apparatus and in underwater detection systems
4. Used in spark-ignition engine, electronic watches and record players
5. Used as a sensing element e.g., piezoelectric microphones
6. Used in ultrasound imaging, chemical and biological sensors

6.25 Photoelectric Transducer

This is an optoelectronic or optical transducer, shown in Figure 6.57. It uses a phototube and a light source, separated by a small window, whose aperture is controlled by the force-summing device. The quantity of incident light on the photosensitive cathode is varied according to the externally applied force, thereby changing the anode current. This device measures both static and dynamic phenomena and it has high efficiency. It does not respond to high frequency light variation.

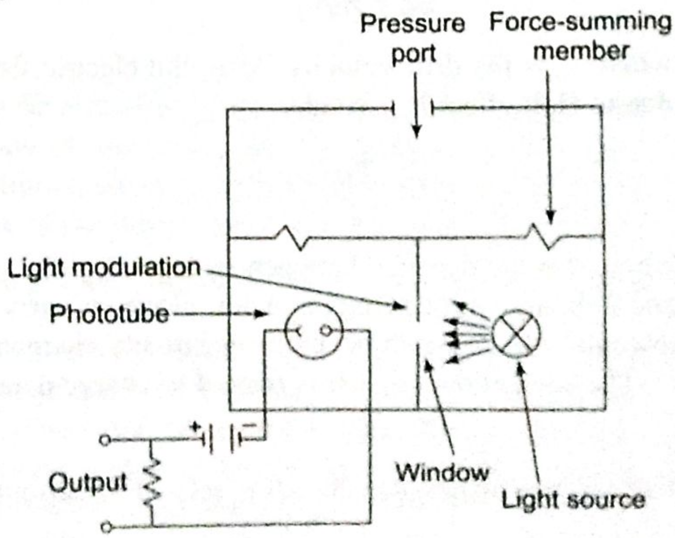


Figure 6.57 Photoelectric Transducer

6.25.1 Advantages, Disadvantages and Application of Photoelectric Transducer

Advantages

1. Capability to sense all the possible materials
2. Has long duration of life
3. Highly sensitive and reliable
4. Has very quick response time
5. Less cost

Disadvantages

1. Gets affected by atmospheric conditions.
2. Sensing range gets affected by target colour and reflexivity.

Application

Used in packaging, material handling and parts detection.

6.26 HALL EFFECT TRANSDUCERS

When a transverse magnetic field B is applied to a specimen (thin strip of metal or semiconductor) carrying current I, an electric field E is induced in the direction perpendicular to both I and B. This phenomenon is known as the *Hall effect*.

A Hall-effect measurement experimentally confirms the validity of the concept that it is possible for two independent types of charge carriers, electrons and holes, to exist in a semiconductor.

The schematic arrangement of the semiconductor, the magnetic field and the current flow pertaining to Hall effect are shown in Figure 6.58. Under equilibrium condition, the electric field intensity, E, due to the Hall effect must exert a force on the carrier of charge, q, which just balances the magnetic force, i.e.,

$$qE = Bqv_d$$

where v_d is the drift velocity. Also, the electric field intensity due to Hall effect is given by

$$E = \frac{V_H}{d}$$

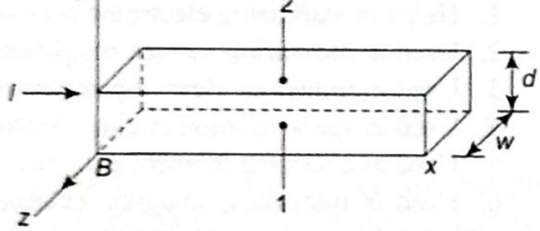


Figure 6.58 Schematic Diagram to Observe Hall Effect

where d is the distance between surfaces 1 and 2, and V_H is the Hall voltage appearing between surfaces 1 and 2. In an N-type semiconductor, electrons carry the current and these electrons will be forced downward towards side 1, which becomes negatively charged with respect to side 2.

The current density (J) is related to charge density (ρ) by

$$J = \rho v_d$$

Further, the current density (J) is related to current (I) by

$$J = \frac{I}{\text{Area}} = \frac{I}{wd}$$

where w is the width of the specimen in the direction of magnetic field (B).
Combining the above relations, we get

$$V_H = Ed = Bv_d d = \frac{BJd}{\rho} = \frac{BI}{\rho w}$$

The Hall coefficient, R_H, is defined by

$$R_H = \frac{1}{\rho}$$

so that $V_H = \frac{R_H}{w} BI$. A measurement of the Hall coefficient R_H, determines not only the sign of the charge carriers but also their concentration. The Hall coefficient for a P-type semiconductor is positive, whereas it is negative for an N-type semiconductor. This is true because the Hall voltage in a P-type semiconductor is of opposite polarity to that in an N-type semiconductor.

The advantage of Hall-effect transducers is that they are non-contact devices with high resolution and small size.

The Hall effect is used to find whether a semiconductor is N or P-type and to determine the carrier concentration. If the terminal 2 becomes charged positively with respect to terminal 1, the semiconductor must be N-type and $\rho = pq$, where n is the electron concentration. On the other hand, if the polarity of V_H is positive at terminal 1 with respect to terminal 2, the semiconductor must be P-type and $\rho = pq$, where p is the hole concentration.

The mobility (μ) can also be calculated with simultaneous measurement of the conductivity (σ). The conductivity and the mobility are related by the equation $\sigma = \rho\mu$ or $\mu = \sigma R_H$.

Therefore, the conductivity for N-type semiconductor is $\sigma = nq\mu_n$ and for P-type semiconductor, $\sigma = pq\mu_n$, where μ_n is the electron mobility and μ_p is the hole mobility.

Thus, if the conductivity of a semiconductor is also measured along with R_H, then mobility can be determined from the following relations.

For N-type semiconductor, $\mu_n = \frac{\sigma}{nq} = \sigma R_H$

and for P-type semiconductor, $\mu_p = \frac{\sigma}{pq} = \sigma R_H$

Since V_H is proportional to B for a given current I, Hall effect can be used to measure the AC power and the strength of magnetic field and sense the angular position of static magnetic fields in a magnetic field meter. It is also used in an instrument called Hall-effect multiplier, which gives the output proportional to the product of two input signals. If I is made proportional to one of the inputs and B is made proportional to the second signal, then from the equation, $V_H = \frac{BI}{\rho w}$, V_H will be proportional to the product of two inputs. Hall devices for such applications are made from a thin wafer or film of Indium Antimonide (InSb) or Indium Arsenide. As the material has very high electron mobility, it has high Hall coefficient and high sensitivity.

An electrical current can be controlled by a magnetic field because the magnetic field changes the resistances of some elements with which it comes in contact. In the magnetic bubble memory, while read-out, the Hall effect element is passed over the bubble. Hence, a change in current of the circuit will create, say, a *one*. If there is no bubble, there will be a *zero* and there will be no current change in the output circuit.

The read-in device would have an opposite effect, wherein the Hall device creates a magnetic field when supplied with a pulse of current. This, in turn, creates a little domain and then a magnetic bubble is created.

Some of the other applications are in measurement of velocity, rpm, sorting, limit sensing, and non-contact current measurements.

6.26.1 Advantages, Disadvantages and Applications of Hall Effect Transducers

Advantages

1. High-speed operation over 100 kHz is possible, whereas at high frequencies, the inductive or capacitive sensor output begins to distort.
2. As there is no wear and friction due to non-contact operation, the number of operating cycles is unlimited.
3. When packed, it is immune to dust, air and water, whereas dust triggers a capacitive sensor.
4. It can measure zero speed.
5. Highly repeatable operation.
6. Capable of measuring large current.

Disadvantages

1. Gets affected by external interfering magnetic field.
2. There exists a large temperature drift.
3. Large offset voltage.

Applications

1. Used in converting magnetic flux to electric transducer.
2. Used as current sensor.
3. Automotive fuel-level indicator.
4. Spacecraft propulsion.
5. Used in brushless DC motor to sense the position of the rotor.
6. Used in measuring power, current and displacement.

6.27 MECHANICAL TRANDUCERS

A transducer that converts one form of physical quantity to another is known as a mechanical transducer. This transducer is the primary transducer, which acts as an input to the electrical or secondary transducer. It can measure the physical quantities such as pressure, force, displacement, flow rate etc. The common mechanical transducers, which convert one form of physical quantity to another form, are:

- ***Flat spiral spring:*** It can produce the controlling torque in the instruments to measure electrical quantities.
- ***Torsion bar of shaft:*** The primary sensing element in torque meter, which is used to measure the torque, is known torsion bar of shaft. Its deflection or twist is directly proportional to the torque applied and hence its deformation is used to measure the torque.
- ***Proving ring:*** It is used to measure force, weight or load. It causes a deflection, which is further measured with the help of electrical transducer.

- ***Spring flexure pivot:*** It is a frictionless device used in measurements. The sensitivity of the device is almost constant for an angular displacement that is less than 15°.
- ***Bourdon tube:*** The different forms of Bourdon tubes are: (i) C type, (ii) spiral, (iii) twisted tube and (iv) helical, as shown in Figure 6.59. It is made of brass or phosphor bronze or beryllium copper or steel. It is made out of an elliptically sectioned elastic tube, which is bent to form the above-mentioned shapes. One end of the tube is closed and other end is opened for the liquid to enter. When the liquid, whose pressure is to be determined, enters the tube, a movement which can be measured is caused in the free end. It is normally used to measure gauge pressure.

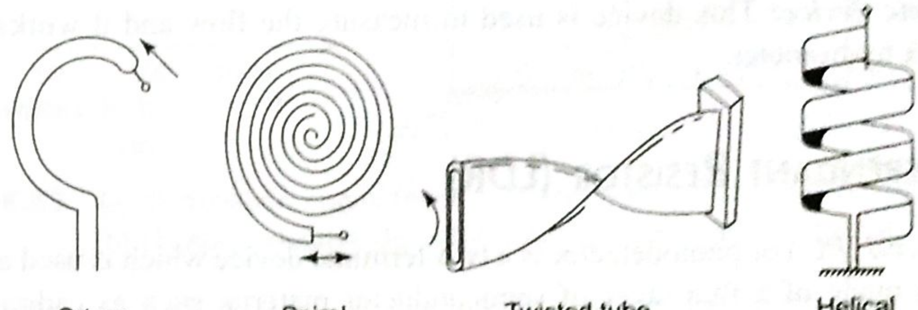


Figure 6.59 Bourdon Tubes

- ***Diaphragm:*** Flat and corrugated diaphragms, shown in Figure 6.60(a), are used to measure pressure by determining the displacement of the diaphragm. The pressure to be measured is applied at one side of the diaphragm and the other side is rigidly fixed. This type of arrangement causes deflection at the centre of the diaphragm, which is directly proportional to the pressure applied.

Figure 6.60(a) Diaphragms

Deformation occurs in the flat diaphragm, when a pressure P is applied to it, as shown in Figure 6.60(b). The relation between the pressure P applied and the displacement d_m at the centre of the diaphragm is given by

$$P = \frac{256Et^3 d_m}{2(1-v^2)D^4}\ \text{N/m}^2$$

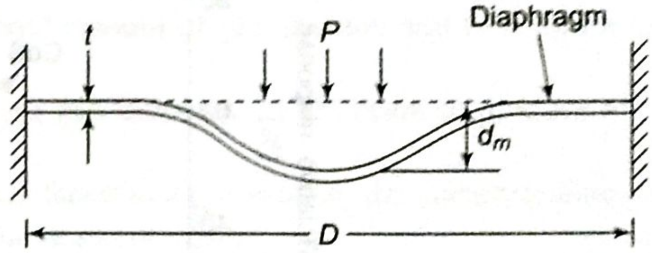


Figure 6.60(b) Flat Diaphragm with Pressure P Applied

where E is the Young's modulus in N/m², t is the thickness of the diaphragm in m, D is the diameter of the diaphragm in m, d_m is the deflection at the centre of the diaphragm in m and v is the Poisson's ratio.

The above relation between pressure P and d_m is linear for $d_m \leq 0.5t$ and non-linear in other cases.

- ***Bellow:*** A thin-walled tube, whose thickness is approximately 0.1 mm and having a corrugated shape, is known as bellow and is made up of a single piece of special brass or stainless steel. Figure 6.61 shows a simple bellow. It is also known as pressure-activated spring and its displacement for a particular pressure depends on its type and the thickness of the material used.

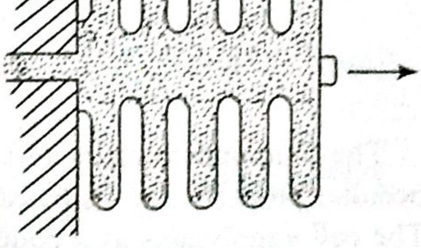


Figure 6.61 Bellow

- *Temperature detector:* The different principles used for detecting temperature are:
  - *Using bimetallic strip:* It consists of two different metals with different coefficients of thermal expansion, which are joint together. When the strip is heated due to expansion of metal, a deflection made by the bimetallic strip is converted into the movement of the pointer to indicate the temperature.
  - *Thermocouple:* Temperature is detected using the thermoelectric emf generated between two metals.
  - *Resistive thermometer and thermistor:* Temperature is detected by changing the resistance of the material used in it.
- *Hydro-pneumatic device:* This device is used to measure the flow and it works on the principle of simple float or a hydrometer.

6.28 LIGHT DEPENDANT RESISTOR (LDR)

The *photoconductive cell* (*PC*) or photodetector is a two-terminal device which is used as a Light Dependent Resistor (LDR). It is made of a thin layer of semiconductor material such as cadmium sulphide (CdS), lead sulphide (PbS), or cadmium selenide (CdSe) whose spectral responses are shown in Figure 6.62. The photoconducting device with the widest applications is the CdS cell, because it has high dissipation capability, with excellent sensitivity in the visible spectrum and low resistance when stimulated by light. The main drawback of CdS cell is its slower speed of response. PbS has the fastest speed of response.

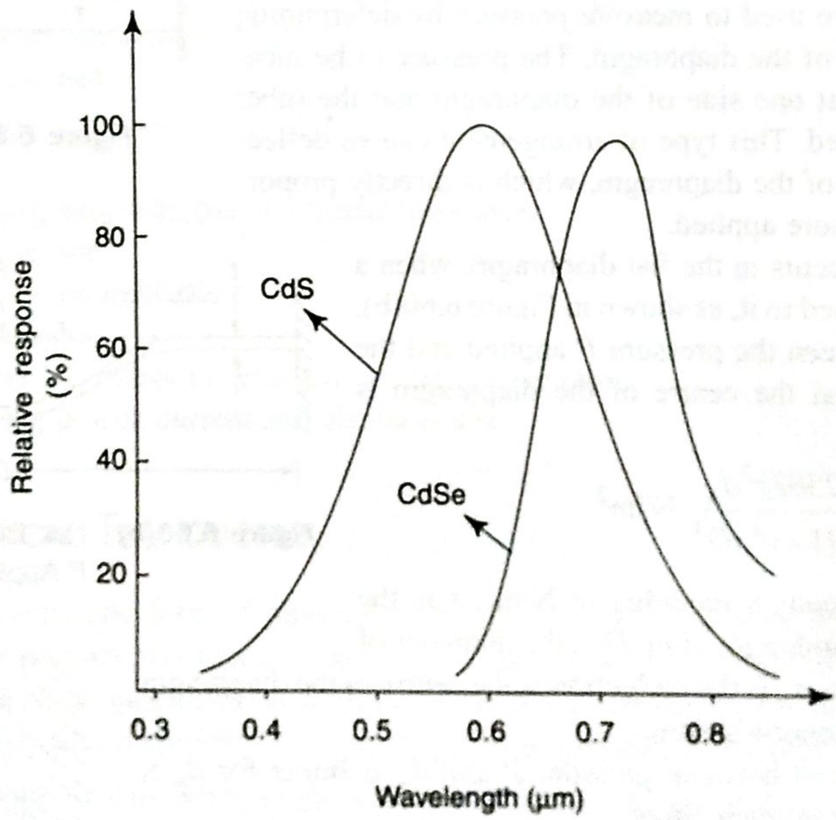


Figure 6.62 Spectral responses of CdS and CdSe

The illumination characteristics of photoconductive detectors are shown in Figure 6.63(a). It exhibits the peculiar property that its resistance decreases in the presence of light and increases in the absence of light. The cell simply acts as a conductor whose resistance changes when illuminated. In absolute darkness, the resistance is as high as 2 MΩ and in strong light, the resistance is less than 10 Ω.

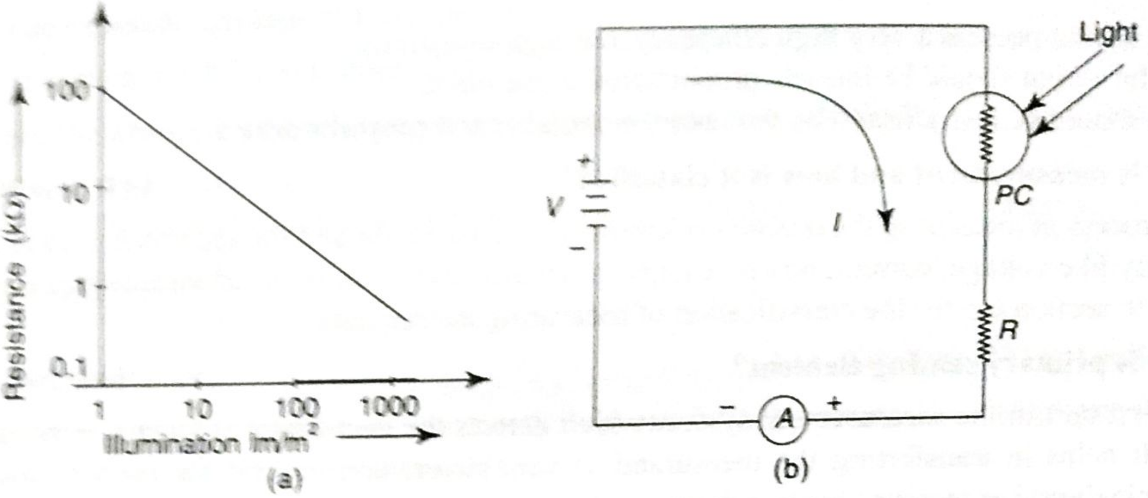


Figure 6.63 (a) Illumination characteristics of the photoconductive detector
(b) Photoconductive detector connected in a simple circuit

A simple circuit for a photoconductive detector is shown in Figure 6.63(b). The semiconductor layer is enclosed in a sealed housing. A glass window in the housing permits light to fall on the active material of the cell. Here, the resistance of the photoconductive detector, in series with R, limits the amount of current I in the circuit. The ammeter A is used to measure the current I. When no light falls on the cell, its resistance is very high and the current I is low. Hence, the voltage drop V_o across R is relatively low. When the cell is illuminated, its resistance becomes very low. Hence, current I increases and voltage V_o increases. Thus, this simple circuit arrangement with slight modification can be used in control circuits to control the current.

Applications

The detector is used either as an ON/OFF device to detect the presence or absence of a light source which is used for automatic street lighting or some intermediate resistance value can be used as a trigger level to control relays and motors. Further, it is used to measure a fixed amount of illumination and to record a modulating light intensity.

It is used in counting systems where the objects on a conveyor belt interrupt a light beam to produce a series of pulses which operates a counter.

It is used in twilight switching circuits. When the day light has faded to a given level, the corresponding resistance of the detector causes another circuit to switch ON the required lights.

It is widely used in cameras to control shutter opening during the flash. Twin photoconductive cells mounted in the same package have been used in optical bridge circuits for position control mechanisms and dual-channel remote volume control circuits.

Two Mark Questions and Answers

1. What are the basic elements of a generalised measurement system? **[AU Nov/Dec, 2013]**

Refer to section 6.3 for the basic elements of a generalised measurement system

2. Mention the basic requirements of measurement. **[AU Nov/Dec, 2014]**

The necessary or essential requirements for any measuring instrument are:

(i) When the instrument is used in the circuit, its conditions should not be altered and therefore the quantity to be measured goes unaffected.

(ii) It should consume low power as possible.
(iii) It should possess a very high efficiency and high sensitivity.
(iv) The output should be linearly proportional to the input.
(v) It should be less affected by the noise, modifiable and properly priced.

3. What is measurement and how is it classified? **[AU April/May, 2014]**

The process of measuring the quantity is known as measurement and the apparatus used to measure the quantity like voltage, current, power, energy, resistance and so on is called *measuring instrument*.
Refer to section 6.6 for the classification of measuring instruments

4. What is primary sensing element? **[AU Nov/Dec, 2012]**

The first unit in the measurement system which detects the measurand is known as primary sensing unit. It helps in transferring the measurand to variable-conversion unit for further processing. For example, liquid or mercury in glass thermometer acts as primary sensing unit. Displacement or voltage is the output in the primary sensing unit.

5. List any four static characteristics of a measuring system. **[AU April/May, 2012]**

Refer to section 6.4.1 for the static characteristics of a measuring system

6. Define the term 'accuracy'. **[AU April/May, 2012]**

Accuracy of a measured value of a quantity is defined as the closeness of the measured value obtained using instrument to the true value of the same quantity. It depends on the accuracy of the instrument itself, variation of the quantity which is to be measured, and observer accuracy, etc.

7. Define the term 'precision'. **[AU April/May, 2012]**

Precision comes from the term precise which indicates clearly or sharply defined and it is a measure of reproducibility of the measurements or a degree of agreement within a measurement group.

8. Define 'static error' and how are static errors classified. **[AU April/May, 2010]**

Static error is the difference between the measured value and true value of the quantity as given by

$$E_s = A_m - A_t$$

where A_m is the measured value of the quantity and A_t is the true value of the quantity
Refer to section 6.5 for classification of static errors.

9. Distinguish between reproducibility and repeatability. **[AU April/May, 2012]**

The reproducibility is the degree of closeness with which a given value may be repeatedly measured using the same instrument under different conditions like changes in the method of measurement, observer, measuring instrument location, conditions of use and time of measurement is known as reproducibility and is specified in terms of scale readings over a given period of time, whereas the repeatability is the instrument characteristic which describes the closeness with which a given value is repeatedly measured on the same instrument, same location, same observer, under the same measurement conditions and when the same input is given to the instrument repetitively over a particular time. It is specified as a variation in scale reading.

10. What is meant by dynamic characteristics of instruments? **[AU April/May, 2011]**

Refer to section 6.4.2 for the dynamic characteristics of instruments

11. Define "error" in measurement. **[AU April/May, 2013; Nov/Dec, 2014]**

The "error" in measurement is defined as the difference between the true or actual value and the measured value.

12. With one example, explain "Instrumental errors". **[AU Nov/Dec, 2012]**

Refer to section 6.5.2 for instrumental error.

13. How are the absolute and relative errors expressed mathematically? **[AU Nov/Dec, 2012]**

Absolute error: $E_s = A_m - A_t$

where A_m is the measured value of the quantity and A_t is the true value of the quantity.

Relative error: $E_r = \dfrac{E_s}{A_t}$

14. What is transducer? **[AU Nov/Dec, 2014; April/May, 2011]**

A transducer is a device which converts energy from one form to another. This energy may be electrical, mechanical, chemical, optical or thermal.

15. What is piezoelectric effect? **[AU April/May, 2015; Nov/Dec, 2011]**

If the dimensions of asymmetrical crystalline materials, such as quartz, Rochelle salt and barium titanite, are changed by the application of a mechanical force, the crystal produces an emf. This property is used in piezoelectric transducers.

16. Distinguish between active and passive transducers. **[AU Nov/Dec, 2013]**

Refer to section 6.28 for the difference between active and passive transducer.

17. How the transducers are classified on the basis of principle of transduction? **[AU April/May, 2010]**

On the basis of principle of transduction, the transducers are classified as

(i) Resistive transducer
(ii) Capacitive transducer
(iii) Inductive transducer

Example: piezoelectric, thermoelectric, magneto restrictive and so on

18. List the factors to be considered for selecting a transducer. **[AU April/May, 2012]**

The factors which are to be considered in selecting a transducer are:

(i) Linearity
(ii) Ruggedness
(iii) Repeatability
(iv) High stability and reliability
(v) Good dynamic response
(vi) Convenient instrumentation
(vii) Good mechanical characteristics

19. Define "gauge factor" of strain gauge. **[AU April/May, 2012]**

The sensitivity of a strain gauge described in terms of a characteristic called the gauge factor G is defined as the unit change in resistance per unit change in length, i.e., $G = \dfrac{\Delta R/R}{\Delta l/l} = \dfrac{\Delta R/R}{S}$

20. Mention the uses of capacitive transducer. **[AU Nov/Dec, 2011]**

Uses of capacitive transducer are:

(i) It helps in measuring linear and angular displacement
(ii) It is used to measure force and pressure
(iii) It is used as pressure transducer where change in dielectric constant occurs and
(iv) It is used to measure the humidity in the gases, volume and density