UNIT 7:

06 Hours

Nearly all engineering applications require some form of measuring, controlling, calculating, communicating and recording of data. These operations, grouped or isolated, are inherent in measurement instrumentation. If the equipment is to be used for the quantitative analysis of an analogue signal, i.e., a naturally occurring signal, the following must be taken into consideration:

The analogue signal to be measured may be temperature, pressure, humidity, velocity, flow rate, linear motion, position, amongst others. This signal must be converted into an analogue electrical signal, typically voltage or current, and then into a digital form that can be processed by an electronic circuit. The first task (see Fig. 1) requires sensors to convert the physical quantities into electrical signals.

Generally, the broad definition of a sensors/ transducers includes devices which convert physical quantities (mechanical force) into analogue electrical signal (in the range of millivolts or milliamps).

Fig. 1 Data acquisition block diagram

Classification of Transducers

The Classification of Transducers is done in many ways. Some of the criteria for the classification are based on their area of application, Method of energy conversion, Nature of
output signal, According to Electrical principles involved, Electrical parameter used, principle of operation, & Typical applications.

The transducers can be classified broadly

i. On the basis of transduction form used

ii. As primary and secondary transducers

iii. As active and passive transducers

iv. As transducers and inverse transducers.

Broadly one such generalization is concerned with energy considerations wherein they are classified as active & Passive transducers.

A component whose output energy is supplied entirely by its input signal (physical quantity under measurement) is commonly called a ‘passive transducer’. In other words the passive transducers derive the power required for transduction from an auxiliary source.

Active transducers are those which do not require an auxiliary power source to produce their output. They are also known as self generating type since they produce their own voltage or current output.

Some of the passive transducers (electrical transducers), their electrical parameter (resistance, capacitance, etc), principle of operation and applications are listed below.

The table 1 & 2 list the principle of operation and applications of the resistance transducers respectively.

The capacitive, inductive, etc transducers are listed next.
Table 1. Type & principle of operation of resistance transducers

<table>
<thead>
<tr>
<th>Resistance Transducer</th>
<th>Principle of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance Potentiometric device</td>
<td>Positioning of the slider by an external force varies the resistance in a potentiometer or a bridge circuit.</td>
</tr>
<tr>
<td>Resistance strain gage</td>
<td>Resistance of a wire or semiconductor is changed by elongation or compression due to externally applied stress.</td>
</tr>
<tr>
<td>Pirani gage or hot-wire meter</td>
<td>Resistance of a heating element is varied by convection cooling of a stream of gas.</td>
</tr>
<tr>
<td>Resistance thermometer</td>
<td>Resistance of pure metal wire with a large positive temperature coefficient of resistance varies with temperature.</td>
</tr>
<tr>
<td>Thermistor</td>
<td>Resistance of certain metal oxides with negative temperature coefficient of resistance varies with temperature.</td>
</tr>
<tr>
<td>Resistance hygrometer</td>
<td>Resistance of a conductive strip changes with moisture content.</td>
</tr>
</tbody>
</table>

Table 1. Type & applications of resistance transducers

<table>
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<tr>
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<th>Application</th>
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<tr>
<td>Resistance Potentiometric device</td>
<td>Pressure, displacement</td>
</tr>
<tr>
<td>Resistance strain gage</td>
<td>Force, torque, displacement</td>
</tr>
<tr>
<td>Pirani gage or hot-wire meter</td>
<td>Gas flow, gas pressure</td>
</tr>
<tr>
<td>Resistance thermometer</td>
<td>Temperature, radiant heat</td>
</tr>
<tr>
<td>Thermistor</td>
<td>Temperature</td>
</tr>
<tr>
<td>Resistance hygrometer</td>
<td>Relative humidity</td>
</tr>
<tr>
<td>Photoconductive cell</td>
<td>Photosensitive relay</td>
</tr>
</tbody>
</table>

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**Capacitance Transducers**

1. Variable capacitance pressure gage -

   Principle of operation: Distance between two parallel plates is varied by an externally applied force

   Applications: Measurement of **Displacement, pressure**

2. Capacitor microphone

   Principle of operation: Sound pressure varies the capacitance between a fixed plate and a movable diaphragm. Applications: **Speech, music, noise**

3. Dielectric gage

   Principle of operation: Variation in capacitance by changes in the dielectric.

   Applications: **Liquid level, thickness**

**Inductance Transducers**

1. Magnetic circuit transducer

   Principle of operation: Self inductance or mutual inductance of ac-excited coil is varied by changes in the magnetic circuit.

   Applications: **Pressure, displacement**

2. Reluctance pickup

   Principle of operation: Reluctance of the magnetic circuit is varied by changing the position of the iron core of a coil.

   Applications: **Pressure, displacement, vibration, position**

3. Differential transformer
Principle of operation: The differential voltage of two secondary windings of a transformer is varied by positioning the magnetic core through an externally applied force.

Applications: **Pressure, force, displacement, position**

4. Eddy current gage

   Principle of operation: Inductance of a coil is varied by the proximity of an eddy current plate.

   Applications: **Displacement, thickness**

5. Magnetostriction gage

   Principle of operation: Magnetic properties are varied by pressure and stress.

   Applications: **Force, pressure, sound**

*Voltage and current Transducers*

1. Hall effect pickup

   Principle of operation: A potential difference is generated across a semiconductor plate (germanium) when magnetic flux interacts with an applied current.

   Applications: **Magnetic flux, current**

2. Ionization chamber

   Principle of operation: Electron flow induced by ionization of gas due to radioactive radiation. Applications: **Particle counting, radiation**

3. Photoemissive cell

   Principle of operation: Electron emission due to incident radiation on photoemissive surface. Applications: **Light and radiation**

4. Photomultiplier tube
Principle of operation: Secondary electron emission due to incident radiation on photosensitive cathode.

Applications: **Light and radiation, photo-sensitive relays**

**Self-Generating Transducers (No External Power) – Active Transducers**

1. **Thermocouple and thermopile**

   Principle of operation: An emf is generated across the junction of two dissimilar metals or semiconductors when that junction is heated.

   Applications: **Temperature, heat flow, radiation**

2. **Moving-coil generator**

   Principle of operation: Motion of a coil in a magnetic field generates a voltage.

   Applications: **Velocity, vibration**

3. **Piezoelectric pickup**

   An emf is generated when an external force is applied to certain crystalline materials, such as quartz

   **Sound, vibration, acceleration, pressure changes**

4. **Photovoltaic cell**

   Principle of operation: A voltage is generated in a semi-conductor junction device when radiant energy stimulates the cell

   Applications: **Light meter, solar cell**
SELECTING A TRANSDUCER

In a measurement system the transducer is the input element with the critical function of transforming some physical quantity to a proportional electrical signal. Selection of the appropriate transducer is therefore the first and perhaps most important step in obtaining accurate results. A number of elementary questions should be asked before a transducer can be selected, for example,

What is the physical quantity to be measured?
Which transducer principle can best be used to measure this quantity?
What accuracy is required for this measurement?

Transducer selection depending on the physical quantity to be measured is Determined by the type and range of the measurand.

Which transducer principle can best be used?

An appropriate answer to the question requires that the input and output characteristic of the transducer be compatible with the recording or measurement system.

In most cases, these two questions can be answered readily, implying that the proper transducer is selected simply by the addition of an accuracy/ tolerance. In practice this is rarely possible due to the complexity of the various transducer parameters that affect the accuracy. The accuracy requirements of the total system determine the degree to which individual factors contributing to accuracy must be considered. Some of the factors affecting accuracy are:

1. **Fundamental transducer parameters.** : type and range of measurand, sensitivity, excitation

2. **Physical conditions** : mechanical and electrical connections, mounting provisions, corrosion resistance
3. Ambient conditions: nonlinearity effects, hysteresis effects, frequency response, resolution

4. Environmental conditions: temperature effects, acceleration, shock and vibration

5. Compatibility of the associated equipment: zero balance provisions, sensitivity tolerance, impedance matching, insulation resistance

The total measurement error in a transducer-activated system may be reduced to fall within the required accuracy range by the following techniques:

1. Using in-place system calibration with corrections performed in data reduction

2. Simultaneously monitoring the environment and correcting the data accordingly

3. Artificially controlling the environment to minimize possible errors

Some individual errors are predictable and can be calibrated out of the system. When the entire system is calibrated, these calibration data may then be used to correct the recorded data. Environmental errors can be corrected by data reduction if the environmental effects are recorded simultaneously with the actual data. Then the data are corrected by using the known environmental characteristics of the transducers. These two techniques can provide a significant increase in system accuracy.

Another method to improve overall system accuracy is to control artificially the environment of the transducer. If the environment of the transducer can be kept unchanged, these errors are reduced to zero. This type of control may require either physically moving the transducer to a more favorable position or providing the required isolation from the environment by a heater enclosure.

The following is the summary of the factors influencing the choice of a transducer for measurement of a physical quantity:

1. Operating principle
2. Sensitivity

3. Operating Range

4. Accuracy

5. Cross Sensitivity: Situations where the actual quantity is measured in one plane and the transducer is subjected to variations in another plane. More than one promising transducer design has had to be abandoned because the sensitivity to variations of the measured quantity in a plane perpendicular to the required plane has been such as to give completely erroneous results when the transducer has been used in practice.

6. Errors. The transducer should maintain the expected input-output relationship as described by its transfer function so as to avoid errors.

7. Transient and Frequency Response. The transducer should meet desired time domain specifications like peak overshoot, rise time, settling time and small dynamic error. It should ideally have a flat frequency response curve. In practice, however, there will be cutoff frequencies and higher cut off frequency should be high in order to have a wide bandwidth.

8. Loading Effects. The transducer should have a high input impedance and a low output impedance to avoid loading effects.

9. Environmental Compatibility. It should be assured that the transducer selected to work under specified environmental conditions maintains its input/output relationship and does not break down. For example, the transducer should remain operable under its temperature range. It should be able to work in corrosive environments, should be able to withstand pressures and shocks and other interactions to which it is subjected to.

10. Insensitivity to Unwanted Signals. The transducer should be minimally sensitive to unwanted signals and highly sensitive to desired signals.
11. Usage and Ruggedness. The ruggedness both of mechanical and electrical intensities of transducer versus its size and weight must be considered while selecting a suitable transducer.

12. Electrical aspects. The Electrical aspects that need consideration while selecting a transducer include the length and type of cable required. Attention also must be paid to signal to noise ratio in case the transducer is to be used in conjunction with amplifiers.

13. Stability and Reliability. The transducers should exhibit a high degree of stability during its operation and storage life. Reliability should be assured in case of failure of transducer in order that the functioning of the instrumentation system continues unaffected.

14. Static Characteristics. Apart from low static error, the transducers should have a low nonlinearity, low hysteresis, high resolution and a high degree of repeatability. The transducer selected should be free from load alignment effects. It should not need frequent calibration, should not have any component limitations, and should be preferably small in size.
Resistive Transducers

The resistance of a metal conductor is expressed by a simple equation that involves a few physical quantities. The relationship is \( R = \frac{\rho L}{A} \), where \( R \) = resistance \( \Omega \), \( L \) = length of conductor m, \( A \) = cross-sectional area of conductor \( m^2 \), and \( \rho \) = resistivity of conductor material \( \Omega m \).

Any method of varying one of the quantities involved in the above relationship can be the design basis of an electrical resistive transducer.

Strain gauges

Strain gauges work on the principle that the resistance of a conductor or a semiconductor changes when strained. This property can be used for measurement of displacement, force and pressure. The resistivity of materials also changes with change of temperature thus causing a change of resistance. If a metal conductor is stretched or compressed, its resistance changes on account of the fact that both length and diameter of conductor change. Also there is a change in the value of resistivity of the conductor when it is strained and this property is piezoresistive effect. Therefore, resistance strain gauges are also known as piezoresistive gauges.

The strain gauges are used for measurement of strain and associated stress in experimental stress analysis. Secondly, many other detectors and transducers, notably the load cells, torque meters, diaphragm type pressure gauges, temperature sensors, accelerometers and flow meters, employ strain gauges as secondary transducers.

Theory of Strain Gauges

The change in the value of resistance by straining the gauge may be partly explained by the normal dimensional behaviour of elastic material.

If a strip of elastic material is subjected to tension, as shown in Fig.1 or in other words positively strained, its longitudinal dimension will increase while there will be a reduction in the lateral dimension.
In order to find how $\Delta R$ depends upon the material physical quantities, the expression for $R = \frac{\rho L}{A}$ is differentiated with respect to stress $s$

$$\frac{dR}{dS} = \frac{\rho}{A} \frac{\partial L}{\partial s} + \frac{L}{A} \frac{\partial \rho}{\partial s} - \frac{\rho L}{A^2} \frac{\partial A}{\partial s}$$

Dividing by $R = \frac{\rho L}{A}$ on both sides we get

$$\frac{dR}{dS} = \frac{1}{L} \frac{\partial L}{\partial s} + \frac{1}{\rho} \frac{\partial \rho}{\partial s} - \frac{1}{A} \frac{\partial A}{\partial s}$$

Observe that per unit change in resistance is due to per unit change in length $\Delta L/L$, per unit change in area $\Delta A/A$, per unit change in resistivity $\Delta \rho/\rho$

Substituting the Area in terms of Diameter $D$ as

$$A = \frac{\pi}{4} D^2 \quad \therefore \quad \frac{\partial A}{\partial s} = 2 \cdot \frac{\pi}{4} D \cdot \frac{\partial D}{\partial s}$$

now the equation $\frac{dR}{dS} = \frac{1}{L} \frac{\partial L}{\partial s} - \frac{1}{A} \frac{\partial A}{\partial s} + \frac{1}{\rho} \frac{\partial \rho}{\partial s}$ becomes
Using Poisson’s ratio

\[
\frac{1}{R} \frac{dR}{ds} = \frac{1}{L} \frac{\partial L}{\partial s} - \frac{2}{D} \frac{\partial D}{\partial s} + \frac{1}{\rho} \frac{\partial \rho}{\partial s}
\]

For small variations, the above relationship can be rewritten as

\[
\frac{\Delta R}{R} = \frac{\Delta L}{L} + 2\nu \frac{\Delta L}{L} + \frac{\Delta \rho}{\rho}
\]

**Gauge factor**

Gauge factor is defined as the ratio of per unit change in resistance to per unit change in length

\[
G_f = \frac{\Delta R/R}{\Delta L/L}
\]

\[
\frac{\Delta R}{R} = G_f \frac{\Delta L}{L} = G_f \times \varepsilon
\]

\[
\epsilon = \text{strain} = \frac{\Delta L}{L}
\]

Hence the Gauge factor \( G_f = 1 + 2\nu + (\Delta \rho/\rho)/\varepsilon \)
Where the term 1 => Resistance change due to change of length, 2ν => Resistance change due to change in area , (Δρ/ρ)/ε => Resistance change due to piezoresistive effect

The strain is usually expressed in terms of microstrain. 1 microstrain = 1 µm/m.

If the change in the value of resistivity of a material when strained is neglected, the gauge factor is:

\[ G_f = 1 + 2\nu \]

The common value for Poisson's ratio for wires is 0.3. This gives a gauge factor of 1.6 for wire wound strain gauges. Poisson's ratio for all metals is between 0 & 0.5. This gives a value of 2

**Example 1:** A resistance wire strain gauge uses a soft iron wire of small diameter. The gauge factor is +4.2. Neglecting the piezoresistive effects, calculate the Poisson's ratio.

**Solution.** The gauge factor is given by Eqn., \[ G_f = 1 + 2\nu = 4.2 \]

Poisson's ratio = \( \nu = (4.2 - 1)/2 = 1.6 \)

**Example 2:** A compressive force is applied to a structural member. The strain is 5 micro-strain. Two separate strain gauges are attached to the structural member, one is a nickel wire strain gauge having a gauge factor of -12.1 and the other is nichrome wire strain gauge having a gauge factor of 2. Calculate the value of resistance of the gauges after they are strained. The resistance of strain gauges before being strained is 120 \( \Omega \).

**Solution:** compressive strain is taken a negative \( \varepsilon = -5 \times 10^{-6} \)

We have \( \Delta R/R = G_f \varepsilon \).

Hence, Change in value of resistance of nickel wire strain gauge =

\[ \Delta R = R \times G_f \times \varepsilon = 120 \times (-12.1) \times (-5 \times 10^{-6}) = 7.26 \Omega \text{ (increase in resistance)} \]

Similarly for nichrome it is 120x(2)x(-5x10^{-6}) = -1.2 \( \Omega \) (decrease)
Strain gauges are broadly used for two major types of applications and they are: (i) experimental stress analysis of machines and structures, and (ii) construction of force, torque, pressure, flow and acceleration transducers.

Types of Strain Gauges

1. Unbonded metal strain gauges
2. Bonded metal wire strain gauges
3. Bonded metal foil strain gauges
4. Vacuum deposited thin metal film strain gauges
5. Sputter deposited thin metal strain gauges
6. Bonded semiconductor strain gauges
7. Diffused metal strain gauges.

Unbonded Metal Strain Gauge

An unbonded metal strain gauge is shown in Fig.2. This gauge consists of a wire stretched between two points in an insulating medium such as air. The wires are of copper nickel, chrome nickel or nickel iron alloys. The flexture element is connected via a rod to a diaphragm which is used for sensing of pressure. The wires are tensioned to avoid buckling when they experience a compressive force.
The unbonded metal wire gauges, used almost exclusively in transducer applications, employ preloaded resistance wires connected in a Wheatstone bridge as shown in Fig. 3.

Fig. 2

Fig. 3.
At initial preload, the strains and resistances of the four arms are nominally equal, with the result the output voltage of the bridge, \( e_0 = 0 \). Application of pressure produces a small displacement which is about 0.004 mm (full scale), the displacement increases tension in two wires and decreases it in the other two thereby increasing the resistance of two wires which are in tension and decreasing the resistance of the remaining two wires. This causes an unbalance of the bridge producing an output voltage which is proportional to the input displacement and hence to the applied pressure. Electric resistance of each arm is 120 \( \Omega \) to 1000 \( \Omega \), the input voltage to the bridge is 5 to 10 V, and the full scale output of the bridge is typically about 20 mV to 50 mV.

Some of the unbonded metal wire gauges are shown in Fig. 4.
Bonded Metal Foil Strain Gauges

This class of strain gauges is only an extension of the bonded metal wire strain gauges. The bonded metal wire strain gauges (Fig. 5) have been completely superseded by bonded metal foil strain gauges.

Advantages

The spreading of wire permits a uniform distribution of stress over the grid. The carrier is bonded with an adhesive material to file specimen under study. This permits a good transfer of strain from carrier to grid of wires. The wires cannot buckle as they are embedded in a matrix of cement and hence faithfully follow both the tensile and compressive strains of the specimen.
Foil type gauges have a much greater heat dissipation capacity as compared with wire wound strain gauges on account of their greater surface area for the same volume. For this reason, they can be used for higher operating temperature range. Also the large surface area leads to better bonding. The sensing elements of foil gauges are formed from sheets less than 0.005 mm thick by photocopying process, which allow greater flexibility with regard to shape.

**Evaporation Deposited Thin Metal Strain Gauges**

Evaporation deposited thin film metal strain gauges are mostly used for the fabrication of transducers. They are of sputter deposited variety. Both processes begin with a suitable elastic metal element. The elastic metal element converts the physical quantity into a strain. To cite an example of a pressure transducer, a thin, circular metal diaphragm is formed. Both the evaporation and sputtering processes form all the strain gauge elements directly on the strain surface, they are not separately attached as in the case of bonded strain gauges.

**Semiconductor Strain Gauges**
For a high sensitivity, a high value of gauge factor is desirable. A **high gauge factor** means a relatively higher change in **resistance** which can be **easily measured** with a good degree of accuracy. Semiconductor strain gauges are used where a very **high gauge factor and a small envelope** are required. They depend for their action upon **piezo-resistive effect** *i.e.* the change in the value of the resistance due to change in resistivity. Semi-conducting materials such as silicon and germanium are used as resistive materials.

![Fig. 6](image)

A typical strain gauge consists of a strain sensitive crystal material and leads that are sandwiched in a protective matrix as shown in Fig.6. The production of these gauges employs conventional semi-conductor technology using semi-conducting wafers or filaments which have a thickness of 0.05 mm and bonding them on a suitable insulating substrates, such as teflon. Gold leads are generally employed for making the contacts.

**Advantages:** high gauge factor of about 130. This allows measurement of very small strains of the order of 0.01 microstrain. Hysteresis characteristics of semi-conductor strain gauges are excellent. Some units maintain it to less than 0.05%. Fatigue life is in excess of 10 x 10^6 operations and the frequency response is upto 10^{12} Hz. Semi-conductor strain gauges can be very small ranging in length from 0.7 to 7 mm. They are very useful for measurement of local strains.

**Disadvantages:** The major and serious disadvantage of semiconductor strain gauges is that they are very sensitive to changes in temperature, Linearity of the semi-conductor strain gauge is poor, semi-conductor strain gauges are more expensive and difficult to attach to the object under study.
**Diffused Strain Gauges**

are primarily used in transducers. The diffusion process used in IC manufacture is employed. In pressure transducers, for example, the diaphragm would be of silicon rather than metal and the strain gauge effect would be realized by depositing impurities in the diaphragm to form an intrinsic strain gauge. This type of construction may allow lower manufacturing costs in some designs, as a large number of diaphragms can be made on a single silicon wafer.

**Rosettes**

In addition to single element strain gauges, a combination of strain gauges called "Rosettes" are available in many combinations for specific stress analysis or transducer applications. In practical problems, an element may be subjected to stresses in any direction and hence it is not possible to locate the direction of principle stress. Therefore, it is not possible to orient the strain gauges along the direction of principle stress. Hence there is a necessity to evolve a strain gauge measurement system which measures the values of principle strains and stresses without actually knowing their directions. The solution to the problem lies in using three strain gauges to form a unit called a *Rosette* as shown in Fig. 7.

3-Element Rosette60º Planer (foil)
3-Element Rosette 60° Planer (wire)

3-Element Rosette 90° Planer (foil)
2-Element Rosette 90° Planer (foil)

2-Element Rosette 45° Planer (foil)

Fig. 7
LVDT

DISPLACEMENT TRANSDUCERS

The concept of converting an applied force into a displacement is basic to many types of transducers. The mechanical elements that are used to convert the applied force into a displacement are called force-summing devices.

Some of the Force-summing Devices Used by Pressure transducers are

1) Diaphragm, flat or corrugated
2) Bellows
3) Bourdon tube, circular or twisted
4) Straight tube

Some of the Force-summing Devices Used in accelerometer and vibration pickups are

1) Mass cantilever, single or double suspension
2) Pivot torque

The above Force-summing Devices are shown in Fig. 8

The displacement created by the action of the force-summing device is converted into a change of some electrical parameter.

The electrical principles commonly used in the measurement of displacement are Capacitive, Inductive, Differential transformer, Ionization, Oscillation, Photoelectric, Piezoelectric, Potentiometric
Diaphragm

Bellows

Bourdon tube
Mass cantilever (single or double suspension)

Fig. 8
Linear Variable Differential Transformer – LVDT Transducer

The differential transformer transducer measures force in terms of the displacement of the ferromagnetic core of a transformer. The basic construction of the LVDT is given in Fig. 9. The transformer consists of a single primary winding and two secondary windings which are placed on either side of the primary. The secondaries have an equal number of turns but they are connected in series opposition so that the emfs induced in the coils OPPOSE each other. The position of the movable core determines the flux linkage between the ac-excited primary winding and each of the two secondary winding.

![Fig. 9 Construction of the LVDT](image-url)
Relative positions of the core generate the indicated output voltages as shown in Fig. 10. The linear characteristics impose limited core movements, which are typically up to 5 mm from the null position.

With the core in the center, (or reference position or Fig. 11,), the induced emfs in the secondaries are equal, and since they oppose each other, the output voltage will be 0 V. When an externally applied force moves the core to the left-hand position, more magnetic flux links the left-hand coil than the right-hand coil and the Differential Output $E_0 = E_{S1} - E_{S2}$ is in-phase with $E_i$ as $E_{S1} > E_{S2}$. The induced emf of the left hand coil is therefore larger than the induced emf of the right-hand coil. The magnitude of the output voltage is then equal to the difference between the two secondary voltages, and it is in phase with the voltage of the left-hand coil.

Similarly, when the core is forced to move to the right, more flux links the right-hand coil than the left-hand coil and the resultant output voltage is now in phase with the emf of
the right-hand coil, while its magnitude again equals the difference between the two induced emfs.

Fig. 11
Ideally the output voltage at the null position should be equal to zero. In actual practice there exists a small voltage at the null position. (refer Fig. 12). This may be on account of presence of harmonics in the input supply voltage and also due to harmonics produced in the output voltage due to use of iron Displacement core. There may be either an incomplete magnetic or electrical unbalance or both which result in a finite output voltage at the null position. This finite residual voltage is generally less than 1% of the maximum output voltage in the linear range. Other causes of residual voltage are stray magnetic fields and temperature effects.
Example 1:

The output of an LVDT is connected to a 5 V voltmeter through an amplifier whose amplification factor is 250. An output of 2 mV appears across the terminals of LVDT when the core moves through a distance of 0.5 mm. Calculate the sensitivity of the LVDT and that of the whole set up. The milli-voltmeter scale has 100 divisions. The scale can be read to 1/5 of a division. Calculate the resolution of the instrument in mm.

Solution:

sensitivity of the LVDT = output voltage / displacement = 2 x 10^{-3} / 0.5

= 4 x 10^{-3} V/mm = 4mV/mm

sensitivity of the Instrument = amplification factor x sensitivity of LVDT

= 4 x 10^{-3} X 250 = 1V/mm = 1000 mV/mm

1 scale division = 5/100 V = 50mV

Minimum voltage that can be read on the voltmeter = (1/5) x 50 = 1mV

Resolution of instrument = 1 x 10^{-3} mm

Applications of LVDT

Acting as a secondary transducer it can be used as a device to measure force, weight and pressure etc. The force measurement can be done by using a load cell as the primary transducer while fluid pressure can be measured by using Bourdon tube which acts as primary transducer. The force or the pressure is converted into a voltage.

In these applications the high sensitivity of LVDTs is a major attraction.
Resistive Transducers for Pressure Measurement

The electrical strain gauges attached to a diaphragm as shown in Fig. 13 may be used for measurement of pressure.

![Diagram of strain gauges and diaphragm](image)

Fig. 13

The output of these strain gauges is a function of the local strain, which in turn is a function of the diaphragm deflection and the differential pressure.

The deflection generally follows a linear variation with differential pressure

\[ P = P_2 - P_1 \] (when the deflection is less than one third of the diaphragm thickness.)

One of the disadvantages of the method is the small physical area is required for mounting the strain gauges. Change in resistance of strain gauges on account of application of pressure is calibrated in terms of the differential pressure. Gauges of this type are made in sizes having a lower range of : 100 kN/m² to 3 MN/m² to an upper range of 100 kN/m² to 100 MN/m².
Inductive Transducers for Pressure Measurement

Inductive transducers have been used as secondary transducers along with a diaphragm for measurement of pressure. Fig.14 shows an arrangement which uses two coils; an upper and a lower coil which form the two arms of an a.c. bridge.

The coils have equal number of turns. The other two arms of the bridge are formed by two equal resistances each of value R. The diaphragm is symmetrically placed with respect to the coils when \( P_1 = P_2 \), the reluctances of the paths of magnetic flux for both the coils are equal and hence the inductances of the coils are equal. Under this condition the bridge is balanced and the output \( e_{o} \), of the bridge is zero. Suppose \( P_2 \) is greater than \( P_1 \) and the differential pressure \( P = P_2 - P_1 \) deflects the diaphragm upwards through a distance \( d \) the reluctance of the flux path of the upper and lower coils vary. The bridge becomes unbalanced and the output voltage is directly proportional to displacement \( d \).
Measurement of Temperature

The principles used in the measurement of pressure are also applied in the measurement of temperature, flow and liquid levels. Hence some of the working principles of the instruments are repeated.

Resistance Thermometers

Resistance-temperature detectors, or resistance thermometers, employ a sensitive element of extremely pure platinum, copper, or nickel that provides definite resistance value at each temperature within its range.

Principle of working: The resistance of a conductor changes when its temperature is changed. This property is utilized for measurement of temperature. The variation of resistance R with temperature T (°K) can be represented by the following relationship for most of the metals as:

\[ R = R_0 (1 + \alpha_1 T + \alpha_2 T^2 + \ldots + \alpha_n T^n + \ldots) \]

where \( R_0 \) = resistance at temperature \( T = 0 \) and \( \alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_n \) are constants.

The resistance thermometer uses the change in electrical resistance of conductor to determine the temperature. The resistivity of metals showing a marked dependence on temperature was discovered by Sir Humphry Davy.

RTD - resistance temperature detector

All metals produce a positive change in resistance with temperature. The requirements of a conductor material to be used in RTDs are:

(i) The change in resistance of material per unit change in temperature should be as large as possible. This implies a metal with a high value of resistivity should be used for RTDs.

ii) The material should have a high value of \( \alpha \) so that minimum volume of material is used.

\[ R_t = R_{ref} (1 + \alpha \Delta T) \]

A high value of \( \alpha \) is desirable in a temperature-sensing element so that a substantial change in resistance occurs for a relatively small change in temperature.
This change in resistance ($\Delta R$) can be measured with a Wheatstone bridge which may be calibrated to indicate the temperature that caused the resistance change rather than the resistance itself.

Fig. 15 shows the variation of resistance with temperature for several commonly used materials. The graph indicates that the resistance of platinum and copper increases almost linearly with increasing temperature, while the characteristic for nickel is decidedly nonlinear.
The sensing element of a resistance thermometer is selected according to the intended application. The Table below summarizes the characteristics of the three most commonly used resistance materials. Platinum wire is used for most laboratory work and for industrial measurements of high accuracy. Nickel wire and copper wire are less expensive and easier to manufacture than platinum wire elements, and they are often used in low-range industrial applications.

<table>
<thead>
<tr>
<th>Type</th>
<th>Temperature range ±°F</th>
<th>Accuracy ±°F</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platinum</td>
<td>−300°F to +1,500°F</td>
<td>±1°F</td>
<td>Low cost High stability Wide operating range</td>
<td>Relatively slow response time (15 s) Not as linear as copper thermometers</td>
</tr>
<tr>
<td>Copper</td>
<td>−325°F to +250°F</td>
<td>±0.5°F</td>
<td>High linearity High accuracy in ambient temperature range High stability</td>
<td>Limited temperature range (to 250°F)</td>
</tr>
<tr>
<td>Nickel</td>
<td>+32°F to −150°F</td>
<td>±0.5°F</td>
<td>Long life High sensitivity High temperature coefficient</td>
<td>More nonlinear than copper Limited temperature range (to 150°F)</td>
</tr>
</tbody>
</table>

Resistance thermometers are generally of the probe type (see Fig. 16) for immersion in the medium whose temperature is to be measured or controlled. A typical sensing element for a probe-type thermometer is constructed by coating a small platinum, or silver tube with ceramic material, winding the resistance wire over the coated tube, and coating the finished winding again with ceramic. This small assembly is then fired at high temperature to assure annealing of the winding and then it is placed at the tip of the probe, The probe is protected by a sheath to produce the complete sensing element. Practically all resistance thermometers for industrial applications are mounted in a tube or well to provide protection against mechanical damage and to guard against contamination and eventual failure. Protecting tubes are used at atmospheric pressure; when they are equipped with a pipe thread bushing, they may be exposed to low or medium pressures. Metal tubes offer adequate protection to
the sensing element at temperatures to 2100 °F, although they may become slightly porous at temperatures above 1,500°F and then fail to protect against contamination.

Fig. 16

A typical bridge circuit with resistance thermometer \( R_t \) in the unknown position is shown in Fig. 17. The function switch connects three different resistors in the circuit.
The Wheatstone bridge has certain **disadvantages** when it is used to measure the resistance variations of the resistance thermometer. These are the effect of contact resistances of connections to the bridge terminals, heating of the elements by the unbalance current, and heating of the wires connecting the thermometer to the bridge. Slight modifications of the Wheatstone bridge, such as the double slide-wire bridge, eliminate most of these problems.

Despite these measurement difficulties, the resistance thermometer method is so accurate that it is one of the standard methods of temperature measurement within the range -183 to 630°C.

To this day platinum is used as the primary element in all high accuracy resistance thermometers. In fact, the platinum resistance temperature detector (PRTD) (see Fig. 17) is used as an interpolation standard from oxygen point (-182.96) to antimony point (630.74 °C). *Platinum* is especially suited for this purpose, as it can **withstand high temperatures** while **maintaining excellent stability**. As a noble metal, it shows **limited susceptibility to contamination**.
Fig. 17 Industrial Platinum Resistance Thermometer
**Thermistors**

Some materials, such as carbon and germanium, have a negative temperature coefficient of resistance that implies that the resistance decreases with an increase in temperature.

Thermistors or *thermal resistors*, are semiconductor devices that behave as resistors with a high, usually *negative temperature coefficient of resistance*.

In some cases, the resistance of a thermistor at room temperature may decrease as much as 6 per cent for each 1°C rise in temperature. This high sensitivity to temperature change makes the thermistor extremely well suited to precision temperature *measurement, control, and compensation*. Thermistors are widely used in *applications*, especially in the lower temperature range of -100°C to 300°C. Thermistors are composed of a sintered mixture of metallic oxides, such as manganese, nickel, cobalt, copper, iron, and uranium. Their resistances range from 0.5 Ω to 75 MΩ and they are available in a wide variety of shapes and sizes. Smallest in size are the beads with a diameter of 0.15 mm to 1.25 mm.

Beads may be sealed in the tips of solid glass rods to form probes that are somewhat easier to mount than beads. Disks and washers are made by pressing thermistor material under high pressure into flat cylindrical shapes with diameters from 2.5 mm to 25 mm. Washers can be stacked and placed in series or in parallel for increased power dissipation.
Thermistors for Measurement of Temperature:

A thermistor produces a large change of resistance with a small change in the temperature being measured. This large sensitivity of thermistor provides good accuracy and resolution. A typical industrial-type thermistor with a 2000 Ω resistance at 25°C and a resistance temperature co-efficient of 3.9% per °C exhibits a change of 78 Ω per degree °C change in temperature.

![Simple Series Circuit for Measurement of Temperature Using a Thermistor](image)

Fig. 18 Simple series circuit for measurement of temperature using a thermistor

![Measurement of Temperature Using a Thermistor & a Bridge Circuit for Getting Higher Sensitivities](image)

Fig. 19 Measurement of temperature using a thermistor & a bridge circuit for getting higher sensitivities

Three important characteristics of thermistors make them extremely useful in measurement and control applications: the resistance-temperature characteristic, the voltage-current characteristic, and the current-time characteristic.
Thermocouples

In 1821 Thomas Seebeck discovered that when two dissimilar metals were in contact, a voltage was generated where the voltage was a function of temperature. The device, consisting of two dissimilar metals joined together, is called a Thermocouple and the voltage is called the Seebeck voltage. As an example, joining copper and Constantan produces a voltage on the order of a few tens of milli-volts (see Fig. 20) with the positive potential at the copper side. An increase in temperature causes an increase in voltage.

![Graph showing thermocouple output voltage as a function of temperature for various thermocouple materials.](vtu.allsyllabus.com)

Fig. 20

There are several methods of joining the two dissimilar metals. One is to weld the wires together. This produces a brittle joint, and if not protected from stresses, this type of thermocouple can fracture and break apart. During the welding process gases from the welding can diffuse into the metal and cause a change in the characteristic of the thermocouple.
Another method of joining the two dissimilar metals is to solder the wires together. This has the disadvantage of introducing a third dissimilar metal. But if both sides of the thermocouple are at the same temperature, the Seebeck voltage due to thermocouple action between the two metals of the thermocouple and the solder will have equal and opposite voltages and the effect will cancel.

A more significant disadvantage is that the thermocouple is a desirable transducer for measuring high temperatures. In many cases the temperatures to be measured are higher than the melting point of the solder and the thermocouple will come apart. There will be at least two thermocouple junctions in the system. To contend with this, it is necessary that the temperature of one of the junctions be known and constant. Therefore, there is a fixed offset voltage in the measuring system. It was customary a long time ago to place this junction in a mixture of ice and water, thus stabilizing the temperature to 0°C as shown in Fig.21

More modern techniques use electronic reference junctions that are not necessarily at 0°C. This junction is called the reference or cold junction due to the fact that this junction was in the ice bath.
Thermocouple Error Sources

**Open junction.** There are many sources of an open junction, some of which were outlined earlier. Usually, the error introduced by an open junction is of such an extreme magnitude that an open junction is easily spotted. By simply measuring the resistance of the thermocouple, the open junction can be identified.

**Decalibration.** This error is a potentially serious fault, as it can cause more subtle errors that may escape detection. Decalibration is due to altering the characteristics of the thermocouple wire, thus changing the Seebeck Voltage. This can be caused by subjecting the wire to high temperatures, diffusion of particles from the atmosphere into the wire, or by cold working the wire. The last effect may be caused by straining the wire by drawing it through a long conduit.

**Insulation degradation.** The thermocouple is often used at very high temperatures. In some cases the insulation can break down and cause a significant leakage resistance which will cause an error in the measurement of the Seebeck voltage. In addition, chemicals in the insulation can diffuse into the thermocouple wire and cause decalibration.

**Galvanic action**

Chemicals coming in contact with the thermocouple wire can cause a galvanic action. This resultant voltage can be as much as 100 times the Seebeck effect, causing extreme errors.

**Thermal conduction.**

The thermocouple wire will shunt heat energy away from the source to be measured. For small masses to be measured, small-diameter thermocouple wire could be used. However, the smaller-diameter wire is more susceptible to the effects described previously. If a reasonable compromise between the degrading effects of small thermocouple wire and the loss of thermal energy and the resultant temperature error cannot be found, thermocouple extension wire can be used. This allows the thermocouple to be made of small-diameter wire, while the extension wire that covers the majority of the connecting distance is of a much larger diameter and not as susceptible to the degrading effects.
Photo-conductive and photo-voltaic cells

Photosensitive elements are versatile tools for detecting radiant energy or light. They exceed the sensitivity of the human eye to all the colors of the spectrum and operate even into the ultraviolet and infrared regions.

The photosensitive device has found practical use in many engineering applications.

Vacuum-type phototubes

observation of light pulses of short duration, or light modulated at relatively high frequencies.

Gas-type phototubes

used in the motion picture industry as sound-on-film sensors.

Multiplier phototubes

tremendous amplifying capability

Photoconductive cells (LDR)

known as photoresistors or light-dependent resistors, find wide use in industrial and laboratory control applications

Photovoltaic cells

semiconductor junction devices used to convert radiation energy into electrical power
example is the solar cell used in space engineering applications.
Photoconductive Cells

Photoconductive cells are elements whose conductivity is a function of the incident electromagnetic radiation. Many materials are photoconductive to some degree, but the commercially important ones are cadmium sulfide, germanium, and silicon. The spectral response of the cadmium sulfide cell closely matches that of the human eye, and the cell is therefore often used in applications where human vision is a factor, such as street light control or automatic iris control for cameras.

<table>
<thead>
<tr>
<th>Photoconductor</th>
<th>Time Constant</th>
<th>Spectral Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdS</td>
<td>100 ms</td>
<td>0.47 – 0.71 μm</td>
</tr>
<tr>
<td>CdSe</td>
<td>10 ms</td>
<td>0.6 – 0.77 μm</td>
</tr>
<tr>
<td>PbS</td>
<td>400 μs</td>
<td>1 – 3 μm</td>
</tr>
<tr>
<td>PbSe</td>
<td>10 μs</td>
<td>1.5 – 4 μm</td>
</tr>
</tbody>
</table>

The essential elements of a photoconductive cell are the ceramic substrate, a layer of photoconductive material, metallic electrodes to connect the device into a circuit, and a moisture-resistant enclosure. (refer Fig. 22)
Fig. 22

Semiconductor junction photocells are used in some applications. The volt-ampere characteristics of a \( p-n \) junction may appear as the solid line in Fig. 23 but when light is applied to the cell, the curve shifts downward, as shown by the broken line.
Current-voltage characteristics of a photojunction diode.

Fig. 23

Fig. 24
Fig. 24 uses the electrical resistance of the material varies with the amount of light energy striking it. When the photo-cell has the appropriate light incident upon it, its resistance is low and the current through the relay is consequently high to operate the relay. When the light is interrupted or shut off partially or completely, the resistance of the photocell increases thereby reducing the current and switching off the relay. The low resistance of photo-conductive cells when they are exposed to light means that they can and are designed to carry moderate currents, such as are capable of operating a relay coil directly without any amplification. They can be designed to operate upon low voltages and are thus used in industrial control equipments. For example, they can be used for counting packages moving on a conveyor belt, in burglar alarm circuits, wherein the interception of light actuates an alarm circuit. The devices used would be sensitive in the infra-red region, so that the burglar cannot see the beam of light.

When the cell is kept in darkness, its resistance is called dark resistance. The dark resistance may be as high as $10 \times 10^{12} \, \Omega$. If the cell is illuminated its resistance decreases.
 Photovoltaic Cells

They generate a voltage which is proportional to EM radiation’s Intensity. They are called photovoltaic cells because of their voltage generating characteristics. They, in fact, convert the EM energy into electrical energy. They are active transducers i.e. they do not need an external source to power them.

Photovoltaic cells may be used in a number of applications. The silicon solar cell converts the radiant energy of the sun into electrical power. The solar cell consists of a thin slice of single crystal p-type silicon, up to 2 cm square into which a very thin (0.5 micron) layer of n-type material is diffused. The conversion efficiency depends on the spectral content and the intensity of the illumination.

A photovoltaic cell is a giant diode, constructing a PN junction between appropriately doped semiconductors. Photons striking the cell pass through the thin P-doped upper layer and are absorbed by electrons in the lower N layer, causing formation of conduction electrons and holes. The depletion zone potential of the N junction then separates these conduction holes and electrons causing a difference of potential to develop across the junction.

Advantages of the photovoltaic cell, is its ability to generate a voltage without any form of bias and its extremely fast response. This means that it can be used as an energy converter directly. One use of this is in photographic exposure meters which require no battery. The cell voltage operates the meter directly, or may be directly linked to the iris to control the aperture.

Multiple-unit silicon photovoltaic devices may be used for sensing light in applications such as reading punched cards in the data-processing industry. Used to sense the pattern of holes in the card tapes. The size of the transducer may be an advantage if the holes are closely spaced. Gold-doped germanium cells with controlled spectral response characteristics act as photovoltaic devices in the infrared region of the spectrum and may be used as infrared detectors.