Chapter 3 on Instrumentation

Unit 3: **Transducer (8 Hours)**

Transducer / Sensor (PICKUPS)

- It is a device converting one form of *energy* into other.
- A device which converts physical energy to electrical signal is transducer.
- Extensively used in instrumentation field as instrumentation deals with measuring and controlling a number of variables like sound, flow, level, angle etc.
- We generally prefer converting physical energy to electrical energy because of many reasons but most important reasons are:
  - Amplification of electrical signal is done easily. Now suppose you want to measure some mechanical form of energy and that is very small so detecting output will be difficult and if we convert them to electrical signals it can be easily amplified as per need.
  - The output when converted to electrical signals can easily be transmitted and processed.
- Transducer can be divided in **two parts**: One is **Sensing element** and other is **Transduction element**.
- **Sensing element** is a detector which is responsible for sensing the element or it is the part which responds to phenomenon and **Transduction element** is used to transform the output of sensing element to electrical output.
- So it is dependent on sensing element, basically it is an electronic circuit.

Application of Transducers

- In the real world everywhere we required transducer.
- So we can say more or less all electronic devices can't complete without transducer.
- Some examples of transducers are given below.
  - In our mobile phone: Microphones, Speakers and touch screens.
  - In our Computer: Mouse optical sensor/ transducer is available.
  - In our Clock: Piezo Crystal is working.
  - In our Computer: Hard Disk Magnetic Sensor is installed.

Classification of Transducers

- The transducers can be classified

1. as Active and Passive
2. as Analog and digital transducer
3. as Transducer and inverse transducer
4. as Primary and secondary transducer

Active or Self Generating Transducers

- Do not require an external power, and produce an analog voltage or current when stimulated by some physical form of energy.
- Examples:
  - Thermocouple
  - Photovoltaic cell
  - Tacho-generators
  - Piezoelectric crystals

Passive Transducers

- Require an external power, and the output is a measure of some variation (resistance or capacitance)
- Example:
  - Slide-wire resistor
  - Resistance strain gauge
  - Differential transformer

Analog Transducers

- These transducers convert the input quantity into an analog output which is a continuous function of time.
- Example:
  - Strain Gauge
  - LVDT
  - Thermocouple
  - Thermistor

Digital Transducers

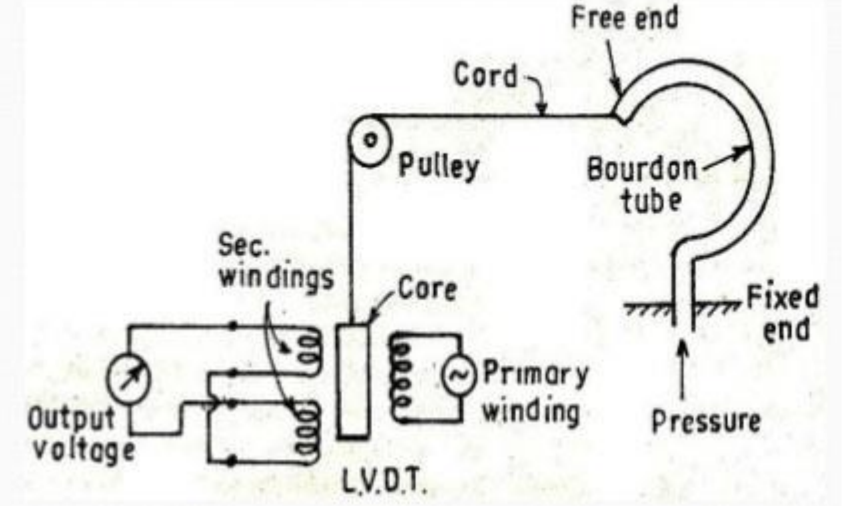
- These transducers convert the input quantity into an electrical output which is in the form of pulses.
- Example:
  - Glass Scale can be read optically by means of a light source, an optical system and photocells.

Transducers and Inverse Transducers

- A **Transducer** can be broadly defined as a device which converts a non-electrical quantity into an electrical quantity. Example: Resistive, inductive and capacitive transducers
- An **inverse transducer** (or **Actuator**) is defined as a device which converts an electrical quantity into a non-electrical quantity. Example: Piezoelectric crystals

Primary Transducers and Secondary Transducers

- Bourden tube acting as a **primary transducer** senses the pressure and converts the pressure into a displacement of its free end.
- The displacement of the free end moves the core of a linear variable differential transformer (**LVDT**) as a **secondary transducer** which produces an output voltage.



Classification of Transducer / Sensor (on the basis of physical principle involved)

1. **Resistive Sensor**

- The input being measured is transformed into change in resistance.
- Example: **Potentiometer**, **Strain Gauge**, **Photoconductive Cells**, **Resistance Thermometer**

2. **Inductive Sensor**

- The input being measured is transformed into change in inductance.
- Example: **LVDT** (**Linear Variable Differential Transformer**)

3. **Capacitive Sensor**

- The input being measured is transformed into change in capacitance.
- Example: **Capacitive Displacement Sensor**, **Capacitive Liquid Level Sensor**, **Capacitive Hydrometer**

4. Thermo – Electrical Sensor

- The input is temperature and the output is emf.
- Example: Thermo - Couple

5. Piezo – Electric Sensor

- Force applied to crystal displace the atom in the crystal and result in the crystal acquiring a surface change.
- Used for the measurement of transient response.

6. Hall – Effect Sensor

- The action of a magnetic field on a flat plate carrying an electric current generates a potential difference which is the measure of the strength of a magnetic field.
- Example: **Hall Effect Device**, **Metal Detector**

7. Electromagnetic Sensor

- The sensor based on Faraday’s law of electromagnetic induction, with the input is measured giving rise to induced emf.
- Example: **Tachogenerator**

Workflow of a Transducer in a Typical System

- A **transducer** is a device that **converts one form of energy into another** (usually physical energy into electrical signals). The typical workflow of a transducer in a system involves the following steps:

Step-by-Step Workflow:

1. Physical Quantity (Input Signal)

- The system starts with a **physical quantity** such as **temperature, pressure, light, sound, force, etc.**
- This is the parameter we want to measure.

2. Sensing Element

- The **sensing element** of the transducer detects the physical quantity.
- Example: A thermocouple senses heat; a strain gauge senses force.

3. Conversion Element (Primary Transduction)

- The sensed physical quantity is **converted into an intermediate electrical signal** (like voltage, current, or resistance).
- This is called **primary transduction**.

4. Signal Conditioning (Amplification, Filtering, ADC)

- The electrical signal is usually **weak and noisy**, so it goes through:
  - **Amplification:** Boosts the signal strength.
  - **Filtering:** Removes unwanted noise.
  - **Analog-to-Digital Conversion (ADC)** (if needed) to convert analog signal to digital for processing.

5. Output (Electrical Signal for Controller/Processor)

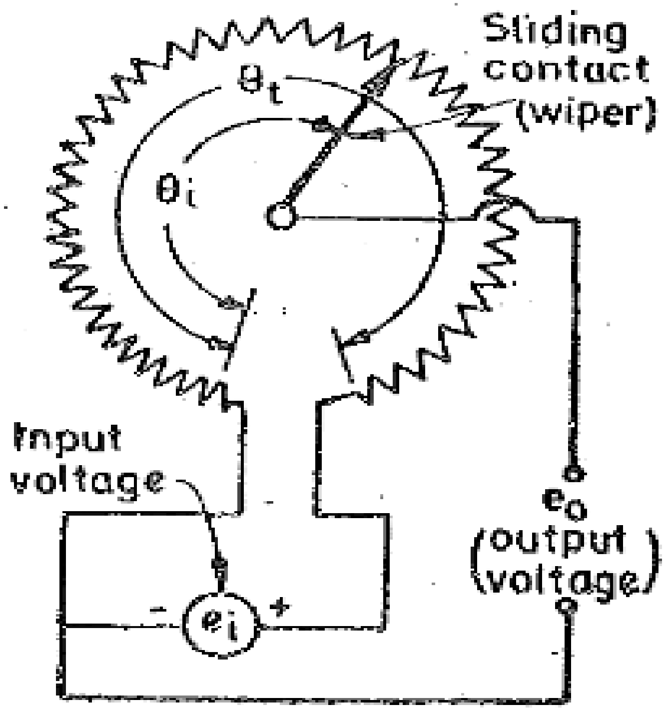
- The processed signal is sent to a **controller**, **microcontroller**, or **display system**.
- The output may be:
  - Displayed on a screen.
  - Stored in memory.
  - Used for control actions (like activating an actuator).

Example: Temperature Measurement System

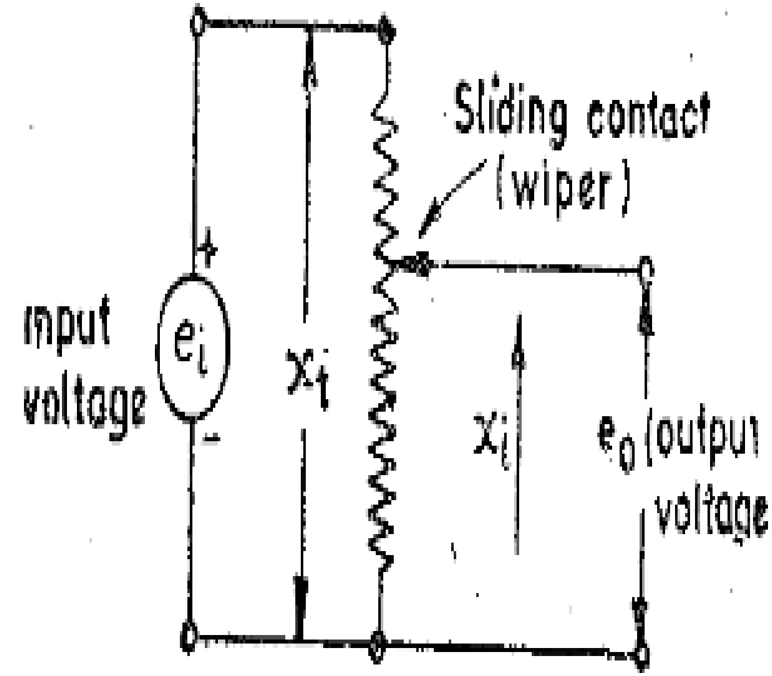
Step	Example Component	Example Process
Physical Quantity	Temperature	Heat energy
Sensing Element	Thermocouple junction	Senses heat and generates EMF
Conversion Element	Thermocouple	Converts temperature to voltage
Signal Conditioning	Amplifier, Filter, ADC	Boosts signal, removes noise, converts to digital
Output	Microcontroller / Display	Displays temperature, or controls fan / AC

Resistive Sensor: POT (Potentiometer)

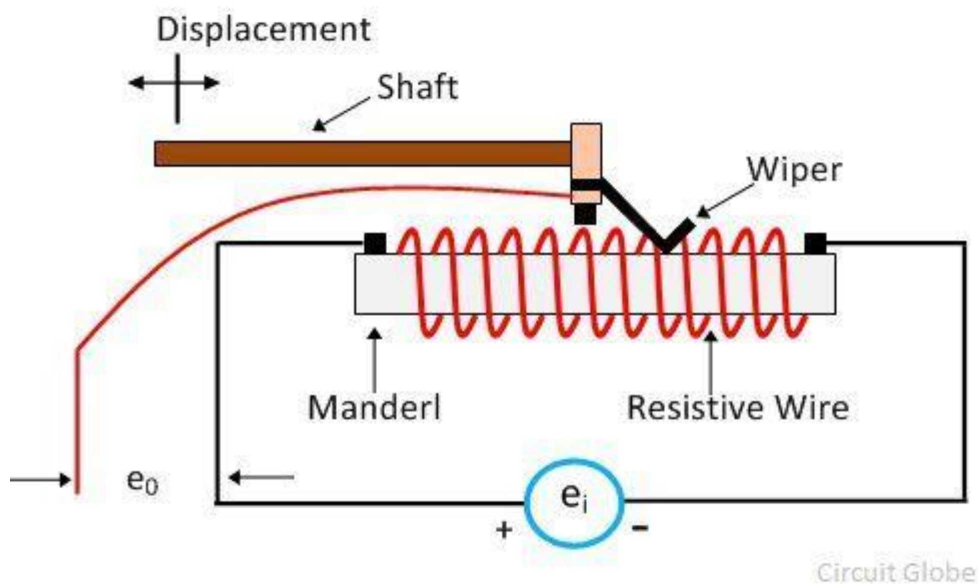
- Basically, a resistive potentiometer, or simply a **pot**, (A **potentiometer** used for the purposes of voltage division is called a **pot**) consists of a resistive element provided with a sliding contact.
- This sliding contact is called a **wiper**.
- The motion of sliding contact may be **translatory** or **rotational**.
- Some **pots** use the **combination** of the two motions, i.e. **tanslational** as well as **rotational**.
- These potentiometers have their resistive element in the form of **helix** and thus, are called **helipots**.
- The **rotational resistive devices** are circular in shape and are used for measurement of **angular displacement**. They have a range of **10º** to **60º** full turns.
- The **helical resistive elements** are multiturn rotational devices which can be used for measurement of either translational or rotary motion.
- The resistance element of a potentiometer may be excited either with a d.c. or an a.c. voltage source.
- The **pot**, is thus, a passive transducer since it requires an external power source for its operation.



(b) Rotational



(a) Translational

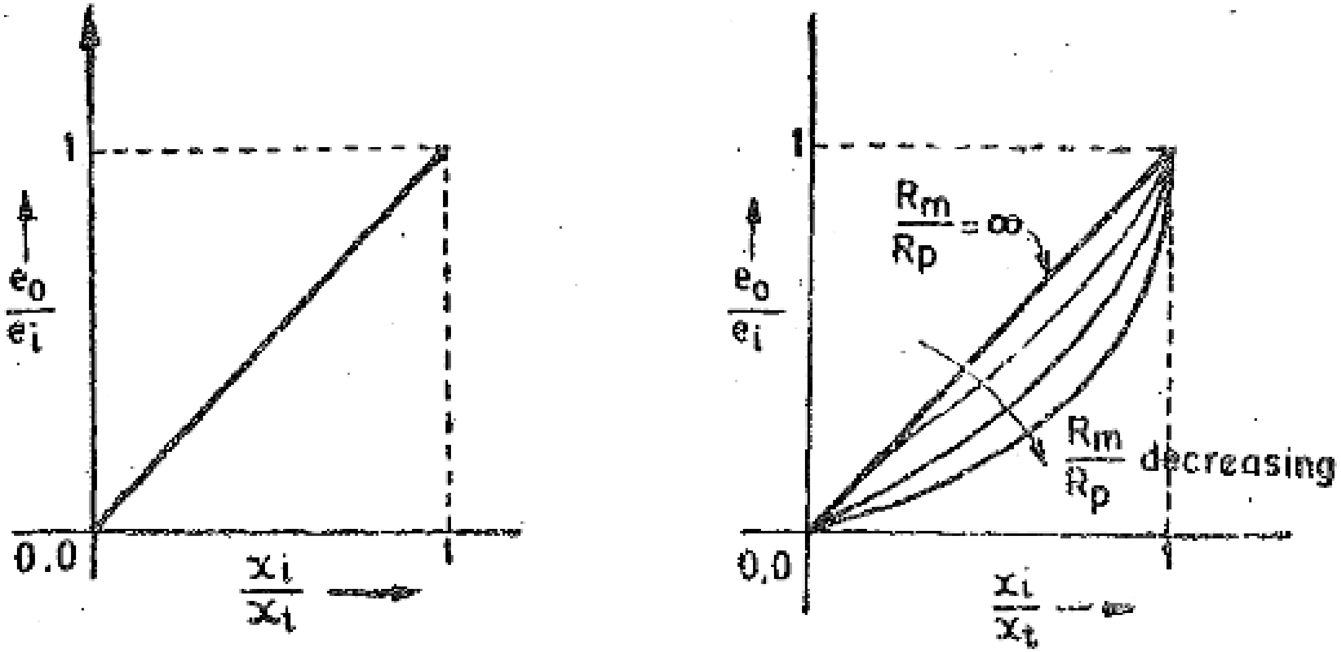


- Let us confine our discussion to d.c. excited potentiometers.
- Consider a translational potentiometer as shown in Figure.
- Let $\mathbf{e_i}$ = input voltage; $\mathbf{R_p}$= total resistance of potentiometer; $\mathbf{x_t}$ = total length of a translational **pot**; $\mathbf{x_i}$ = displacement of the slider from its 0 position; $\mathbf{e_o}$ = output voltage.
- If the distribution of the resistance with respect to translational movement is linear, the resistance per unit length is $\mathbf{R_p/x}_t$.
- The output voltage under ideal conditions is :

$\mathbf{e_o}$ = **Voltage across output resistance [use voltage divider rule]**

$= (\mathbf{x_i} / \mathbf{x_t}) * \mathbf{e_i}$

- Thus under ideal circumstances, the output voltage varies linearly with displacement.



(a) Unloaded pot (b) Loaded pot

- Sensitivity = **s** = output / input = $\mathbf{e_o / x_i}$ = $\mathbf{e_i / x_t}$ **= Constant**
- Thus under ideal conditions the sensitivity is constant and the output is faithfully reproduced and has a linear relationship with input.
- The sane is true of rotational motion.
- Let $\boldsymbol{\theta_i}$ = input angular displacement and $\boldsymbol{\theta_t}$ =total travel of the wiper .
- Output voltage $\mathbf{e_o} = \mathbf{e_i}\ (\boldsymbol{\theta_i} / \boldsymbol{\theta_t})$
- This is true of single turn potentiometers only.

Strain Gauges

- 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 called **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**, or in other words **positively strained**, its **longitudinal dimension** will **increase** while there will be a **reduction** in the **lateral dimension**.
- So when a gauge is subjected to a **positive strain**, its **length increases** while its **area** of **cross-section decreases**.
- Since the resistance of a conductor is proportional to its length and inversely proportional to its area of cross – section, the resistance of the gauge increases with positive strain.
- The change in the value resistance of strained conductor is more than what can be accounted for an increase in resistance due to dimensional changes.
- The extra change in the value of resistance is attributed to a change in the value of resistivity of a conductor when strained.
- This property, as described earlier, is known as **peizoresistive effect**.

- Let us consider a strain gauge made of circular wire.
- The wire has the dimensions: length = **L**, area = **A**, diameter = **D** before being strained.
- The material of the wire has a resistivity $\boldsymbol{\rho}$.
- Resistance of unstrained gauge $\mathbf{R = \rho L/A}$.
- Let a tensile stress **s** be applied to the wire.
- This produces a positive strain causing the length to increase and area to decrease.
- Thus when the wire is strained there are changes in its dimensions.
- Let $\boldsymbol{\Delta L}$ = change in length, $\boldsymbol{\Delta A}$ = change in area, $\boldsymbol{\Delta D}$ = change in diameter and $\boldsymbol{\Delta R}$= change in resistance.
- In order to find how $\boldsymbol{\Delta R}$ depends upon the material physical quantities, the expression for **R** is differentiated with respect to stress **s**.
- Thus we get :

$$\frac{dR}{ds}=\frac{\rho}{A}\frac{\partial L}{\partial s}-\frac{\rho L}{A^2}\frac{\partial A}{\partial s}+\frac{L}{A}\frac{\partial \rho}{\partial s} \quad \text{...(25·20)}$$

Dividing Eqn. 25·20 throughout by resistance $R=\rho L/A$, we have

$$\frac{1}{R}\frac{dR}{ds}=\frac{1}{L}\frac{\partial L}{\partial s}-\frac{1}{A}\frac{\partial A}{\partial s}+\frac{1}{\rho}\frac{\partial \rho}{\partial s} \quad \text{...(25·21)}$$

It is evident from Eqn. 25·21, that the per unit change in resistance is due to :

(*i*) per unit change in length $=\Delta L/L$. (*ii*) per unit change in area $=\Delta A/A$.

Area $\quad A=\frac{\pi}{4}D^2 \quad \therefore \quad \frac{\partial A}{\partial s}=2.\frac{\pi}{4}D.\frac{\partial D}{ds}$ ...(25·22)

or

$$\frac{1}{A}\frac{dA}{ds}=\frac{(2\pi/4)D}{(\pi/4)D^2}\frac{\partial D}{\partial s}=\frac{2}{D}\frac{\partial D}{\partial s} \quad \text{...(25·23)}$$

$\therefore$ Eqn. 25·21 can be written as :

$$\frac{1}{R}\frac{dR}{ds}=\frac{1}{L}\frac{\partial L}{\partial s}-\frac{2}{D}\frac{\partial D}{\partial s}+\frac{1}{\rho}\frac{\partial \rho}{\partial s} \quad \text{...(25·24)}$$

Now, Poisson's ratio $\quad \nu=\frac{\text{lateral strain}}{\text{longitudinal strain}}=-\frac{\partial D/D}{\partial L/L}$ ...(25·25)

or $\quad \partial D/D=-\nu\times\partial L/L$

$$\therefore \quad \frac{1}{R}\frac{dR}{ds}=\frac{1}{L}\frac{\partial L}{\partial s}+\nu\frac{2}{L}\frac{\partial L}{\partial s}+\frac{1}{\rho}\frac{\partial \rho}{\partial s} \quad \text{...(25·26)}$$

For small variations, the above relationship can be written as :

$$\frac{\Delta R}{R}=\frac{\Delta L}{L}+2\nu\ \frac{\Delta L}{L}+\frac{\Delta \rho}{\rho} \qquad \text{...(25·27)}$$

The gauge factor is defined as the ratio of per unit change in resistance to per unit change in length.

Gauge factor $$G_f=\frac{\Delta R/R}{\Delta L/L} \qquad \text{...(25·28)}$$

or $$\frac{\Delta R}{R}=G_f\ \frac{\Delta L}{L}=G_f\times\epsilon \qquad \text{...(25·29)}$$

where $$\epsilon=\text{strain}=\frac{\Delta L}{L}$$

The gauge factor can be written as :

$$G_f=\frac{\Delta R/R}{\Delta L/L}=1+2\nu+\frac{\Delta \rho/\rho}{\Delta L/L}=1+2\nu+\frac{\Delta \rho/\rho}{\epsilon} \qquad \text{...(25·30)}$$

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 :

$$G_f=1+2\nu \qquad \text{...(25·31)}$$

Resistance Thermometers (Metal)

- 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** can be represented by the following relationship for most of the metals as:

$$\mathbf{R = R_o\,(1 + \alpha_1\,T + \alpha_2\,T^2 + \ldots\ldots + \alpha_n\,T^n + \ldots)}$$

  where $\mathbf{R_o}$ = resistance at temperature **T = 0** and $\boldsymbol{\alpha_1}$, $\boldsymbol{\alpha_2}$, $\boldsymbol{\alpha_3}$, ..., $\boldsymbol{\alpha_n}$ are constants.
- The requirements of a conductor material to be used in these thermometers are :
  - the change in resistance of material per unit change in temperature should be as large as possible.
  - the resistance of the materials should have a continuous and stable relationship with temperature
  - The material should have a high value of resistivity so that the minimum volume of the material is used to construct.
- The ideal linear relationship assumes only $\boldsymbol{\alpha_1}$ (or $\boldsymbol{\alpha}$)in the above equation.

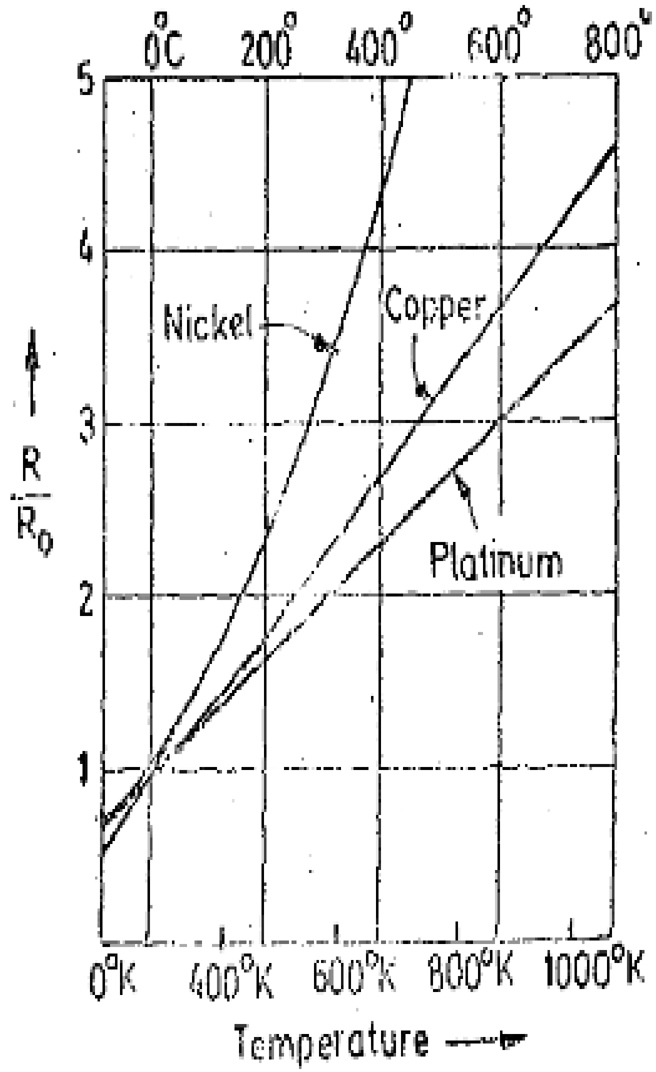


Fig. 25·20. Characteristics of materials used for resistance thermometers.

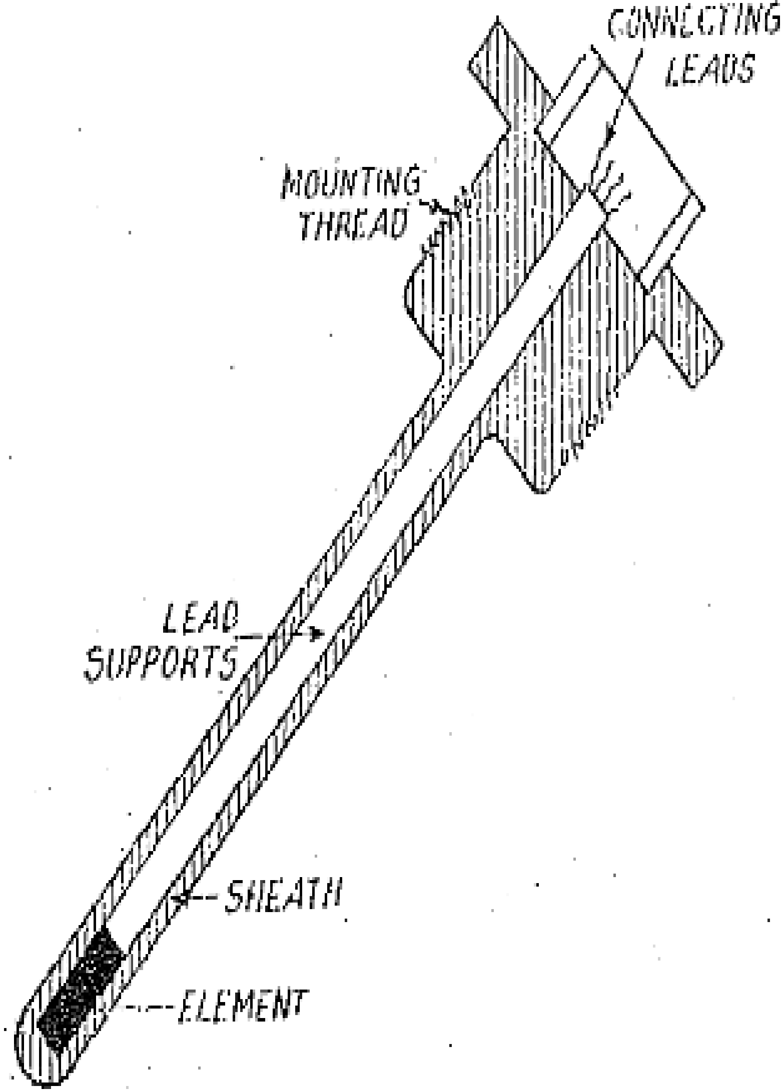


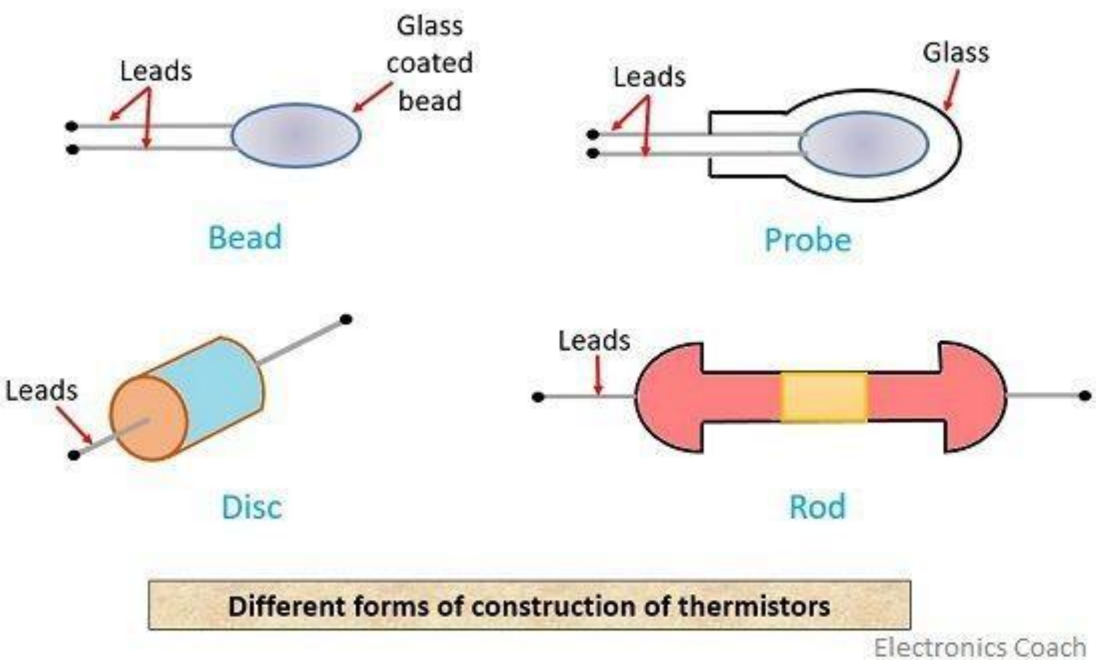
Fig. 25·21. Industrial platinum resistance thermometer

Thermistors (Semiconductor Resistance)

- It is a contraction of term “**Thermal Resistors**".
- They are essentially semi-conductors which behave as resistors with a high **negative temperature coefficient** of resistance.
- In some cases, the resistance of a **thermistor** at room temperature may decrease as much as **5%** for each **1°C** rise in temperature.
- This high sensitivity to temperature changes make the **thermistors** extremely useful for precision **temperature measurements**, **control** and **compensation**.
- **Thermistors** are widely used in such applications especially in the temperature range of **-60ºC** to **+15ºC**.
- The resistance of **thermistors** ranges from **0·5 Ω** to **0·75 MΩ**.

Construction

- **Thermistors** are composed of sintered mixture of metallic oxides such as **manganese**, **nickel**, **cobalt**, **copper**, **iron** and **uranium**.
- They are available in variety of sizes and shapes.
- The **thermistors** may be in the form of **beads**, **rods** or **discs**.
- Commercial forms are shown in **figure**.



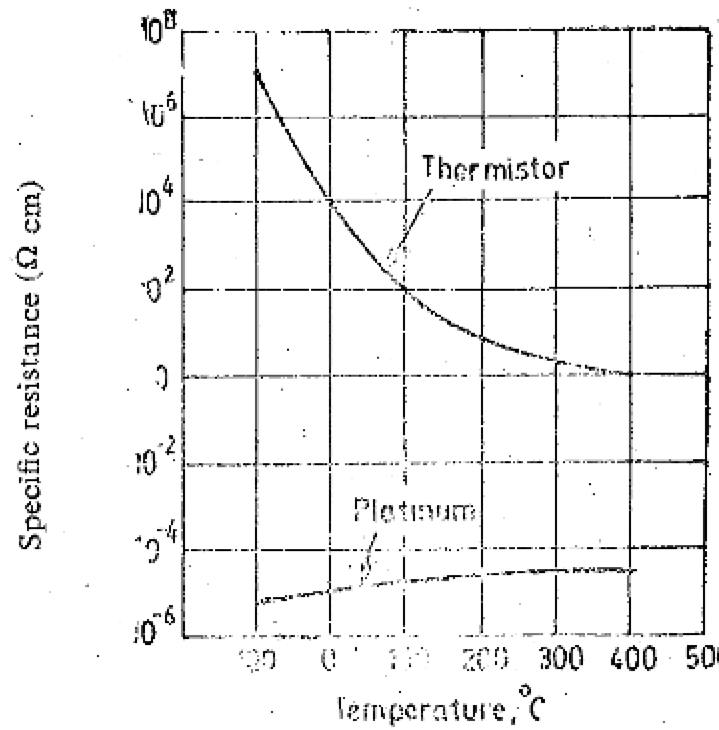


Fig. 25·24. Resistance-temperature characteristics of a typical thermistor and platinum.

$$R_{T1} = R_{T2} \exp. \left[\beta \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \right]$$

where R_{T1} = resistance of the thermistor at absolute temperature T_1 ; K,

R_{T2} = resistance of the thermistor at absolute temperature T_2 ; K,

and β = a constant depending upon the material of thermistor, typically 3500 to 4500 K.

Photocouductive Transducers

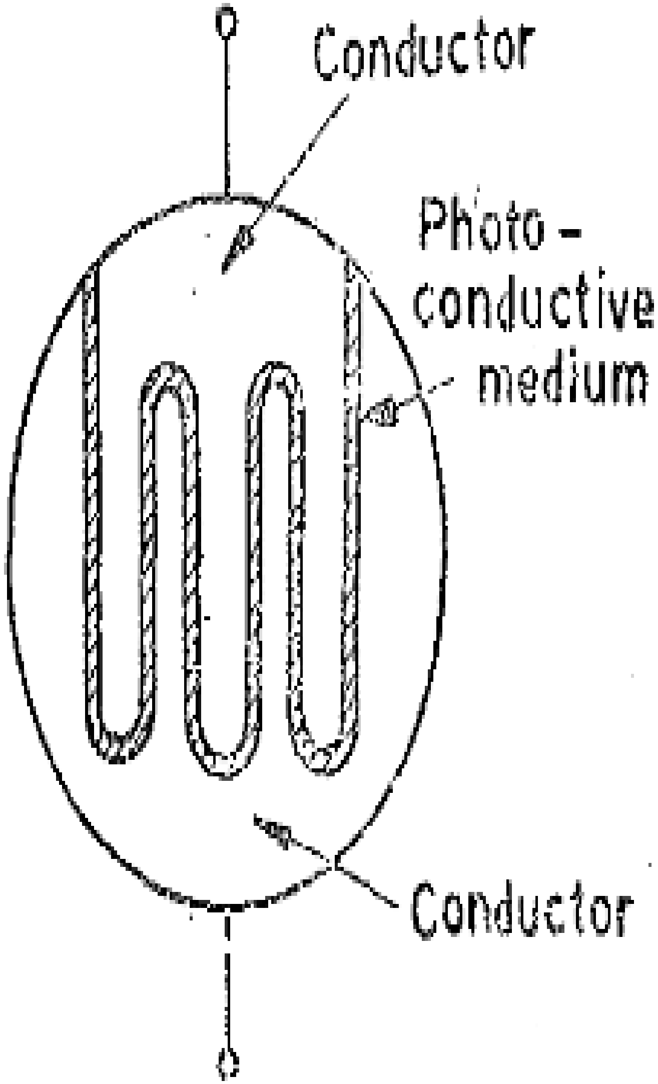
- The working of one of the most common **photodetectors** is based upon the change in conductivity of a semi-conducting material with change in radiation intensity.
- The change in conductivity appears as change in resistance and therefore these devices are **phtoresistive cells**.
- Thus from the point of view of transduction, the resistance changes with light intensity.
- The principle of a **photoconductive devices** can be explained as under:
- In a semiconductor, an energy gap exists between conduction electrons and valence electrons. In a semi-conductor photoconductive transducer, a photon is absorbed and thereby excites an electron from valence band to conduction band. As electrons are excited from valence band to conduction band, the resistance decreases, making the resistance an inverse function of radiation intensity.
- The maximum wavelength is given by :

$$\lambda_0 = \frac{h\ c}{e\ E_{10}}$$

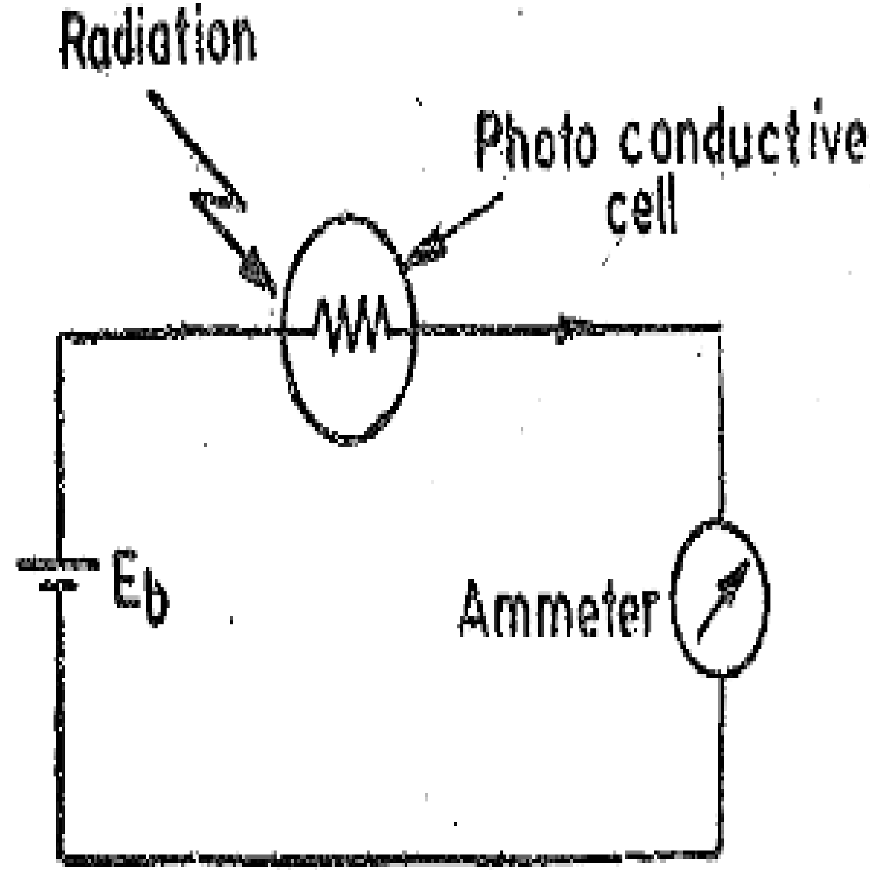
- Note that any radiation with wavelength greater than that given by Equation cannot produce any change in the resistance of the semiconductor.

Photoconductive Cells

- The most two commonly used photoconductive semiconductor materials are **cadmium sulphide** (**CdS**) with a band gap of **2.42 eV** and **cadmium selenide** (**CdSe**) with at **1.74 eV** band gap.
- On account of these large energy band gaps, both the materials have a very high resistivity at ambient temperature.
- This gives a **very large resistance** for practical purposes.
- A special kind of construction has to be used, which minimises resistance while providing maximum surface.
- This special type of construction is shown in **Figure (a)**.
- This construction gives minimum length and maximum area.
- By using a thin narrow strip and by winding this arrangement back and forth, we get a maximum surface area.
- The photoconductive material is deposited on a ceramic substrate.
- The electrodes are of tin or indium.
- The basic circuit for the photoconductive cell is shown in **Figure (b)**.


Conductor
Photo -
conductive
medium
Conductor

(a)


Radiation
Photo conductive
cell
E_b
Ammeter

(b)

Capacitive Transducer

- Capacitive transducers are nothing but the capacitors with the variable capacitance. It is a **Passive ty**pe of Transducer.
- These are mainly used for the measurement of displacement, pressure etc.
- The capacitive transducer comprises of two parallel metal plates that are separated by the material such as air, which is called as the dielectric material.
- In the typical capacitor, the distance between the two plates is kept varying.
- In the instruments using capacitance transducers the value of the capacitance changes due to the change in the value of the input quantity that is to be measured.
- This change in capacitance can be measured easily and it is calibrated against the input quantity, thus the value of the input quantity can be measured directly.
- The **capacitance:** $\mathbf{C = \varepsilon o \times \varepsilon r \times A / d}$
- Where **C** is the **capacitance** of the capacitor or the variable capacitance transducer, **Ɛo** is the **absolute permittivity**, **Ɛr** is the **relative permittivity**, the product of **Ɛo** & **Ɛr** is also called as the **dielectric constant** of the capacitive transducer, **A** is the **area** of the plates, **d** is the **distance** between the plates.

Capacitance transducer work on 3 principles:

1. Change in overlapping area (a)

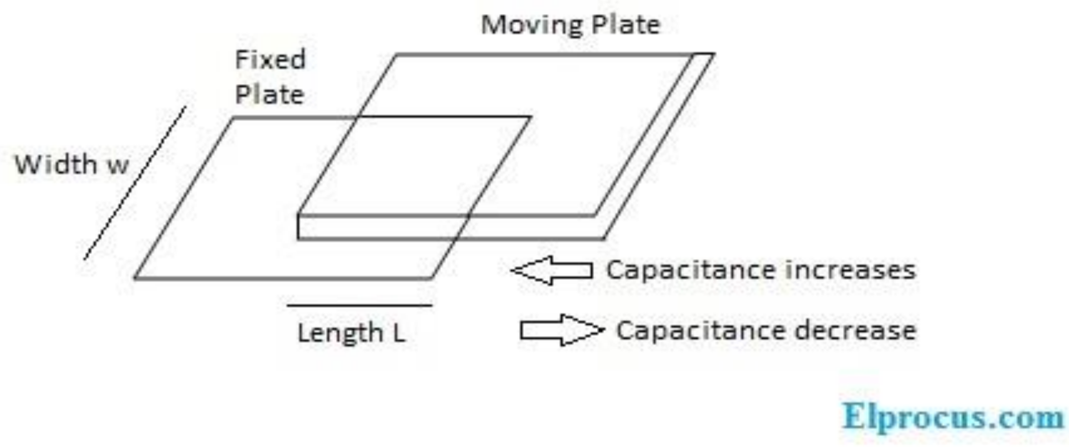
- **x (L)-** length of overlapping plate, **w** -width of the overlapping area, **d** –distance between then

$$\text{therefore , capacitance-}\ c = \frac{\in a}{d} = \frac{\in wx}{d}$$

$$\text{Sensitivity , } s = \frac{\partial c}{\partial x} = \frac{\in w}{d}$$

Sensitivity for fractional change in capacitance-

$$s' = \frac{\partial c}{c \partial x} = \frac{1}{x}$$

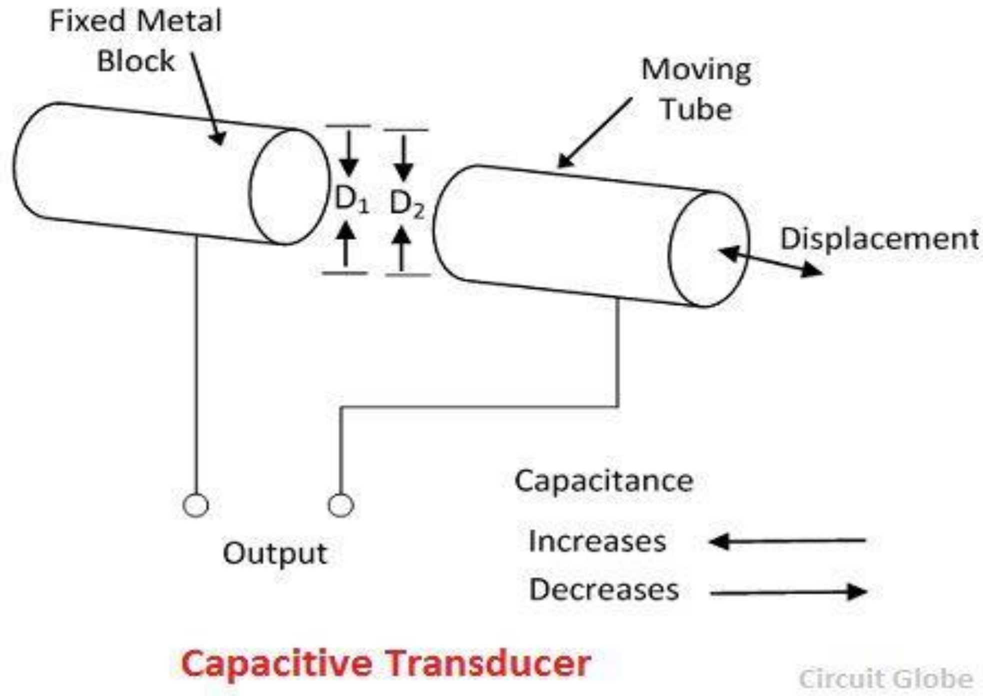


For cylindrical capacitor:

- **x** – length of overlapping region, $\mathbf{d_2}$– inner diameter of outer cylinder, $\mathbf{d_1}$– outer diameter of inner cylinder

$$\text{therefore , capacitance } \; c = \frac{2\pi \in x}{\log_e {d_2}/{d_1}};$$

$$\text{Sensitivity } \; s = \frac{\partial c}{\partial x} = \frac{2\pi \in}{\log_e {d_2}/{d_1}}$$



Capacitive Transducer

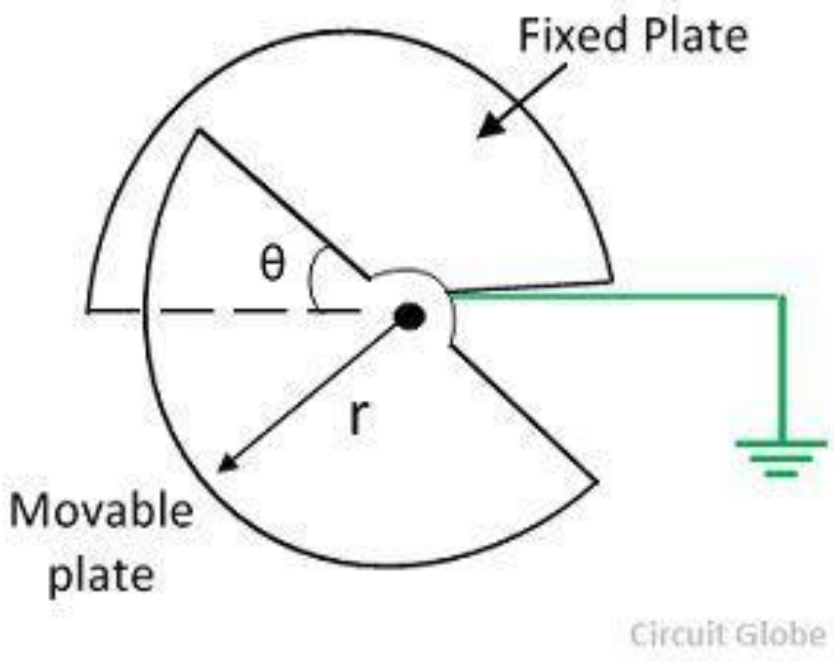
For circular capacitor:

- Here the angular rotation of second plate changes the overlapping area.
- The capacitance is maximum when they are completely overlapping i.e. θ=180.

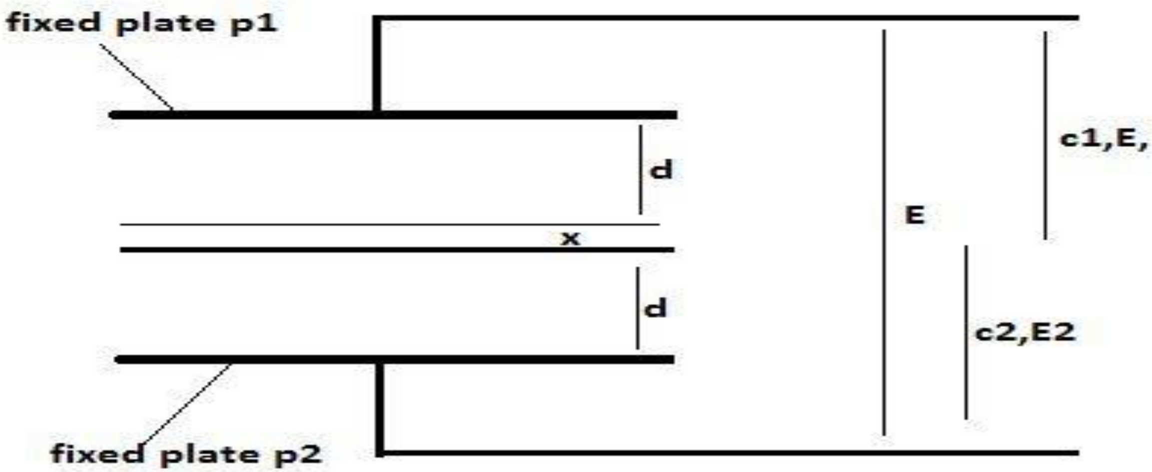
Therefore, $c_{max} = \frac{\in a}{d} = \frac{\in \pi r^2}{2d}$

And capacitance at angle θ , $c_\theta = \frac{\in \theta r^2}{2d}$

Sensitivity $s = \frac{\partial c}{\partial \theta} = \frac{\in r^2}{2d}$



2. Change in distance between the plate



When the moveable plate is not moving in either direction, initially both the capacitor having same value.

$$c_1 = \frac{\in a}{d}, c_2 = \frac{\in a}{d}$$

As, $C_1 = C_2$ then $E_1 = E_2$

voltage across the C_1 is-- $E_1 = \frac{Ec_2}{(c_1+c_2)} = \frac{E}{2}$ and $E_2 = \frac{Ec_1}{(c_1+c_2)} = \frac{E}{2}$

therefore differential output, $\Delta E = E_1 - E_2 = 0$

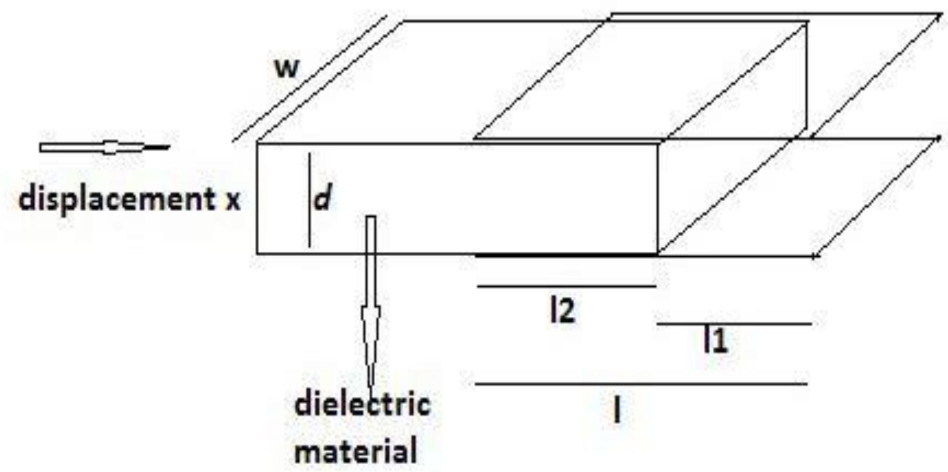
now moveable plate goes upward for a distance x, $c_1 = \frac{\in a}{d-x}$ and $c_2 = \frac{\in a}{d+x}$

therefore, $E_1 = \frac{d-x}{2d}E$ and $E_2 = \frac{d+x}{2d}E$

differential output voltage $\Delta E = E_2 - E_1 = \frac{Ex}{d}$, so, output voltage varies linearly with displacement x. hence sensitivity,-- $s = \frac{\Delta E}{\Delta x} = \frac{E}{d}$

3. Variation of dielectric constant for measurement of displacement

- Initially dielectric placed between the two plates are $\boldsymbol{\varepsilon_r}$



For this arrangement initial capacitance is— $c = \epsilon_0 \frac{wl_1}{d} + \epsilon_0 \epsilon_1 \frac{wl_2}{d}$

Now consider the capacitor moves distance x along the direction indicated.so change of capacitor is Δc

So , $c + \Delta c = \frac{\epsilon_0 w}{d}(l_1 - x) + \frac{\epsilon_0 \epsilon_r w}{d}(l_2 + x)$

$$= \epsilon_0 \frac{w}{d}[l_1 - x + \epsilon_r (l_2 + x)]$$

$$= \epsilon_0 \frac{w}{d}(l_1 + \epsilon_r l_2) + \epsilon_0 \frac{w}{d}(\epsilon_r - 1)x$$

$$= c + \epsilon_0 \frac{w}{d}(\epsilon_r - 1)x$$

Therefore change in capacitance-- $\Delta c = \epsilon_0 \frac{w}{d}(\epsilon_r - 1)x$

Here also change in capacitance proportional to displacement.

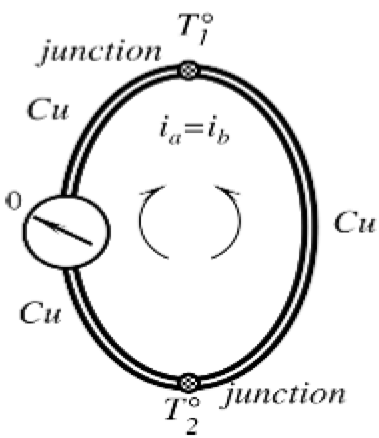
THERMOELECTRIC SENSORS

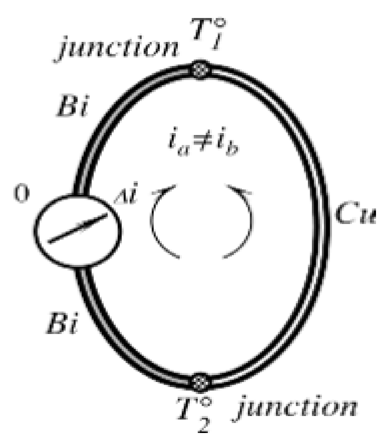
Thermoelectric effect

- Measurement device is part of the circuit
- Measurement device should use different material compared to metal bar (otherwise currents cancel each other).
- Thermoelectric effect occurs at junction (Peltier effect): $Q_P = \pi_{AB} \cdot I \cdot \Delta T$
- Thermoelectric effect occurs in bar (Thomson effect): $Q_P = \sigma_{AB} \cdot I \cdot \Delta T$
- Combination of both effects leads to Seebeck effect

$$V_{AB} = \alpha_{AB} \cdot \Delta T$$

- **Seebeck potential** is small.
- copper-constantan has **Seebeck** potential of 41µV/K





Seebeck potential can be approximated by

$$V_{AB} \approx C_1(T_1 - T_2) + C_2(T_1^2 - T_2^2) \approx (T_1 - T_2)\left[C_1 + C_2(T_1 + T_2)\right]$$

- C_1, C_2 – constants depending on material

Seebeck potential depends on

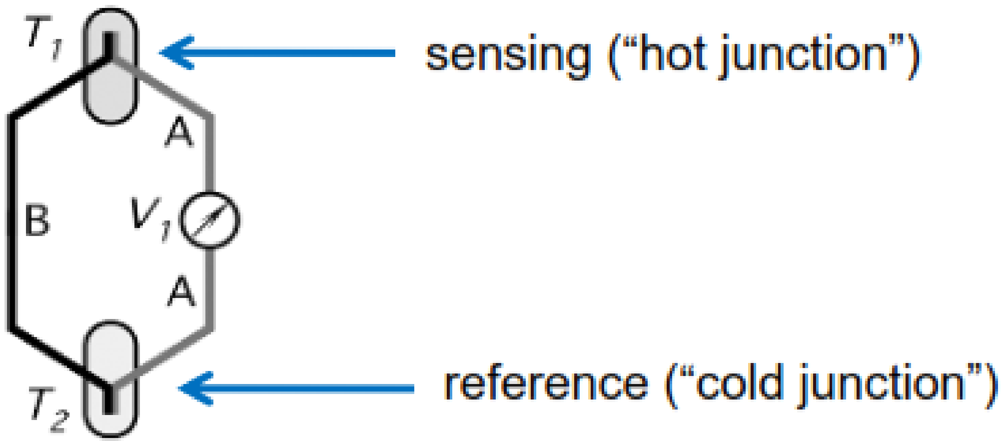
- temperature difference
- absolute temperature

Seebeck coefficient

- not dependent on nature of thermocouple (e.g. welded, pressed)
- depends only on the temperature and materials at the junction

Thermoelectric laws

- temperature difference between two thermocouple junctions leads to a voltage between the open ends of the circuit
  - junctions of different materials lead to different sensitivity
  - voltage is proportional to the temperature difference
  - reference junction must be at known, constant temperature

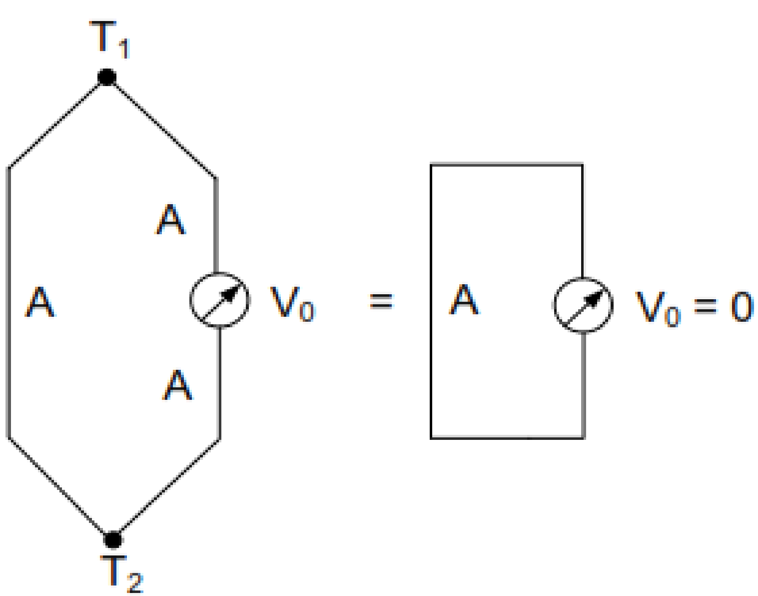


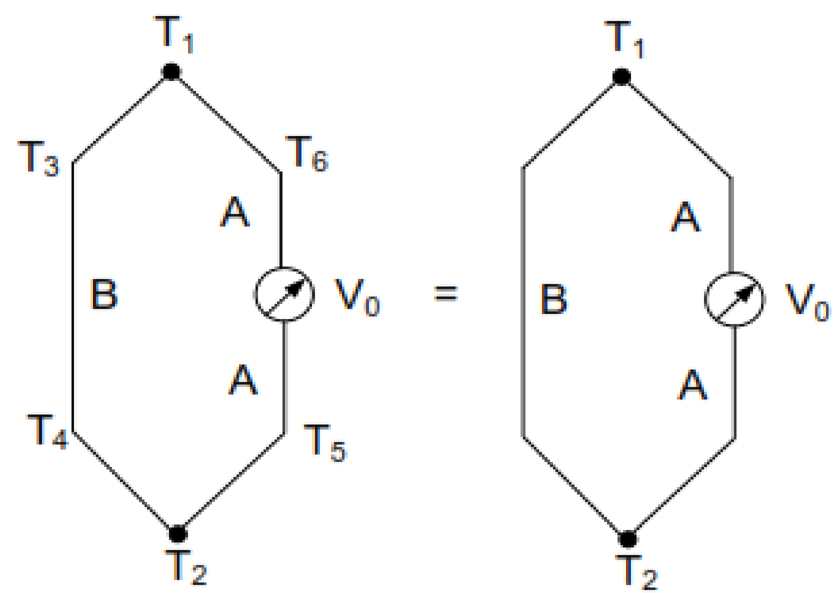
- operation of thermocouples governed by three thermoelectric laws
- thermoelectric laws simplify the analysis of thermocouple circuits
- useful as practical systems may contain more than just two junctions

Thermoelectric laws

- law of homogeneous circuits: thermoelectric current cannot be maintained in a homogeneous circuit by heat alone

- implications
  - junctions of different materials must be used
  - single conductor will never cause a Seebeck potential
  - intermediate temperatures do not influence Seebeck potential

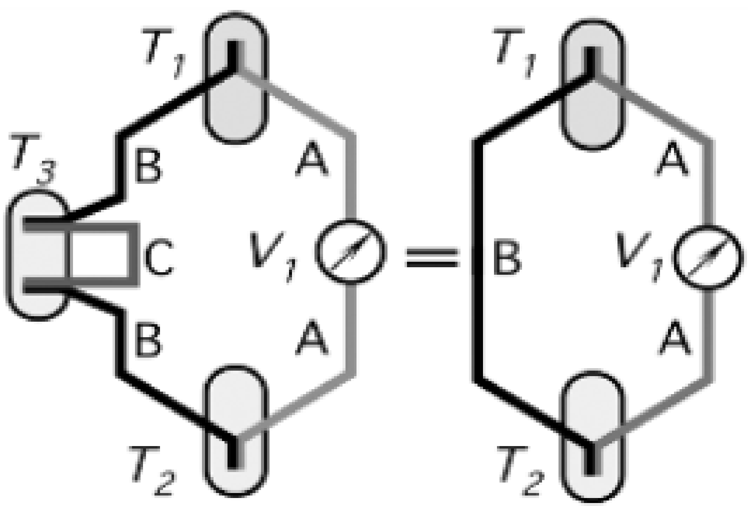




Thermoelectric laws

- law of intermediate metals: algebraic sum of all Seebeck potentials in a circuit composed by several different materials remains zero when the whole circuit is at a uniform temperature

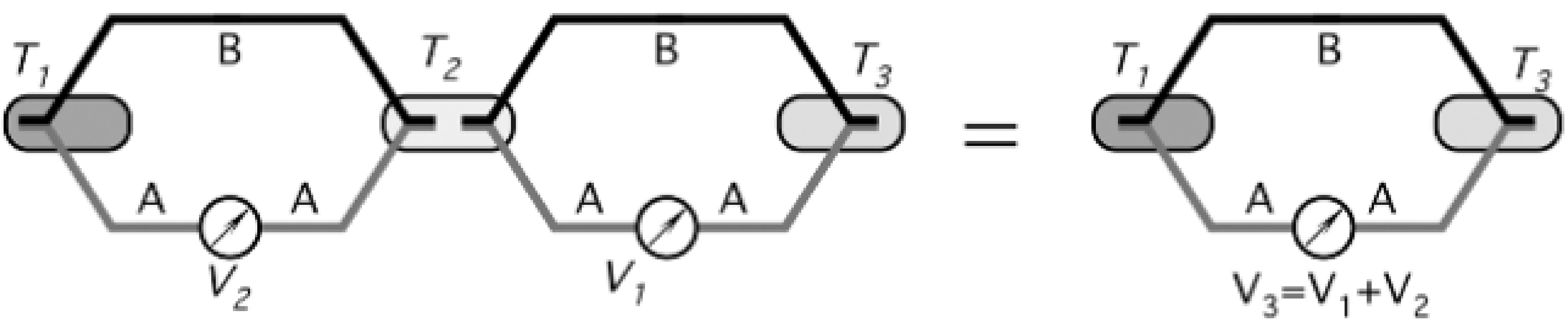
- implication
  - materials may be connected in the circuit without affecting the output of the circuit as long as the new junctions are kept at the same temperature



Thermoelectric laws

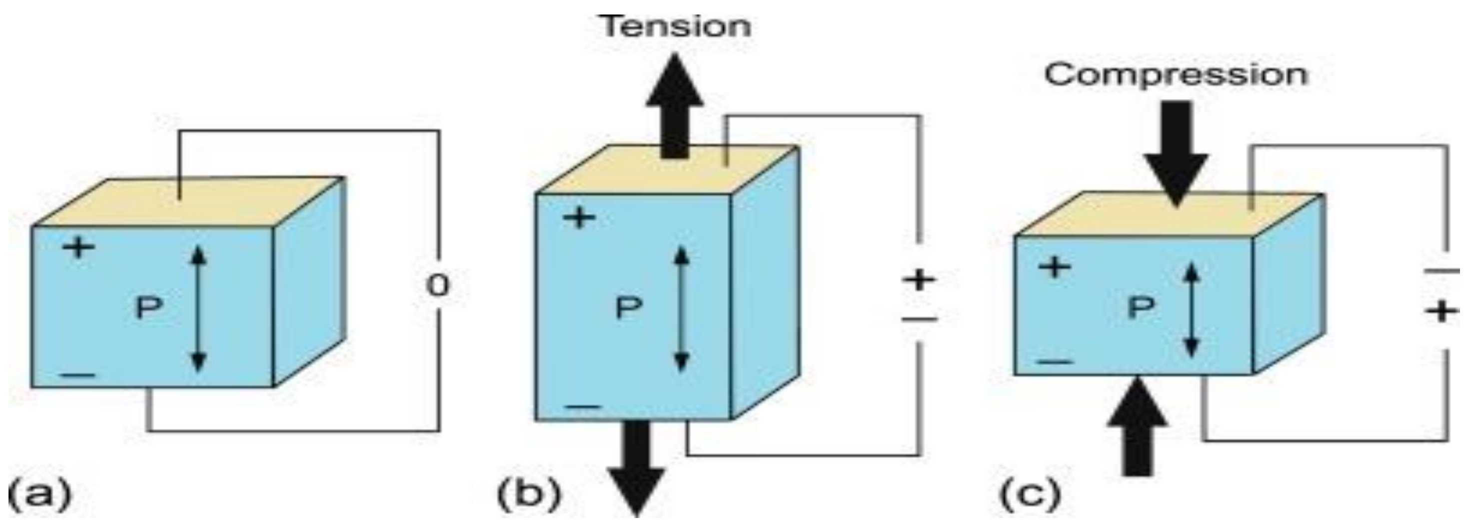
- law of intermediate temperatures:
  - two junctions at T_1 and T_2 produce Seebeck voltage V_2
  - two junction at T_2 and T_3 produce Seebeck voltage V_1
  - then temperatures T_1 and T_3 will produce $V_3 = V_1 + V_2$

- implications
  - calibration can be done at reference temperature T_2 and device can used with different reference temperature T_3



Piezoelectric Sensor

- The **piezoelectric effect**, discovered in 1880 by French physicists **Jacques** and **Pierre Curie**, is defined as the linear electromechanical interaction between the mechanical and electrical state (in a crystalline material with no inversion symmetry) such that electric charge is accumulated in response to the applied mechanical stress.
- The **piezoelectric effect** is a **reversible process** in that the direct piezoelectric effect (generation of electrical charge under an applied mechanical strain) can be reversed to generate a mechanical strain via the application of an electrical charge (**reverse piezoelectric effect**).



- **Piezoelectric materials**, a subset of **ferroelectric materials**, exhibit the formation of a local charge separation known as **electrical dipoles** due to their non-centrosymmetric crystal structure and some examples of the materials include:
  - **naturally occurring biological piezoelectric materials** such as **human bone**, **tendon**, **cellulose**, **collagen**, **deoxyribonucleic acid**
  - **naturally occurring piezoelectric crystals** such as **quartz** (**SiO_2**), **Rochelle's salt** (**$NaKC_4H_4O_6 \cdot 4H_2O$**), **topaz**, **tourmaline group minerals**, etc.
  - **synthetic piezoelectric ceramics** such as **lead zirconium titanate**, **PZT ($Pb[Zr_xTi_{1-x}]O_3$ $0 \leq x \leq 1$), barium titanate** (**$BaTiO_3$**), **potassium niobate** (**$KNbO_3$**), **bismuth ferrite** (**$BiFeO_3$**), **zinc oxide** (**ZnO**), etc.
  - **synthetic piezoelectric polymers** such as **poly (vinylidene fluoride)** ((**CH_2-CF_2)$_n$**), **co-polymers** of **PVDF** such as **poly** (**vinylidenefluoride-*co*-trifluoroethylene**) **P(VDF-TrFE)**, **polyimide**, **odd numbered polyamides**, **cellular polypropylene**, **etc**.

The piezo-electric effect is direction sensitive. A tensile force produces a voltage of one polarity while a compressive force produces a voltage of opposite polarity.

A piezo-electric crystal is shown in Fig. 25'61.

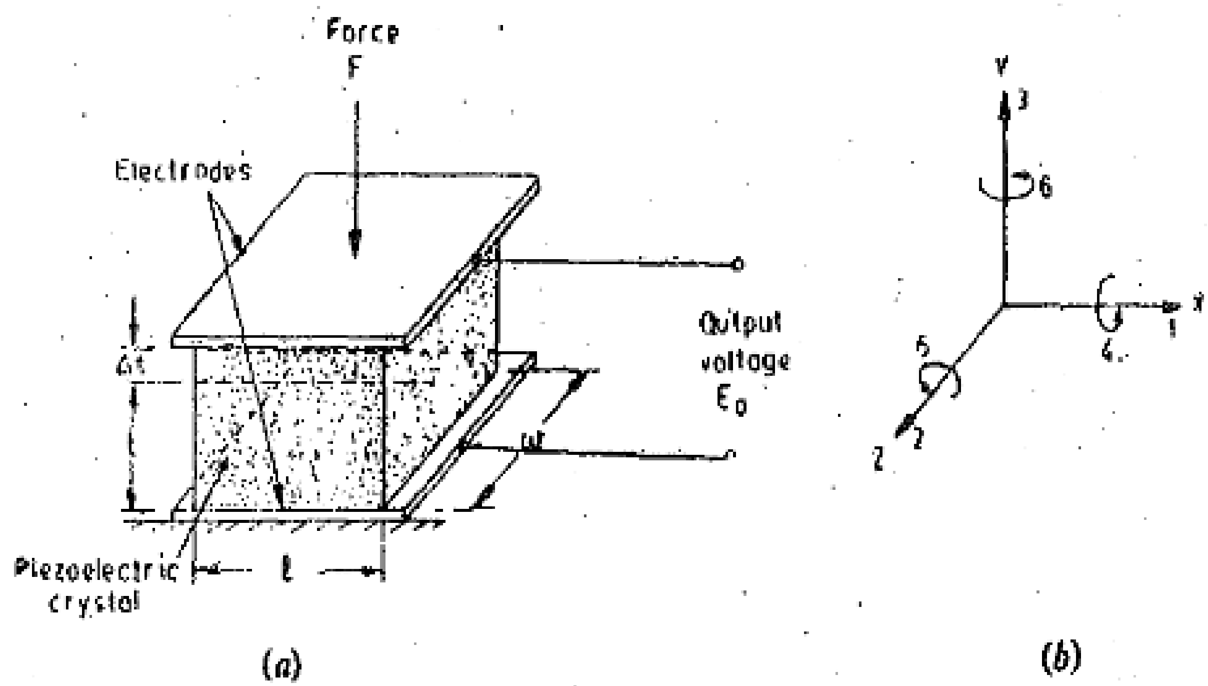


Fig. 25'61. (*a*) Piezo electric crystal used for measurement of force.
(*b*) Axis numbering system for the crystal.

The magnitude and polarity of the induced surface charges are proportional to the magnitude and direction of the applied force *F*.

Charge $Q = dF$ coulomb ...(25'63)

where d = charge sensitivity of the crystal C/N ; (It is constant for a given crystal)

and F = applied force, N.

The magnitude and polarity of the induced surface charges are proportional to the magnitude and direction of the applied force F.

Charge $Q = dF$ coulomb ...(25·63)

where d = charge sensitivity of the crystal C/N ; (It is constant for a given crystal)

and F = applied force, N.

The force F causes a change in thickness of the crystal.

$$\therefore \quad F = \frac{AE}{t} \Delta t \text{ newton} \qquad ...(25·64)$$

where A = area of crystal ; m^2, t = thickness of crystal ; m, and E = Young's modulus, N/m^2.

$$\text{Young's modulus } E = \frac{\text{stress}}{\text{strain}} = \frac{Ft}{A\Delta t} \text{ N/m}^2 \qquad ...(25·65)$$

Area $A = wl$ where w = width of crystal ; m, and l = length of crystal ; m.

$\therefore$ From Eqns. 25·63 and 25·64, we have, charge :

$$Q = d\frac{AE}{t} \Delta t \text{ coulomb} \qquad ...(25·66)$$

The charge at the electrodes gives rise to an output voltage E_0, Voltage $$E_0=\frac{Q}{C_p}\text{ volt} \quad \text{...(25·67)}$$

where C_p=capacitance between electrodes ; F.

Capacitance between electrodes $C_p=\epsilon_r\epsilon_0 A/t$

From Eqns. 25·63 and 25·67 we have :

$$E_0=\frac{d\,F}{\epsilon_r\epsilon_0 A/t}=\frac{d\,t}{\epsilon_r\epsilon_0}\cdot\frac{F}{A} \quad \text{...(25·68)}$$

But $\frac{F}{A}=P$=pressure or stress in N/m^2.

$$\therefore \quad E_0=\frac{d}{\epsilon_r\epsilon_0}t\,P \quad \text{...(25·69)}$$

$$=g\,t\,P \quad \text{...(25·70)}$$

where $$g=\frac{d}{\epsilon_r\epsilon_0} \quad \text{...(25·71)}$$

'g' is the voltage sensitivity of the crystal. This is constant for a given crystal cut. Its units are Vm/N.

Now $$g=\frac{E_0}{t\,P}=\frac{E_0/t}{P} \quad \text{...(25·72)}$$

But E_0/t=electric field strength, V/m, Let $\epsilon=E_0/t$=electric field

$$\therefore \quad g=\frac{\text{electric field}}{\text{stress}}=\frac{\epsilon}{P} \quad \text{...(25·73)}$$

Equivalent Circuit of Piezo-electric Transducer

The source is a charge generator. The value of the charge is $Q = dF$.

The charge generated is across the capacitance, C_{cr}, of the crystal and its leakage resistance R_{cr}.

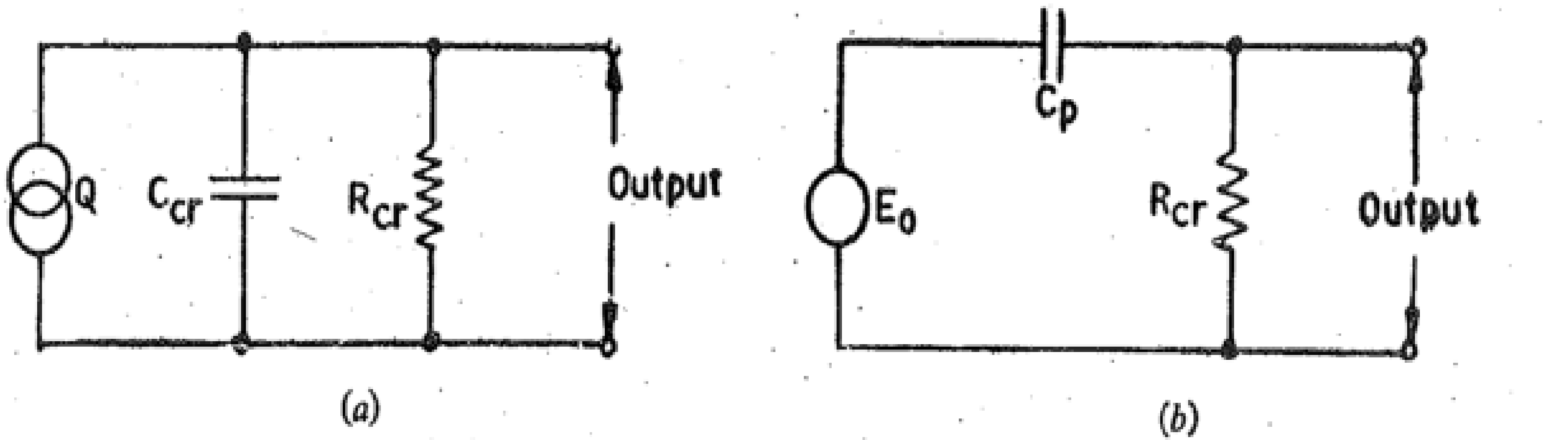


Fig. 25·64. Equivalent circuits of piezo-electric transducers.

The charge generator can be replaced by an equivalent voltage source having a voltage of

$$E_0 = \frac{Q}{C_{cr}} = \frac{dF}{C_{cr}} \qquad ...(25·79)$$

in series with a capacitance, C_{cr}, and resistance, R_{cr}, as shown in Fig. 25·63 (*a*).

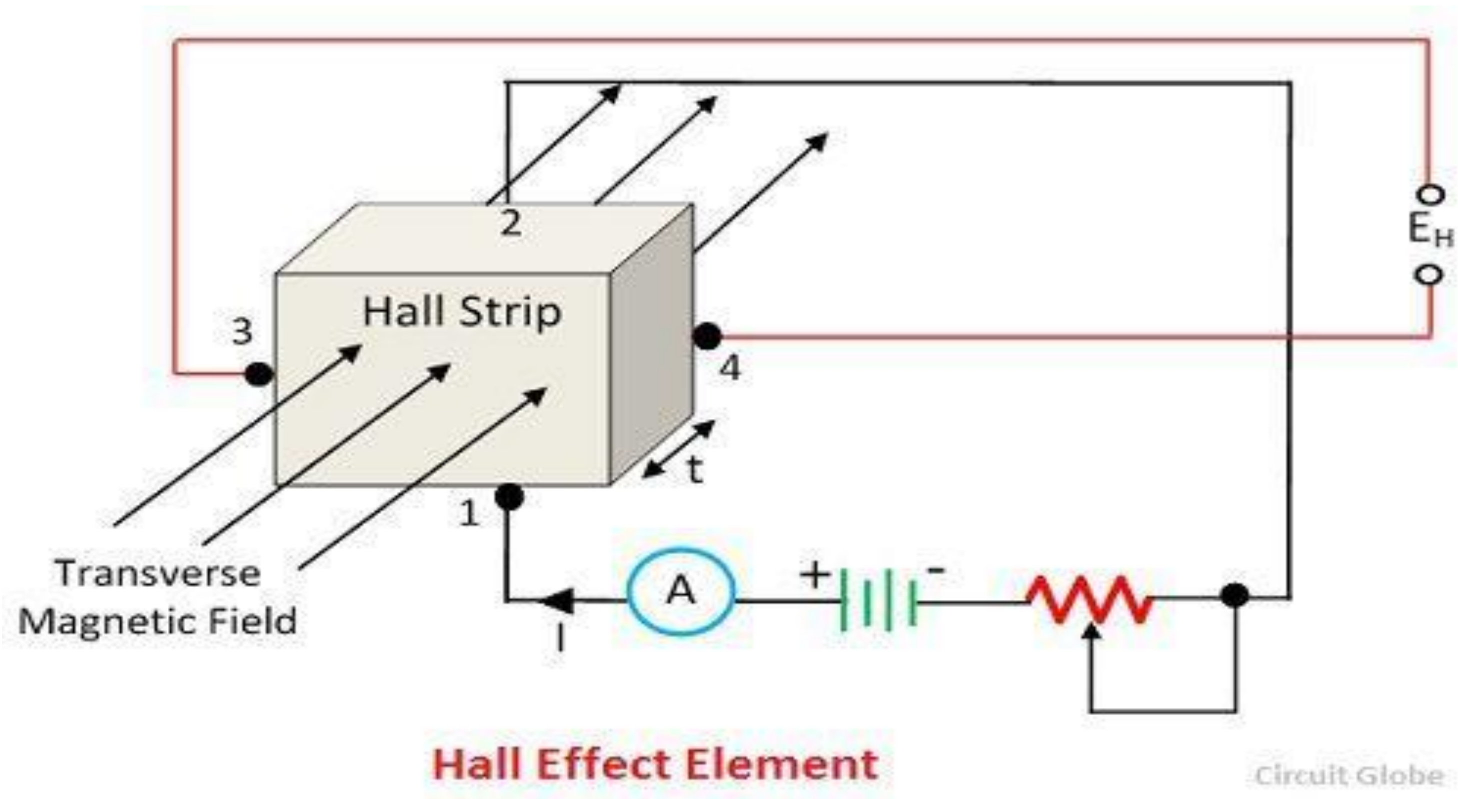
The value of resistance R_{cr} is very large. It is of the order of $0·1 \times 10^{12}\ \Omega$ and thus the equivalent circuit of the transducer is reduced to a voltage source of voltage E_0 in series with a series capacitance C_{cr} as shown in Fig. 25·64 (*b*). Under no load conditions, the voltage apperaring across the terminals of the transducer is E_0.

Hall Effect Transducer

- **Definition:** The **hall effect** element is a type of transducer used or **measuring** the **magnetic field** by **converting** it into an **emf**.
- The direct measurement of the magnetic field is not possible.
- Thus the **Hall Effect Transducer** is used.
- The **transducer converts** the **magnetic field** into an **electric quantity** which is easily **measured** by the **analogue** and **digital meters.**

Principle of Hall Effect Transducer

- The principle of hall effect transducer is that if the current carrying strip of the conductor is placed in a transverse magnetic field, then the **EMF** develops on the edge of the conductor.
- The magnitude of the develop voltage depends on the density of flux, and this property of a conductor is called the **Hall effect**.
- The **Hall effect element** is mainly used for magnetic measurement and for sensing the current.
- The metal and the semiconductor has the property of hall effect which depends on the densities and the mobility of the electrons.
- Consider the **Hall effect element** shown in the figure below.
- The current supply through the lead **1** and **2** and the output is obtained from the strip **3** and **4**.
- The lead **3** and **4** are at same potential when no field is applied across the strip.



- When the magnetic field is applied to the strip, the output voltage develops across the output leads **3** and **4**.
- The develops voltage is directly proportional to the strength of the material.

- The output voltage is,

$$E_H = K_H IB/t$$

- where,

$$K_H - Hall\ effect\ coefficient\ ; \frac{V-m}{A-Wbm^{-2}}$$

$$t - thickness\ of\ Strip\ ; m$$

- The **I** is the current in ampere and the **B** is the flux densities in **Wb/m²**
- The current and magnetic field strength both can be measured with the help of the output voltages.
- The **Hall effect EMF** is very small in conductors because of which it is difficult to measure.
- But semiconductors like germanium produces large **EMF** which is easily measured by the moving coil instrument.

Applications of Hall Effect Transducer

1. **Magnetic to Electric Transducer**
   - The Hall effect element is used for converting the magnetic flux into an electric transducer. The magnetic fields are measured by placing the semiconductor material in the measurand magnetic field. The voltage develops at the end of the semiconductor strips, and this voltage is directly proportional to the magnetic field density.
   - The Hall Effect transducer requires small space and also gives the continuous signal concerning the magnetic field strength. The only disadvantage of the transducer is that it is highly sensitive to temperature and thus calibration requires in each case.

2. Measurement of Displacement

- The Hall effect element measures the displacement of the structural element. **For example –** Consider the ferromagnetic structure which has a permanent magnet.

Generation of Sensors

1st Generation: Basic Sensors (1950s–1970s)

- **Nature**: Simple **analog sensors**.
- **Function**: Directly convert a physical quantity into an electrical signal (like voltage, current).
- **Examples**:
  - Thermocouples
  - Strain gauges
  - Basic photoresistors (LDRs)
  - Potentiometers for displacement measurement.
- **Limitations**:
  - Low accuracy
  - Poor signal conditioning
  - No data processing
  - Prone to noise and errors.

2nd Generation: Sensors with Signal Conditioning (1970s–1990s)

- **Nature**: Sensors with **integrated signal conditioning circuits** (amplification, filtering, compensation).
- **Function**: Provide a more stable, amplified, and filtered analog output.
- **Examples**:
  - Temperature sensors with linearization.
  - Pressure sensors with onboard amplifiers.
- **Improvements**:
  - Reduced noise
  - Better sensitivity and accuracy.
- **Limitation**: Still mostly analog, limited digital integration

3rd Generation: Intelligent Sensors (1990s–2000s)

- **Nature**: **Microprocessor or microcontroller integrated** within the sensor.
- **Features**:
  - Self-calibration
  - Self-diagnostics
  - Digital output
  - Communication interfaces (e.g., SPI, I2C, UART)
- **Examples**:
  - Digital temperature sensors (e.g., DS18B20)
  - Smart accelerometers (e.g., MPU6050)
- **Advantages**:
  - Improved accuracy
  - Built-in error detection
  - Easier integration with digital systems (like microcontrollers, IoT devices).

4th Generation: Smart & Networked Sensors (2010–Present)

- **Nature**: Sensors with **networking capability**, embedded AI/ML, and integration into **IoT ecosystems**.
- **Features**:
  - Wireless communication (Bluetooth, WiFi, LoRa)
  - Cloud connectivity
  - Edge computing capabilities
  - AI/ML for local data processing.
- **Examples**:
  - Environmental sensors with WiFi (e.g., Air Quality sensors)
  - Smart cameras with object detection (e.g., Raspberry Pi cameras with TensorFlow).
- **Impact**:
  - Real-time data sharing
  - Interconnected systems (IoT)
  - Advanced decision-making capabilities.

5th Generation: Autonomous & Self-Optimizing Sensors (Emerging)

- **Future Trends**:
  - **Self-learning sensors** with adaptive algorithms.
  - Integration with **cyber-physical systems** (Industry 5.0).
  - **Energy harvesting** for self-powered sensors.
  - **Bio-sensors** interfacing with the human body.
- **Examples (Emerging)**:
  - AI-enabled sensors in robotics and healthcare.
  - Sensors in autonomous vehicles.

Comparison Table

Generation	Features	Example
1st Gen	Analog output, no processing	Thermocouple, LDR
2nd Gen	Analog with signal conditioning	Pressure sensor with amp
3rd Gen	Digital output, microcontroller inside	MPU6050 accelerometer
4th Gen	IoT-enabled, AI integration	Smart weather station
5th Gen	Autonomous, AI/ML-driven, bio-sensors	AI medical diagnostic sensor

Types of Sensors

- Sensors are devices that detect changes in their environment and convert them into electrical signals for measurement and analysis. They can be broadly categorized as follows:

1. Electrical Sensors

- **Purpose:** Measure electrical parameters.
- **Examples:**
  - Voltage sensors
  - Current sensors
  - Resistance sensors (e.g., potentiometers)
  - Capacitance sensors
  - Inductance sensors
- **Applications:** Electric circuits, industrial monitoring, etc.

2. Chemical Sensors

- **Purpose:** Detect specific chemical substances.
- **Examples:**
  - pH sensors
  - Gas sensors (e.g., CO_2, NO_2)
  - Oxygen sensors
  - Humidity sensors (detect water vapor)
- **Applications:** Pollution control, medical diagnostics, chemical industry.

3. Biological Sensors (Biosensors)

- **Purpose:** Detect biological molecules.
- **Examples:**
  - Glucose sensors
  - DNA sensors
  - Enzyme-based sensors
- **Applications:** Medical diagnostics, food safety, environmental monitoring.

4. Acoustic Sensors

- **Purpose:** Detect sound or vibration.
- **Examples:**
  - Microphones
  - Ultrasonic sensors
  - Vibration sensors
- **Applications:** Sound recording, sonar, industrial vibration analysis.

5. Optical Sensors

- **Purpose:** Detect light and optical properties.
- **Examples:**
  - Photodiodes
  - Phototransistors
  - Fiber optic sensors
  - LDR (Light Dependent Resistor)
- **Applications:** Light detection, imaging, communication (fiber optics).

6. Motion Sensors

- **Purpose:** Detect movement, position, or orientation.
- **Examples:**
  - Accelerometers (detect acceleration)
  - Gyroscopes (detect rotation)
  - Proximity sensors (detect nearby objects)
- **Applications:** Robotics, smartphones, automotive safety systems.

Characteristics of Sensors

Characteristic	Description
Range	Minimum and maximum values the sensor can measure.
Sensitivity	Change in output per unit change in input.
Accuracy	Closeness of the measured value to the true value.
Precision	Reproducibility of measurements under unchanged conditions.
Linearity	Ability to follow a straight-line relationship between input and output.
Resolution	Smallest change in input that can be detected.
Response Time	Time taken for the sensor to respond to a change in input.
Drift	Slow change in output over time without change in input.
Hysteresis	Difference in output when input increases vs. decreases.
Stability	Ability to maintain performance over time and conditions.
Repeatability	Ability to give the same output for the same input repeatedly.

Classification of Sensors

1. Analog Sensors

- **Definition:**
  Sensors that provide a **continuous output** signal (voltage or current) proportional to the measured quantity.
- **Output Nature:**
  The output varies smoothly and can have an infinite number of possible values within a range.
- **Examples:**
  - Temperature sensor (thermocouple, RTD)
  - Light sensor (LDR)
  - Pressure sensor
  - Strain gauge
- **Applications:**
  - Industrial automation
  - Weather monitoring
  - Medical devices

2. Digital Sensors

- **Definition:**
  Sensors that provide a **discrete (digital) output**, usually in the form of 0 or 1 (binary), or specific digital values.
- **Output Nature:**
  Output is in the form of **discrete steps** or pulses, representing the measured parameter in digital form.
- **Examples:**
  - Proximity sensor (IR sensor)
  - Digital temperature sensor (DHT11, DHT22)
  - Digital humidity sensor
  - Encoders
- **Applications:**
  - Digital systems (microcontrollers, microprocessors)
  - Robotics
  - Smart devices

Comparison Table

Feature	Analog Sensor	Digital Sensor
Output	Continuous signal (e.g., voltage)	Discrete signal (e.g., 0 or 1)
Resolution	Infinite within range	Limited (based on bits)
Noise sensitivity	High	Less
Processing	Requires ADC (Analog to Digital Converter)	Directly compatible with digital circuits
Example	Thermistor, LDR, Strain gauge	IR sensor, Proximity sensor, Digital temp sensor

Introduction to Actuator

- An **actuator** is a device that converts energy (often electrical, hydraulic, or pneumatic) into mechanical motion. It is used to control a system or mechanism based on signals from a controller or sensor.
- **Actuators** are the **muscles** of a system, providing the physical movement or control needed in automation.

Classification of Actuators

- Actuators are classified into four main types based on the energy source they use:

1. Hydraulic Actuators

- **Energy Source:** Pressurized liquid (usually oil).
- **Characteristics:** High force and torque, slow and steady motion.
- **Applications:** Heavy machinery, excavators, industrial presses.

2. Pneumatic Actuators

- **Energy Source:** Compressed air or gas.
- **Characteristics:** Quick response, clean, simple design, less powerful than hydraulics.
- **Applications:** Automation systems, robotics, air brakes.

3. Electric Actuators

- **Energy Source:** Electrical power.
- **Characteristics:** Precise control, easy integration, suitable for light to medium tasks.
- **Applications:** Robotics, home automation, motorized valves.

4. Mechanical Actuators

- **Energy Source:** Manual or mechanical energy.
- **Characteristics:** Simple, no external power required, reliable for small-scale systems.
- **Examples:**
  - Levers
  - Gears
  - Pulleys
- **Applications:** Door handles, mechanical linkages.

Characteristics of Actuators

Characteristic	Description
Force/Torque Output	Amount of mechanical power produced by the actuator.
Speed	How quickly the actuator can move or operate.
Accuracy	Precision in reaching the target position.
Repeatability	Ability to perform the same action repeatedly without deviation.
Power Consumption	Energy required for operation.
Control Method	How the actuator is controlled (manual, electrical signal, etc.)
Response Time	Time taken by the actuator to respond to control signals.
Durability	Life span and ability to withstand harsh conditions.
Size & Weight	Physical dimensions, affecting ease of integration into systems.
Maintenance	Requirements for upkeep and repair.