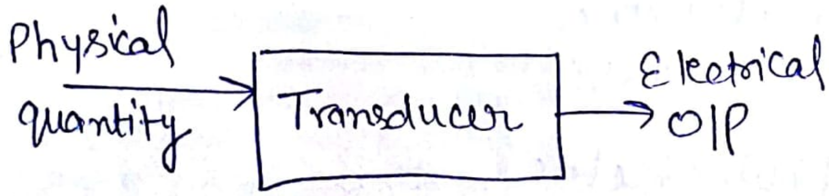
# Sensor & Instrumentation UNIT NO-01

**Sensor:** A Sensor (also called detector) is a converter that measures a physical quantity and converts it into a signal which can be read by an observer or by an instrument. For example, a mercury-in-glass thermometer converts the measured temperature into expansion and contraction of a liquid which can be read on a calibrated glass tube.

**Transducers:** In general, a transducer may be defined as a device that converts one form of energy into another form of energy.



* **Definition:-** In general, a transducer may be defined as a device that converts one form of energy into another form of energy.

Physical quantity → | Transducer | → Electrical o/p

Most transducers converts a nonelectrical physical quantity (such as displacement, force, temp., light etc) to an electrical voltage or current proportional to the magnitude of the physical quantity being measured.

The function of a transducer may be related with two important parts of a transducer. These two parts are

(i) Sensing or Detector Element:- A detector or a sensing element is that part of transducer which responds to a physical phenomenon or a change in a physical phenomenon. The response of the sensing element must be closely related to phenomenon

(ii) Transduction Element:- A transduction element transforms the output of a sensing element to an electrical output

* Electrical Transducer:- In electrical transducer to measure non-electrical quantities a detector is used which usually converts the physical quantity into a displacement. This displacement actuates an electrical transducer, which acting as a secondary transducer, gives an output that is electrical in nature.

## * Classification of Transducers:-

1. On the basis of transduction form used
2. as primary and secondary transducers
3. as passive and active transducers
4. as analog and digital transducers
5. as transducers and inverse transducers

### 1. Classification based upon Principle of Transduction:-

The transducers can be classified on the basis of principle of transduction as resistive, inductive, capacitive etc. depending upon how they convert the input quantity into resistance, inductance or capacitance respectively. They can be classified as piezoelectric, thermoelectric, magnetorestrictive, electrokinetic and optical.

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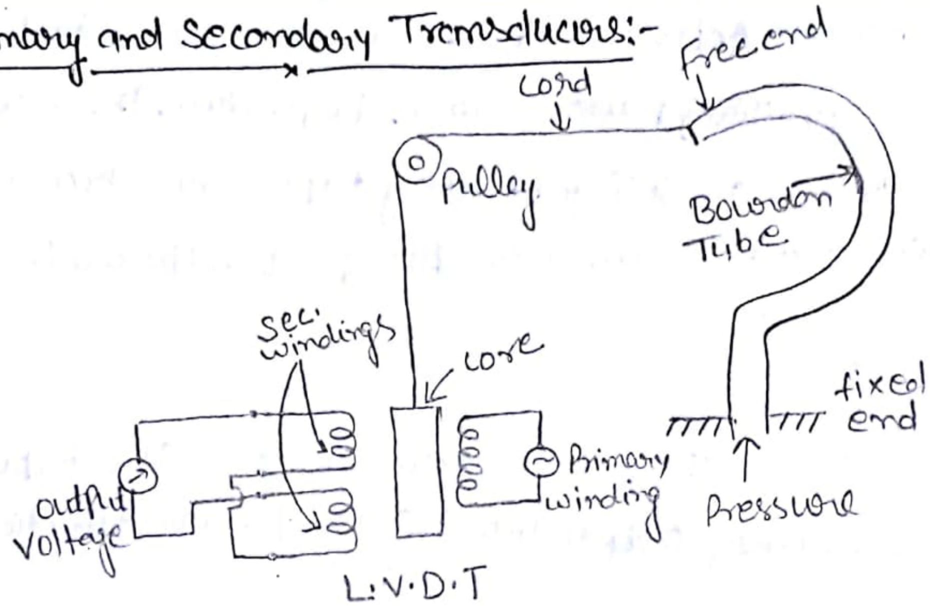
② Primary and Secondary Transducers:-




L.V.D.T

The Bourdon tube acting as a primary detector 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 (L.V.D.T) which produces an output voltage which is proportional to the movement of the core, which is proportional to the displacement of the free end which in turn is proportional to the pressure. Thus there are two stages of transduction, firstly the pressure is converted into a displacement by Bourdon tube then the displacement is converted into an analogous voltage by L.V.D.T. The Bourdon tube is called a "Primary Transducer" while the L.V.D.T is called a "Secondary Transducer".

③ Passive and Active Transducers:-

Passive Transducers:- Passive transducers derive the power required for transduction from an auxiliary power source. They are also known as "externally powered transducers". Examples – Resistive, inductive and capacitive transducers.

Active Transducers:- Active transducers are those which do not require an auxiliary power source to produce their output. They are also known as self generating type transducers. examples- piezoelectric, thermocouple, photovoltaic cells etc.

(4) Analog and Digital Transducers:-

Analog Transducers:- These transducers convert the input quantity into an analog output which is a continuous function of time.
Examples- Strain gauge, L.V.D.T, thermocouple, thermistor

Digital Transducers:- These transducers convert the input quantity into an electrical output which is in the form of pulses. examples- optical Encoder

(5) Transducers and Inverse Transducers:-

Transducers:- A transducer can be defined as a device which converts a non-electrical quantity into an electrical quantity.

Inverse Transducers:- An inverse transducer is defined as a device which converts a electrical quantity into a non-electrical quantity.
ex- A piezoelectric crystal acts as an inverse transducer because when a voltage is applied across its surface, it changes its dimensions causing a mechanical displacement

## Sensors classification:

**Sensors**

- Transduction principles using physical or chemical effect
  - Active sensor
  - Passive sensor
- Primary i/p quantity that is the measured
- Material & technology
- Application based
- Property based

**Application based sensors**

- Industrial process control/measurement
- Non Industrial
  - Automobiles
  - Medical product
  - Aircraft
  - Consumer electronics
  - other sensors

**Property based sensors**

- Flow
  - Differential pressure
  - thermal mass
  - electromagnetic
  - Ultrasonic
  - anemometer
- Level
  - Mechanical, magnetic, vibrating rod, magneto-strictive
- Temp.
  - RTD,
  - Thermister,
  - Thermocouple
- Pressure
  - Elastic
  - Piezoelectric
  - MEMS
  - fiber optic
- Proximity & displacement
  - LVDT,
  - capacitive,
  - photoelectr
  - Potentio-metric

Chacteristics of Transducers → Transducer have two general chacteristics 1. Static 2. Dynamic

Static characteristics →

(a) Accuracy → It is the closeness with which an instrument reading approaches the true value of the quantity being measured.

(b) Precision → It is the agreement of group of measured quantity. ~~being~~ or Reproducibility of measured value.

(c) Resolution → It is defined as the smallest change in input that would produce a detectable change in the output.

(d) Threshold → At the zero value condition of the measurand, the smallest input change that produce detectable output is called the threshold.

(e) Sensitivity → It is the ratio of the incremental o/p to incremental i/p.

$$S = \frac{\Delta y}{\Delta x}$$

(f) Nonlinearity → It is defined as the smallest change in q/p the largest change in o/p.

**Drift:-** It is an undesired change in input and output relationship.

**Dead Zone:-** It is the largest change of i/p quantity for which there is no output of the instrument

**Dynamic characteristics→** These involve determination of transfer function, frequency response, impulse response as also step response and then evaluation of the time-dependent outputs. The two important parameters in this connection are

(a) Fidelity determined by dynamic error

(b) Speed of response determined by lag.

* Factors affecting the Choice of Transducers:-

① Operating Principle – The transducers are many a times selected on the basis of operating principle used by them. The operating principles used may be resistive, inductive, Capacitive, optoelectronic, piezoelectric etc

② Sensitivity → The transducer must be sensitive enough to produce detectable output.

③ Accuracy:- High degree of accuracy

④ Errors → The transducer should maintain the expected i/p output relationship as described by its transfer function so as to avoid errors.

⑤ Loading Effects:→ The transducer should have a high input impedance and low output impedance to avoid loading effects.

⑥ 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.

⑦ Electrical aspects → Length and type of cable required.

⑧ Stability and Reliability → High degree of stability to be operative during its operation and storage life. Realiability should be assured in case of failure of transducer. Inorder that the functioning of the instrumentation system continues uninterrupted.

⑨ Static characteristics → Low non-linearity, low hysteresis, high resolution and high degree of repeatability.

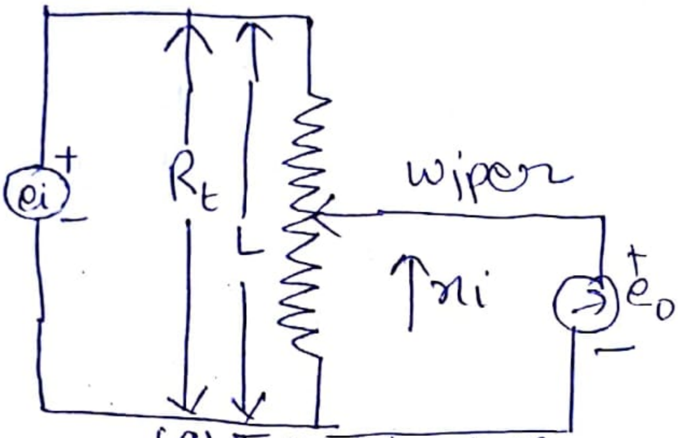
## Displacement Sensors:

**Potentiometer** → Potentiometer is a passive transducer since it requires an external power source for its operation. A Pot is a resistive transducer powered by a source voltage $e_i$. This Pot is used for measurement of linear displacement $x_i$

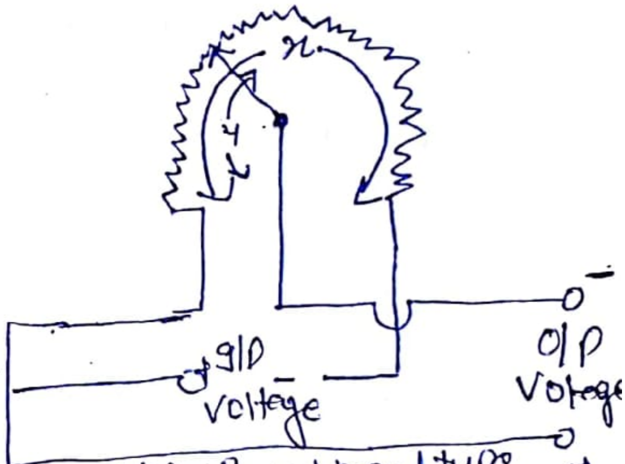
Suppose L is the total length of potentiometer whose total resistance $R_i$. The i/p displacement is $x_i$

O/P voltage $e_0 = \frac{x_i}{L} e_i$

$$x_i = \left(\frac{e_0}{e_i}\right) L$$



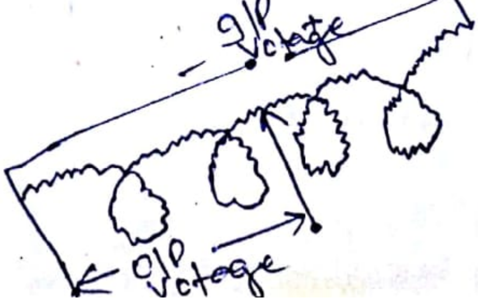

(a) Translatory type




(b) Rotational type

The POT consist of a resistive element provided with a sliding contact. This sliding contact is called a wiper. The motion of the sliding contact may be translatory or rotational.

In some pot use the combination of two motions translational or rotational. Thes type of pots are known as helipots



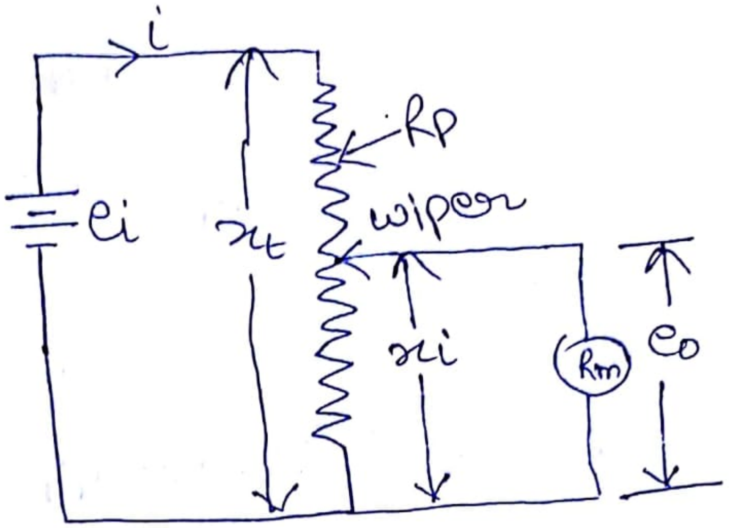
If a force is applied to wiper then its gets shifted from its original position. This displacement of wiper changes the resistance and is recorded in terms of o/p voltage.

If $x$ is the total length of the resistance element and $y$ is the displacement of the wiper from its zero position then,

$$\frac{\text{o/p voltage, } V_o}{\text{i/p voltage, } V_{in}} = \frac{y}{x}$$

$$\text{or } \quad V_o = \frac{y}{x} \times V_{in}$$

## Loading Effect →




The output voltage without load

$$e_o = \frac{x_i}{x_t} e_i$$

$$e_o = K e_i$$

$$K = x_i / x_t$$

The resistance of the parallel combination of load resistance and the portion of the resistance of the potentiometer is

$$R_{eq} = x_i/x_t R_p \| R_m$$

$$= \frac{x_i/x_t R_p \cdot R_m}{\frac{x_i}{x_t} R_p + R_m} = \frac{K R_p R_m}{K R_p + R_m}$$

The Total resistance seen by the source is

$$R = R_p(1-K) + \frac{K R_p R_m}{K R_p + R_m}$$

$$R = \frac{K R_p^2 (1-K) + R_p R_m}{K R_p + R_m}$$

$$\text{current } i = \frac{e_i}{R} = \frac{e_i (K R_p + R_m)}{K R_p^2 (1-K) + R_p R_m}$$

The output voltage under load conditions is

$$e_o = i \frac{K R_p R_m}{K R_p + R_m} = \frac{e_i (K R_p + R_m)}{K R_p^2 (1-K) + R_p R_m} \cdot \frac{K R_p R_m}{(K R_p + R_m)}$$

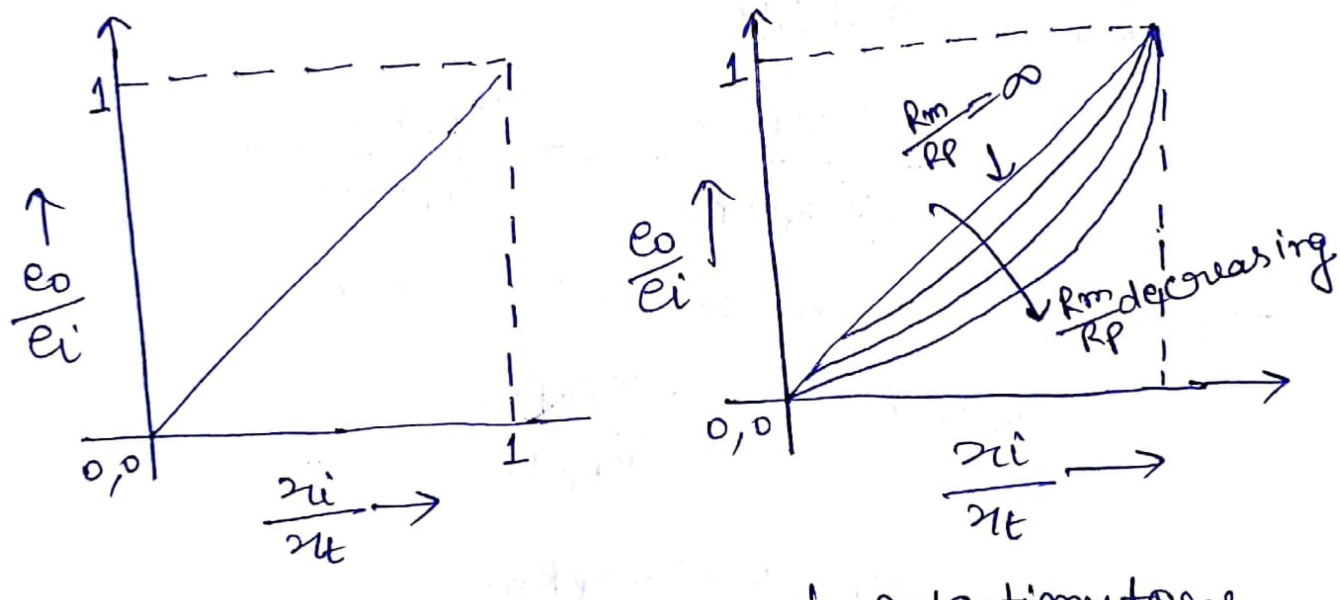
$$= \frac{e_i K}{K(1-K)(R_p/R_m)+1}$$

The ratio of output voltage to input voltage under load condn is

$$\frac{e_o}{e_i} = \frac{K}{K(1-K)\,R_p/R_m+1}$$

there exists a non linear relationship b/w output voltage $e_o$ and input displacement $x_i$ since $K = x_i/x_t$

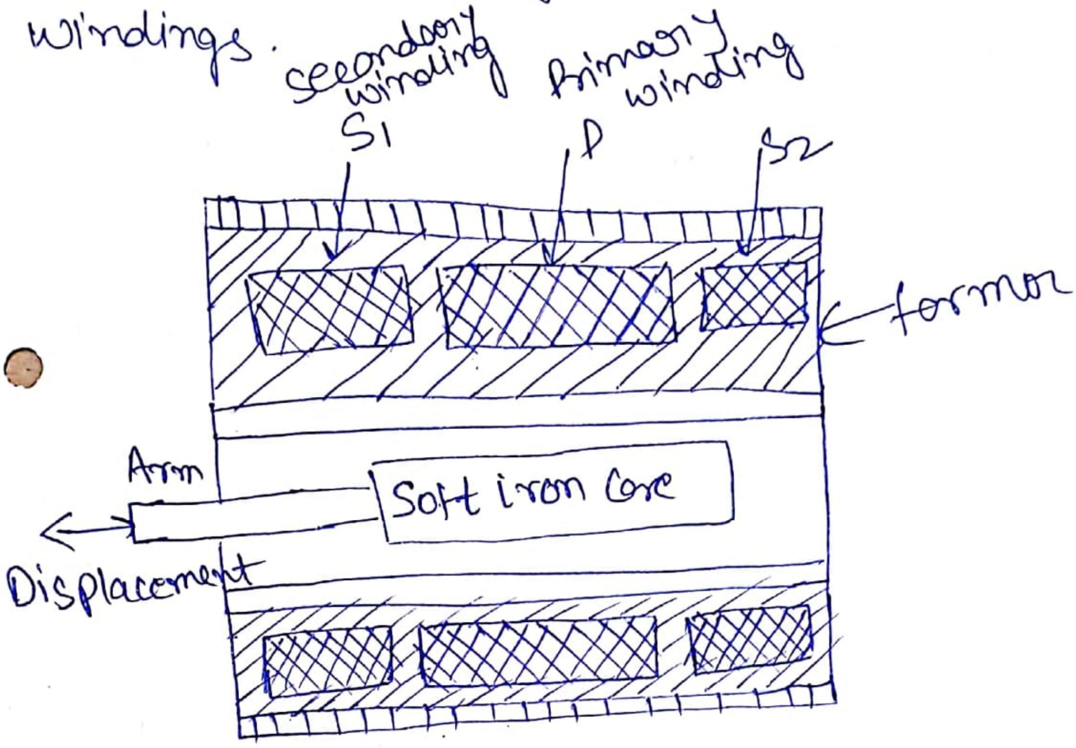
In case $R_m = \infty$, $e_o/e_i = K$

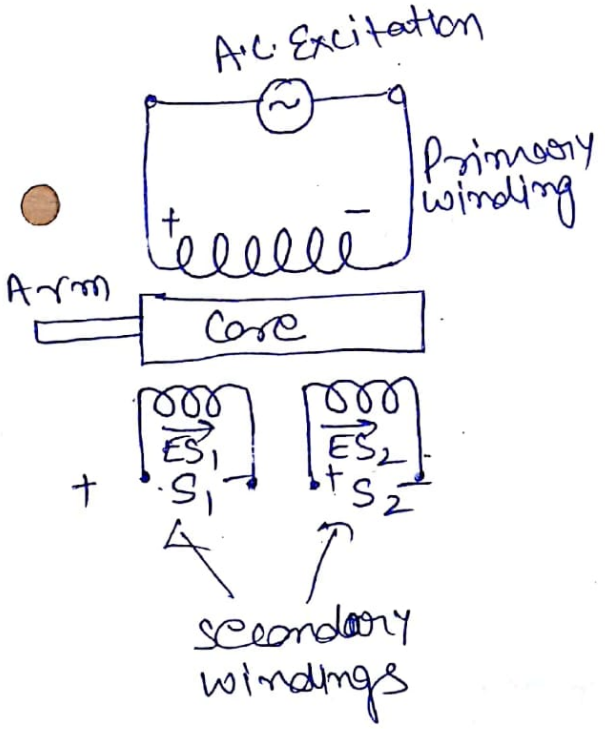


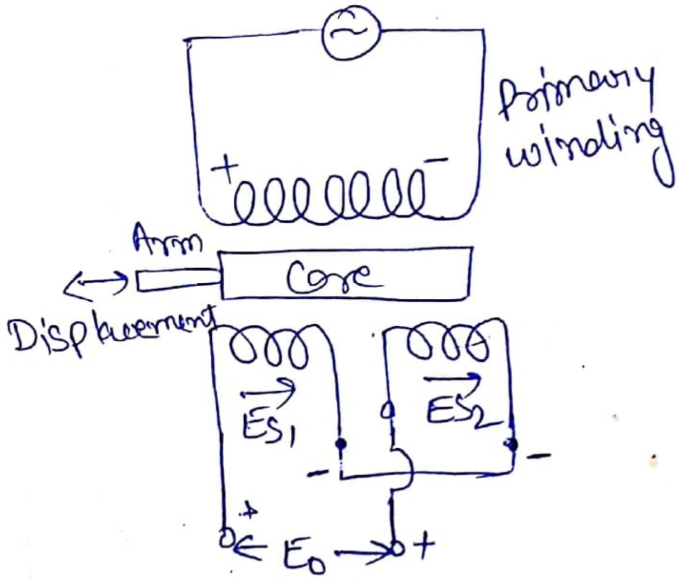

Characteristics of potentiometers

LVDT: This is the most widely used inductive Transducer for translating linear motion into an electrical signal. The Transformer consists of a single primary winding P and two secondary windings $S_1$ and $S_2$ wound on a cylindrical former. The secondary windings have equal number of turns and are identically placed on either side of the primary winding. The primary winding is connected to an alternating current source. A movable soft iron core is placed inside the former. The displacement to be measured is applied to the arm attached to the soft iron core. The core is made of high permeability, nickel iron which is hydrogen annealed. This gives low harmonics, low null voltage and a high sensitivity. This is slotted longitudinally to reduce eddy current losses.

Since the primary winding is excited by an a.c source, it produces an alternating magnetic field which in turn induces alternating current voltages in the two secondary windings.



The output voltage of secondary $S_1$ is $ES_1$ and that of secondary $S_2$ is $ES_2$. In order to convert the outputs $S_1$ and $S_2$ into a single voltage signal, the two secondaries $S_1$ & $S_2$ are connected in series opposition. Thus the O/P voltage.

$$E_0 = ES_1 - ES_2$$

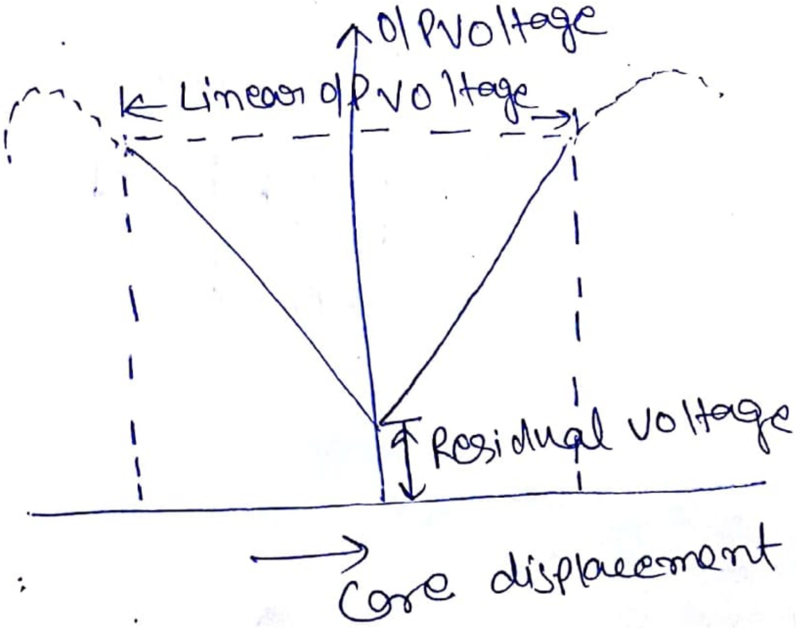
When the core is at its normal (Null) position, the flux linking with both the secondary windings is equal hence equal emf's are induced in them. Thus at null position $ES_1 = ES_2$

$$E_0 = 0$$

Now if the core is moved to the left of the null position, more flux links with $S_1$ and less with $S_2$

$\therefore ES_1 > ES_2$ , $E_0 = ES_1 - ES_2$

Similarly $\therefore ES_1 < ES_2$ $E_0 = ES_2 - ES_1$



Ideally output voltage should be zero at null position. but practically, there is a small voltage at the O/P when $E_1 = E_2$. This is due to presence of harmonics in the input supply voltage and also due to harmonics produced in the o/p voltage on account of use of iron core. There may be either magnetic or electric unbalance. This voltage is known as Residual Voltage.

$$\text{Sesitivity of LVDT } S = \frac{\text{O/P Voltage}}{\text{Displacement}} \ (\text{mV/mm})$$

Optical Encoder:- An encoder is a device that provides a digital output as a result of angular or linear displacement.

Position Encoder can be grouped in two categories:

(i) Incremental Encoder

(ii) Absolute Encoder

Incremental Encoders:- These detect changes in position displacement from some datum position (part of placement from which light can not pass through)

Absolute Encoder:- They gives the Actual position or displacement.

**Measurement Errors:**– No measurement can be made with perfect accuracy but it is important to find out what accuracy actually is and how different errors have entered into the measurement.

Errors
- Gross Error
- Systematic error (commulative)
  - Instrumental
    - Due to Inherent shortcoming in the instrument
    - Due to misuse of the instrument
    - due to loading effect
  - Environmental
  - Observational.
- Random Error (accidental)

**Gross Errors:**– These errors mainly covers human mistakes in reading instruments and recording and calculating measurement results. They can be avoided by adopting two means. They are

① Great care should be taken in reading and recording the data.

② Two, three or even more reading should be taken for the quantity under measurement. These readings should be taken preferably by different experimentors should be taken at a different reading the reading should be taken at a different reading point to avoid re-reading with the same error.

Environ-
exte

## Systematic Errors:-

### ① Instrumental Errors:-

(i) Due to Inherent shortcomings of instruments:-

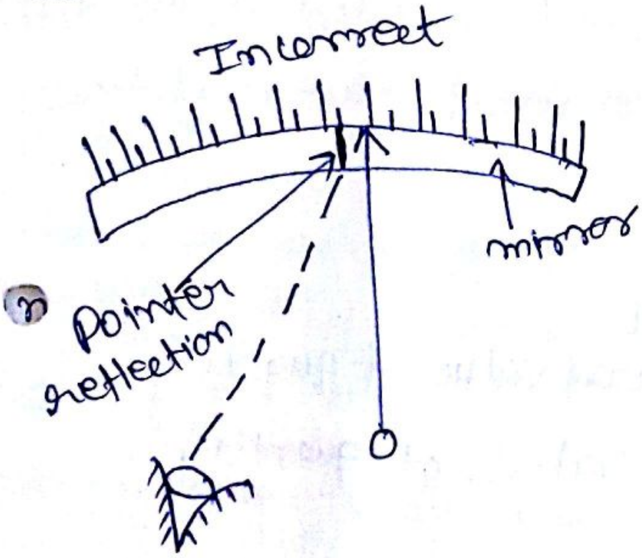
These errors are inherent in instruments because of their mechanical structure. They may be due to construction, calibration or operation of the instruments or measuring devices. These errors may cause the instrument to read too low or too high.

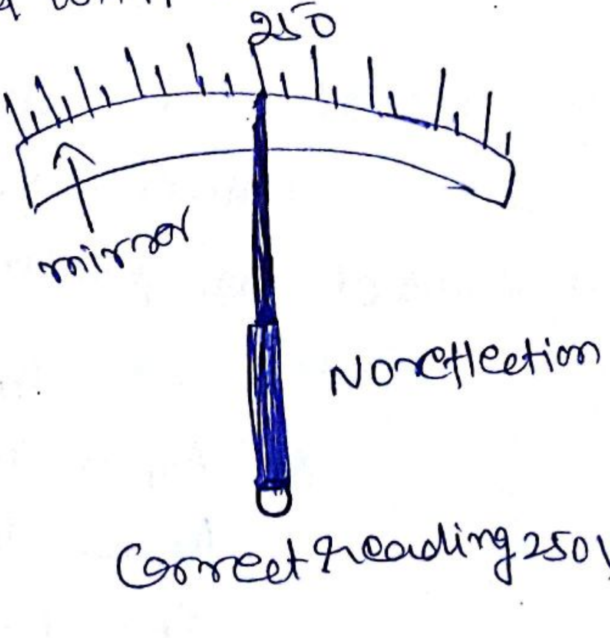
(ii) Misuse of Instruments:- There is an old saying that instruments are better than the people who use them. Too often, the errors caused in measurements are due to the fault of the operator than that of the instrument. A good instrument used in an unintelligent way may give erroneous results.

(iii) Loading Effects:- One of the most common errors committed by beginners, is the improper use of an instrument for measurement work. for exp a well calibrated voltmeter may give a misleading voltage reading when connected across a high resistance ckt. The same voltmeter when connected in a low resistance ckt may give a more dependable reading. These example illustrate that the voltmeter has a loading effect on the ckt. altering the actual ckt conditions by the measurement process.

Environmental Errors:- These errors are due to conditions external to the measuring device including conditions in the area surrounding the instrument. These may be effects of temp pressure, humidity, dust, vibrations or of external magnetic or electrostatic fields.

(3) Observational Errors:- There are many sources of observational errors. As an example the pointer of a Voltmeter rests slightly above the surface of the scale. Thus an error on account of parallax will be incurred unless the line of vision of the observer is exactly above the pointer. To minimize parallax errors highly accurate meters are provided with mirrored scales.



**Random (Residual) Errors:→** It has been consistently found that experimental results show variations from one reading to another, even after all systematic errors have been accounted for. We are aware of and account for some of the factors influencing the measurement but about the rest we are unaware. The happenings or disturbance about which we are unaware are lumped together and called Random or Residual. Hence the errors caused by these happenings are called Random errors.

$$\text{Random error} = \text{Total error} - (\text{Gross Error} + \text{systematic error})$$

Optical Encoder:- An encoder is a device that provides a digital output as a result of angular or linear displacement.

Position Encoder can be grouped in two categories:

(i) Incremental Encoder

(ii) Absolute Encoder

Incremental Encoders:- These detect changes in position displacement from some datum position (part of placement from which light can not pass through)

Absolute Encoder:- They gives the Actual position or displacement.

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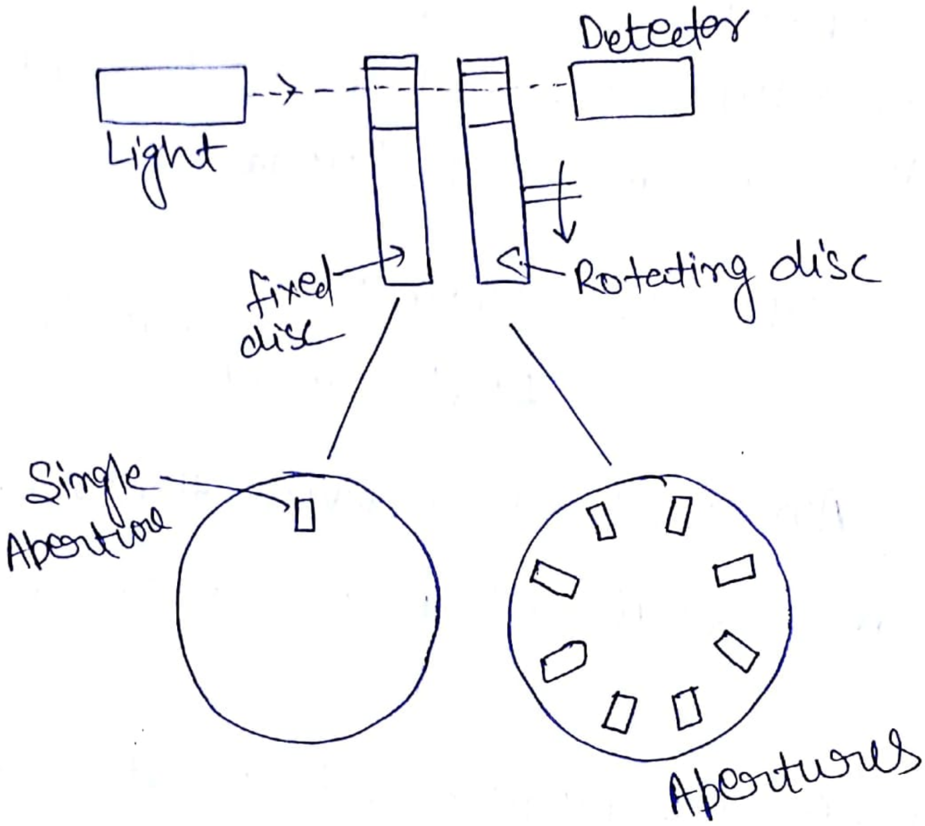
Incremental Encoder: — The basic incremental encod[er] for the measurement of angular displacement o[f] a shaft.

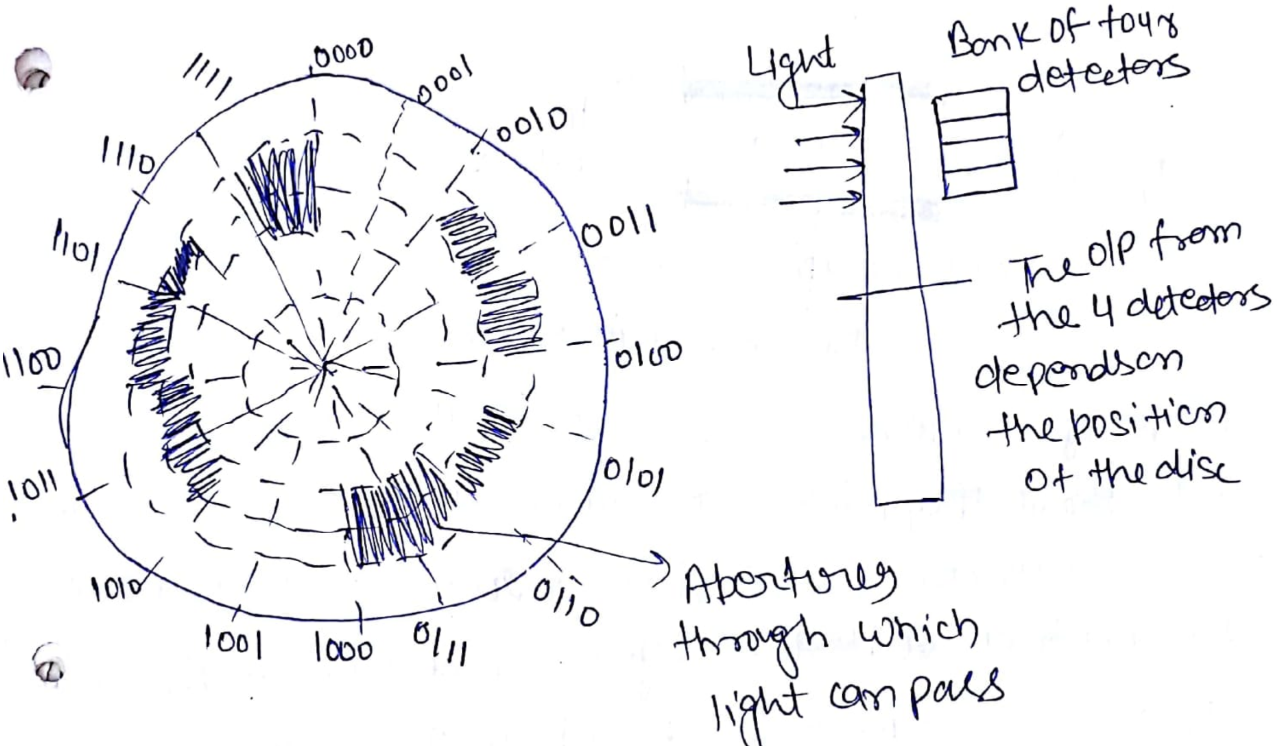



It consist of a disc which rotates along with the shaft Rotatable disc has a number of window through which a beam of light can pass and be detected by a suitable light sensor. when shaft rotates and disc rotates, a pulsed o/p is produced by the sensor with the number of pulse being proportional to the angle through which the disc rotates. The angular displacement of disc, and shaft rotating it, can be determined by the number of pulses produced angular displacement.

...lution: → with 60 slot occuring with 1 revolution the
. Since 1 revolution is a rotation of 360°, so

$$\text{Resolution} = \frac{360}{60} = 6^\circ$$

**Absolute Encoder:** — It gives an o/p in the form of a binary number of several digits, each such number representing a particular angular ~~displ~~ position.



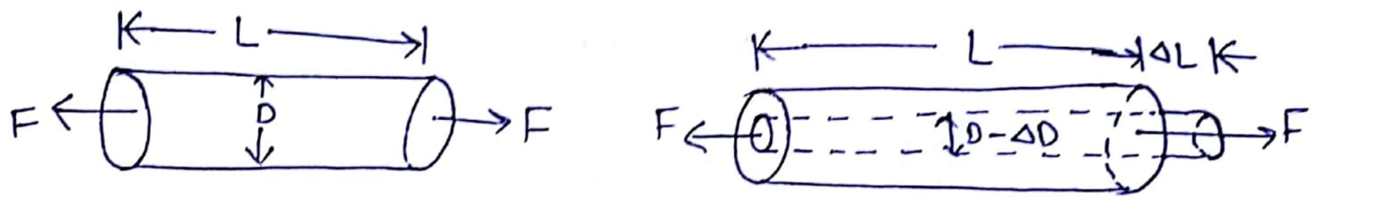

The rotating disc has four concentric circles of slots and four sensors to detect the light pulses. The slots are arranged in such a way the sequential o/p from sensors is a number of binary code, each such number corresponding to a particular angular position.
The number of bits in binary number will be equal to number of tracks. So with 10 tracks, there

will be 10 bits ∴ no. of positions that can be detected is $2^{10} = 1024$

$$\text{Resolution :- } \frac{360}{1024} = 0.35^{0}$$

**Strain Gauge:** 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 piezo-resistive gauges. The strain gauges are used for measurement of strain and associated stress.

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 ρ.




Resistance of unstrained gauge $R = \rho L/A$

Let a tensile stress S be applied to the wire. This produces a positive strain causing the length to increase and area to decrease. When the wire is strained there are changes in its dimensions. Let $\Delta L$ = change in length, $\Delta A$ = change in area, $\Delta D$ = change in diameter & $\Delta R$ = change in resistance.

The expression for R is differentiated with respect to stress S

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

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

$$A = \frac{\pi}{4} D^2$$

$$\frac{\partial A}{\partial S} = 2 \cdot \frac{\pi}{4} D \cdot \frac{\partial D}{\partial S}$$

$$\frac{1}{A}\frac{\partial A}{\partial S} = \frac{(2\pi/4) D}{(\pi/4) D^2}\frac{\partial D}{\partial S} = \frac{2}{D}\frac{\partial D}{\partial S}$$

$$\frac{1}{R}\frac{dR}{dS} = \frac{1}{L}\frac{\partial L}{\partial S} - \frac{2}{D}\frac{\partial D}{\partial S} + \frac{1}{\rho}\frac{\partial \rho}{\partial S}$$

Poisson's ratio $\nu = \dfrac{\text{lateral Strain}}{\text{longitudinal Strain}} = -\dfrac{\partial D/D}{\partial L/L}$

$$\frac{\partial D}{D} = -\nu \times \frac{\partial L}{L}$$

$$\frac{1}{R}\frac{dR}{dS} = \frac{1}{L}\frac{\partial L}{\partial S} + \nu\frac{2}{L}\frac{\partial L}{\partial S} + \frac{1}{\rho}\frac{\partial \rho}{\partial S}$$

(i) per unit change in length $= \Delta L/L$

(ii) per unit change in area $= \Delta A/A$

(iii) Per Unit change in resistivity $= \Delta\rho/\rho$

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

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

$$G_f = \frac{\Delta R/R}{\Delta L/L}$$

$$\frac{\Delta R}{R} = G_f \frac{\Delta L}{L}$$

$$= G_f \times \epsilon$$

$$\epsilon = \text{Strain} = \frac{\Delta L}{L}$$

$$G_f = 1 + 2\nu + \frac{\Delta \rho / \rho}{\epsilon}$$

The strain is usually expressed in terms of microstain

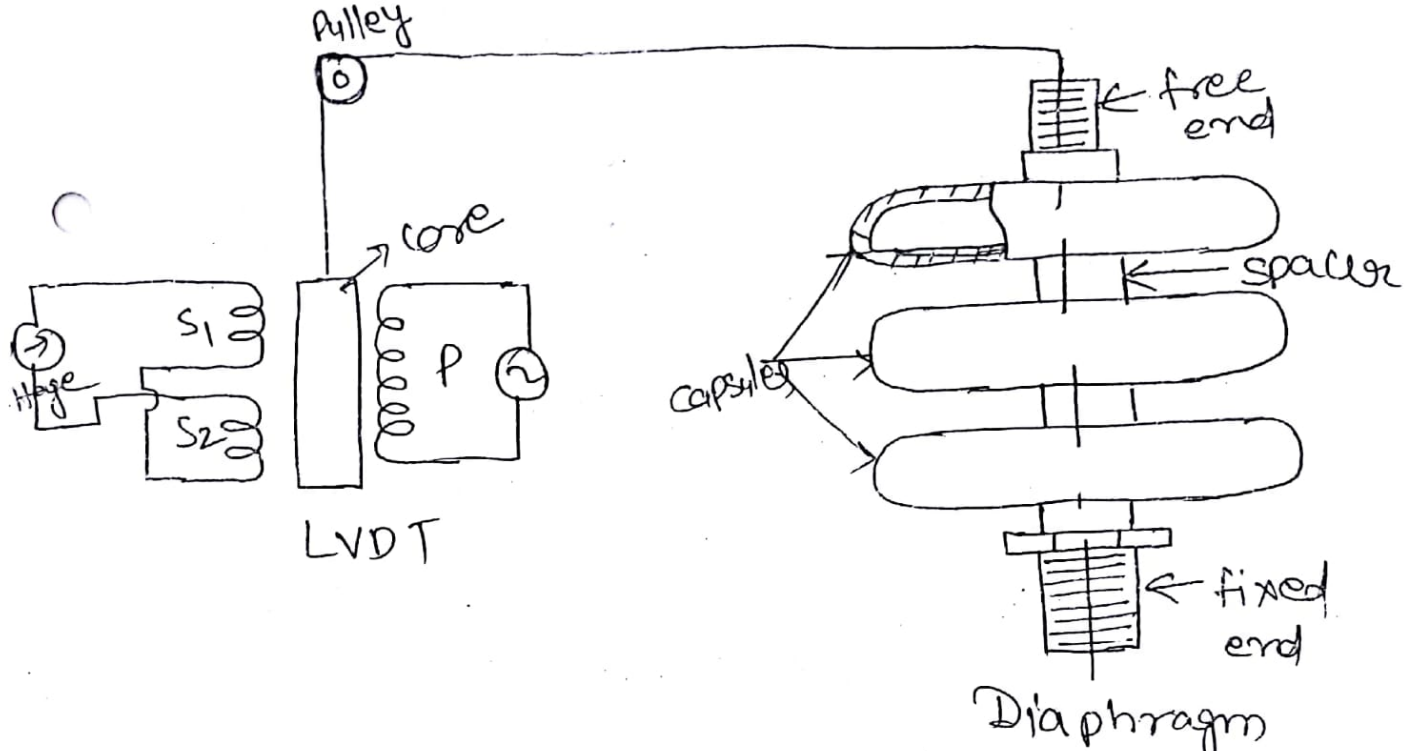
If the change in the value of resistivity of a material when strained is neglected, the gauge factor is

$$\boxed{G_f = 1 + 2\nu}$$

Semiconductor Strain Gauges:- Semiconductor strain gauges are used when a high value of gauge factor is desired. Their gauge factor is 50 times as high as that of wire gauges.

Basic principle of operation of the semiconductor strain gauge is piezoresistive effect the change in value of resistance due to change in resistivity of the semiconductor because of strain applied. However, in metallic gauges, the change in resistance is mainly due to change in dimension when strained. Semiconductor materials used are germanium and silicon

LVDT based Diaphragm:- The operating principle of diaphragm elements is similar to that of bellows. The pressure to be measured is applied to the diaphragm causing it to deflect, the deflection being proportional to the applied pressure. The movement of diaphragm depends on its thickness and diameter.




In some cases, a diaphragm element may consist of a single disc which in others, two diaphragms are bonded together at their circumference by soldering or pressure welding to form a capsule. A diaphragm element may consist of one capsule or two or more capsules connected together with each capsule deflecting on the application of pressure.

The displacement of the free end moves the core of a LVDT which produces an output voltage which is proportional to movement of the core which is proportio to the displacement of the free end which in turn is proportional to the pressure.

## piezoelectric Transducers:-

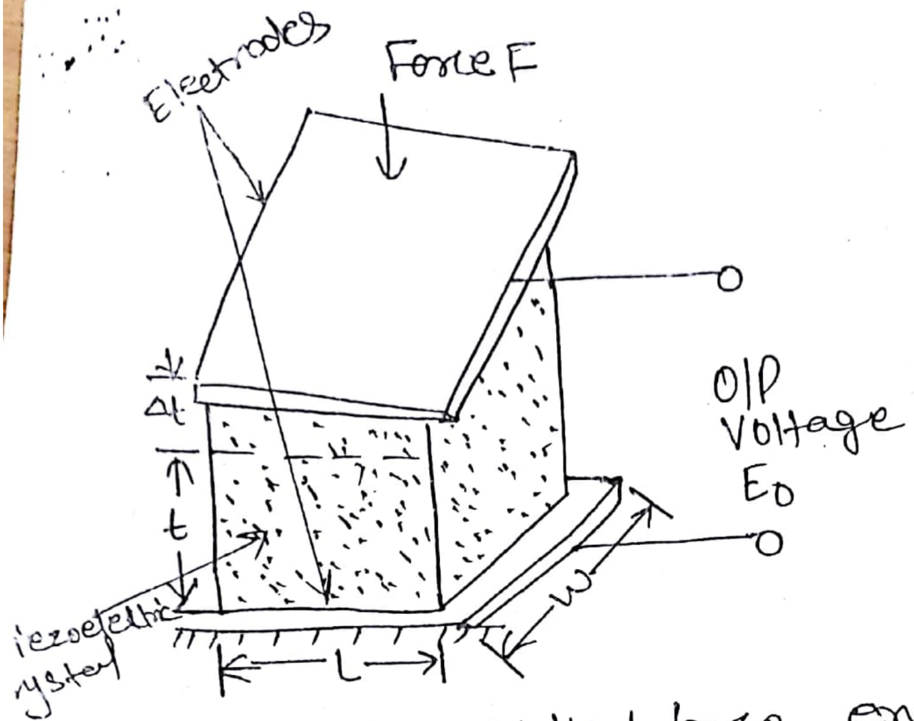
A piezo electric material is one in which an electric potential appears across certain surfaces of a crystal if the dimensions of the crystal are changed by the application of a mechanical force. This potential is produced by the displacement of charges. The effect is reversible. if a varying potential is applied to the proper axis of the crystal it will change the dimensions of the crystal thereby determing it. This effect is known as piezoelectric effect.

Common piezo electric materials include Rochelle salts, ammonium dihydrogen phosphate, lithium sulphate, dipotassium tartarate, potassium dihydrogen phosphate, quartz and Ceramics.

The materials that exhibit a significant and useful piezo electric effect are divided into two categories:

(i) Natural group (ii) Synthetic group.

Quartz and Rochelle salt belong to natural group while materials like lithium sulphate belong to the synthetic group.




An externally applied force, entering the transducer through its pressure port, applies pressure to the top of the crystal. This causes to produce an emf across the electrodes. Mechanical deformation generates a charge and this charge appears as a voltage across the electrodes. The voltage $E = \frac{Q}{C}$

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

$$\text{charge } Q = d \times F \text{ coulomb}$$

where d = charge sensitivity of the crystal
F = applied force, N

charge $Q = d \times F$

$d$ = charge sensitivity of the crystal C/N

$F$ = applied force, N

Force F causes a change in thickness of the crystal

$$F = \frac{AE\Delta t}{t}$$

$A$ = Area of crystal, $m^2$

$E$ = Young's Modulus, $N/m^2$

$t$ = thickness of crystal ; m

$$E = \frac{\text{stress}}{\text{strain}} = \frac{F/A}{\Delta t/t} = \frac{Ft}{A\Delta t} \; N/m^2$$

$A = wl$ where $w$ = width of crystal

$L$ = Length of crystal

$$Q = d \times \frac{AE\Delta t}{t}$$

The charge at the electrodes gives rise to an output voltage $E_0$

$$E_0 = Q/C_p$$

$C_p$ = Capacitance b/w electrodes

$$C_p = \epsilon_r \epsilon_0 A/t$$

$$E_0 = \frac{Q}{C_p} = \frac{dF}{\epsilon_0 \epsilon_r A/t} = \frac{dt}{\epsilon_r \epsilon_0} \frac{F}{A}$$

$$E_0 = \frac{dt}{\epsilon_r \epsilon_0} P \qquad P = \frac{F}{A}$$

Pressure

$$\boxed{E_0 = gtP}$$

$g = d/\epsilon_r \epsilon_0$

where $g$ is the voltage sensitivity of the crystal.