Chapter: 3

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NO : Physical variables and Transducers

3.1 Physical Variable :- A physical variable is a quantity or condition whose values vary when it is subjected to changes. It has got a magnitude and a unit. These variables may vary and depend from system to system. They can be either electrical or non-electrical quantities depending upon the system or condition we deal with. In fact, they denote various variable parameters related to a particular system. They can be generalized into the following types:

(i) Physical Variables: They denote the quantities or variables pertaining to various physical conditions or phenomena like time, temperature, pressure, humidity, etc.

(ii) Electrical variable :- They denote electrical quantity like voltage, current, flux, frequency, magnetic field, etc.

(iii) Mechanical variables :- variables related to mechanical system. eg: Force, torque, load or weight, mechanical displacement, etc.

(iv) Process variables :- These are the variables related to process control system. eg: temperature flow rate.

(v) Bio-physical variable :- They indicate the variables related to various biological phenomena of living cells. eg:

ECG (Electro cardiogram) :→ records bioelectric potential of heart.

EEG (Electro encephalogram) → electrical activity of brain.

EMG (Electro Myogram) → Skeletal muscle.

ERG (Electro retinogram) → Retina of ~~ge~~ eye.

EOG (Electro oculogram) → related to pupil dialation.

3.2 Transducer :- A transducer is a device which is capable of being activated by an energizing i/p from one or more transmission system or media and in turn generates a signal (ie. supplies energy) in the same form or in another form to one or more transmission system or media. The o/p signal may be an electrical or non-electrical quantities and so the transduction may be from mechanical, optical or electrical to any other related form. Also the responding device may be mechanical, electrical, magnetic, optical, chemical, acoustic, thermal or a combination of any two or more of them.

eg: Loudspeaker : changes electrical to acoustic
Microphone : acoustic energy to electrical
LVDT : displacement to electrical energy
· Bourden tube : pressure to displacement.

The o/p of the transducer may also be either electrical or non-electrical quantity.

A mechanical transducer possess a high accuracy, relatively low cost and operate without any external power supply. Still the mechanical transducers are not suitable because of their poor frequency response, requirement of large force to overcome mechanical friction, incompatibility when remote control is used or required. To overcome these drawbacks, electrical transducers are used.

An electrical transducer is a sensing device by which a physical, mechanical or optical quantity to be measured is converted directly with a suitable mechanism into electrical voltage or current proportional to the quantity being measured.
eg: LVDT, potentiometric device, etc.

Advantages of Electrical transducers :-

(i) Electrical o/p can be easily attenuated or amplified to desired level.
(ii) The effect of friction can be minimized.
(iii) The o/p can be indicated or recorded remotely from the sensing medium.
(iv) The o/p can be modified to meet the requirements of the indicating and recording devices.

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(v) The development in the field of electronic instrumentation has led to the reduced in size and hence occupy less space.
(vi) Power Consumption of electrical transducers is very low.

Disadvantages :-

(i) Sometimes, less reliable than their mechanical counterpart due to ageing and drift of active components.
(ii) The sensing elements and associated signal conditioning may sometimes be comparatively expensive.

Classification of Transducers :-

Transducers can be classified

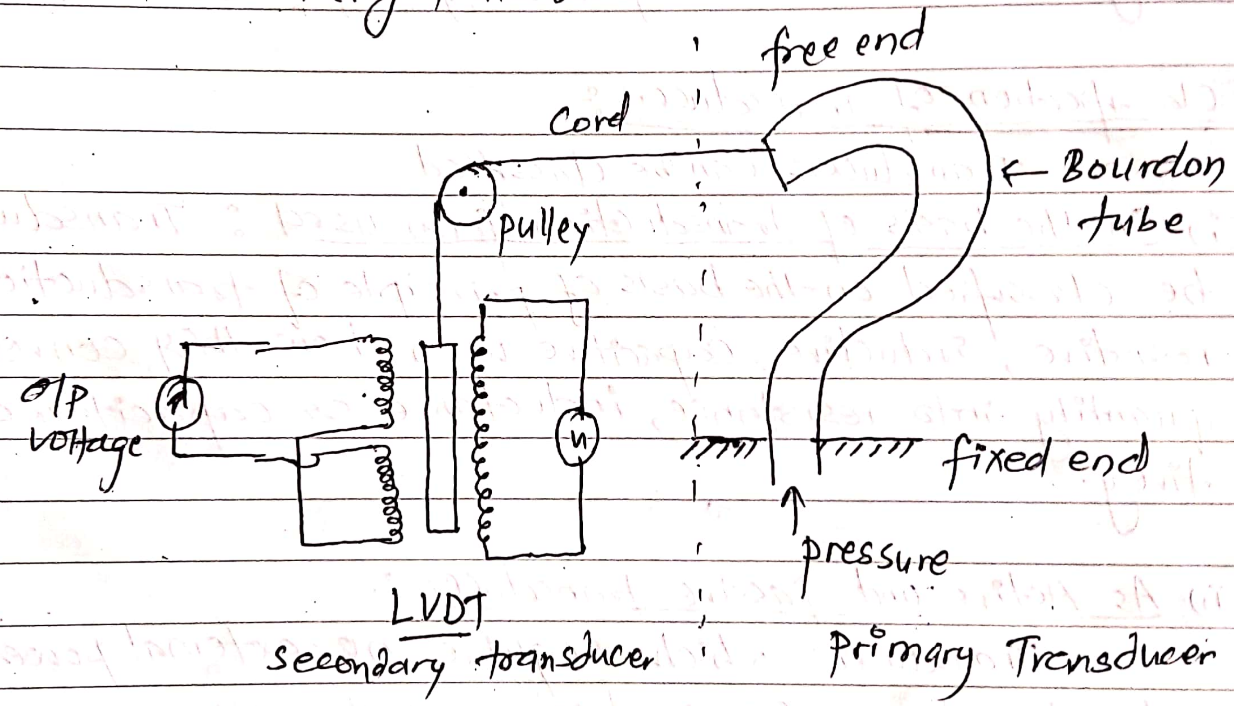
(i) On the basis of transduction form used : Transducers can be classified on the basis of principle of transduction as resistive, inductive, capacitive upon how they convert the i/p quantity into resistance, inductance or capacitance respectively.

(ii) As Active and passive transducer :-

Transducers which require no external power are active transducers. They produce an analog voltage or current when stimulated by some physical form of energy. eg: Thermocouple ~~Transducers~~ thermopile, moving coil generator, piezo-electric pick-up, photo voltaic cell.

Transducers which require external power are passive transducers. They produce a variation in some electrical parameters such as resistance, capacitance & so on which can be measured as a voltage or current variation. eg: Potentiometric device, Resistance strain gauge, resistance thermometer, thermistor, photo conductive cell, Differential transformer, Hall effect pick-up.

(iii) <u>as primary and Secondary transducer</u> :- If the transduction involve two stages, the Ist stage is primary and the 2nd stage transducer is secondary transducer. Let us take an example of transduction of <u>pressure</u> into analogous o/p voltage. It involves two stages i.e. Ist stage is the conversion of pressure into displacement by the use of Bourdon tube and the 2nd stage is the conversion of displacement into voltage using LVDT. Here, Bourdon tube is primary transducer & the LVDT is secondary transducer.



(iv) <u>as a transducer and Inverse transducer</u> :-

A transducer converts non electrical quantity to ~~non~~ electrical quantity whereas an inverse transducer converts electrical quantity into non electrical quantities. eg. for ~~to~~ inverse transducers are piezoelectrical crystal, moving coil. It is seen in a closed loop circuits.

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(v) as analog and digital transducer :-

Analog transducer converts i/p quantity into analog o/p i.e. continuous time function. eg: strain gauge, LVDT, thermocouple, thermistor, etc.

On the other hand, the digital transducers convert i/p quantity into electrical o/p which is in the form of pulses.

3.2.1 Strain Gauges :

Strain gauge is one of the most commonly used electrical (passive) transducer. The principle of operation of electrical resistance strain gauge is based on piezo resistive effect i.e. the resistance of the wire changes as the function of strain, increasing with tension and decreasing with compression. It basically converts mechanical displacement into change in resistance. These gauges are manufactured from small diameter resistance wire or from thin foil of sheets. The resistance of the wire changes to the length of the material to which it is attached under tension or compression. This change in resistance is proportional to the applied strain and is measured specially with wheatstone bridge.

Strain is defined as the change in length of a material owing to an externally applied force or stress.

$$\text{strain}(\sigma) = \frac{\Delta L}{L}$$

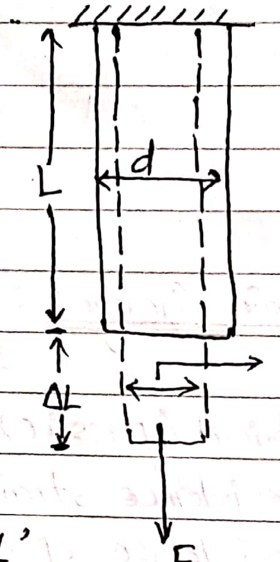
where, ΔL = change in length owing to applied force

L = original length.

Gauge Factor (K):

The sensitivity of a strain gauge is described in terms of gauge factor (K). It is defined as the unit change in resistance per unit change in length.

i.e. $$K = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\sigma} \quad \text{—— (i)}$$



Let us consider a conductor of length 'L' and cross-sectional area 'A' suspended from a fixed support as shown in the figure above. Let 'R' be the resistance of the wire and 'ρ' be the specific resistance of the conductor. Let the conductor be strained axially in tension causing an increase in length.

The resistance change ΔR of a conductor with length 'L' can be calculated by using the expression for the resistance of a conductor of uniform cross-section.

$$R = \frac{\rho \text{ length}}{\text{Area}} = \frac{\rho L}{\pi d^2/4} \quad \text{—— (ii)}$$

Tension on conductor causes increase in its length (ΔL) and a simultaneous decrease in its diameter (Δd). The resistance of the conductor then changes to

$$R + \Delta R = \frac{\rho (L + \Delta L)}{\frac{\pi}{4}(d - \Delta d)^2} = \frac{\rho L}{\pi d^2/4}\left[\frac{1 + \Delta L/L}{(1 - \Delta d/d)^2}\right] \quad \text{—— (iii)}$$

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Substituting the value of R from eqⁿ (II) in eqⁿ (III), we get,

$$R+\Delta R = \frac{R\,(1+\Delta L/L)}{(1-\Delta d/d)^2}$$

or, $$R+\Delta R = \frac{R\,(1+\Delta L/L)}{\{1-2\Delta d/d+(\Delta d/d)^2\}} \quad \text{———— (IV)}$$

Neglecting the higher order terms in denominator,

$$R+\Delta R = \frac{R\,(1+\Delta L/L)}{(1-2\Delta d/d)} \quad \text{———— (V)}$$

But we know that the Poisson's ratio is defined as the ratio of lateral strain to longitudinal strain ie;

Poisson's ratio $(\mu) = \dfrac{\Delta d/d}{\Delta L/L}$ ———— (VI)

or, $\Delta d/d = \mu(\Delta L/L)$ ———— (VII)

from eqⁿ (V) & (VII), we get,

$$R+\Delta R = \frac{R\,(1+\Delta L/L)}{1-2\mu(\Delta L/L)}$$

or, $$R+\Delta R = R\,\frac{(1+\Delta L/L)}{(1-2\mu\,\Delta L/L)} \times \frac{(1+2\mu\,\Delta L/L)}{(1+2\mu\,\Delta L/L)}$$

or, $$\frac{R+\Delta R}{R} = \frac{1+2\mu\,\Delta L/L+\Delta L/L+2\mu(\Delta L/L)^2}{1-(2\mu\,\Delta L/L)^2}$$

neglecting the higher order terms,

$$1+\Delta R/R = 1+\Delta L/L\,(2\mu+1)$$

or, $$\Delta R/R = \Delta L/L\,(2\mu+1)$$

or, $$\frac{\Delta R/R}{\Delta L/L} = (1+2\mu)$$

$$\therefore \boxed{K = (1+2\mu)} \quad \text{———— (VIII)}$$

This is the required expression for gauge factor.

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For strain gauge applications, a high sensitivity is very desirable. A large gauge factor means a relatively large resistance change which can be more easily measured than a small resistance change.

We know that within an elastic limit, the stress is directly proportional to strain.

i.e. $S \propto \sigma$

or, $S = E\sigma$

$\therefore \boxed{\sigma = S/E}$

where σ = strain (no unit)

S = stress (kg/cm²)

E = Young's modulus (kg/cm²).

(8) A strain gauge with a gauge factor of 2 is fastened to a steel member subjected to a stress of 1050 kg/cm². The modulus of Elasticity of steel is 21×10^6 kg/cm². Calculate the percentage change in resistance.

⇒ Soln Here, Gauge factor (K) = 2

Modulus of elasticity (E) = 21×10^6 kg/cm²

Stress (S) = 1050 kg/cm².

we have,

$$\text{Strain } (\sigma) = S/E = \frac{1050}{21\times10^6} = 5\times10^{-5}$$

Again,

$$K = \frac{\Delta R/R}{\sigma}$$

$$\text{or, } 2 = \frac{\Delta R/R}{5\times10^{-5}}$$

$$\text{or, } \Delta R/R = 10^{-4}$$

$\therefore$ percentage change in resistance $= \frac{\Delta R}{R}\times100\% = 10^{-4}\times100 = 10^{-2}\%$

Ans

Materials for Strain Gauge :-

The materials employed for the fabrication of electrical strain gauge and their installation for stress/strain measurement should possess a few basic qualities and minimum reproducibility, good sensitivity, long life and stability to operate under required environmental condition. Some of these qualities are achieved by choosing materials having high specific resistance, low temperature coefficient of resistance, constant gauge factor & constant strain sensitivity over a wide range of strain values. The various materials employed for the fabrication and installation of the strain gauges basically consists of the following:

(i) Wire Resistance Material (metallic Sensing element).
(ii) Backing Material
(iii) Gauge Bonding ~~mat~~ element.

(i) Wire resistance material :-

→ Choice of material depends upon the application & temperature range.

→ Most Commonly used wire materials are:
Constantan
Nichrome
V. Dynaloy
Stabiloy and platinum-Tungsten

* Constantan : → high specific resistance, Alloy of copper & Nickel
→ Constant gauge factor over wide range
→ Good stability over large temp. range (0-300°C)
→ Commonly used in dynamic strain measurement.

→ Nichrome : Used for static strain measurement. [375°C to 650°C]

* V. Dynaloy : → High gauge factor and high resistance.
→ Used for dynamic strain application when high temp sensitivity can be tolerated.
→ alloy of Nickel and Iron

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(ii) Backing material :- That portion of strain gauge to which strain sensitive grid structure is attached. Primary function of backing material is electrical insulation. And the secondary function is that it helps to retain the geometrical shape of the grid pattern and protect the gauge. Commonly used backing materials are: paper, epoxy paper, fiber glass, glass weave, etc.

(iii) Gauge bonding element :- It is the adhesive used to fix the strain gauge into the strain material. Its vital function is to transmit the strain from the specimen to the sensing element. Commonly used bonding elements are: Durofix (Nitrocellulose), Araldite (phenolic cement), Estman 910 (acrylic cement), Ceramic cement.

Classification of strain Gauge :-

Depending upon the principle of operation and construction operational features, strain gauge can be classified as:

(i) Mechanical strain gauge :- The change in length is magnified mechanically by using levers and gears. eg: Berry type strain gauge.

(ii) Optical strain Gauge :- The change in length is magnified by using multiple reflectors.

(iii) Electrical strain gauge :- Principle of operation is based upon the measurement of change in resistance, inductance or capacitance proportional to the strain transferred from the specimen to the basic gauge element.

Among all, most commonly used is electrical resistance strain gauge.

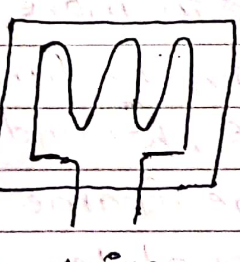
Depending upon the method of fabrication, electrical resistance strain gauge is classified as:

Electrical Resistance Strain Gauge
- Wire Gauge
  - flat grid type
  - wrap type
  - Single wire type
  - woven type
- foil gauge
- unbonded strain gauge
- Semiconductor strain gauge

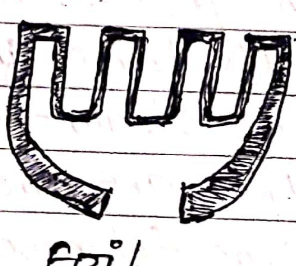
Gauge Configuration :-

The shape of the sensing element is selected according to the strain to be measured.as uniaxial, Biaxial and Multiaxial

Uniaxial application often use ~~leg~~ long narrow sensing element. Here, the direction of strain is known and it maximizes the sensitivity in the direction of interest and minimizes the effect of strain in other direction. Gauge length is selected according to the strain field to be investigated. Most commonly used is 6mm gauge length which offers good performance and easy installation. Types: wire and foil.



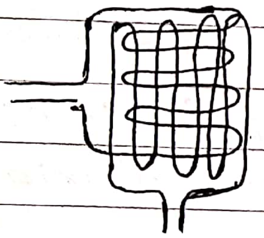
wire



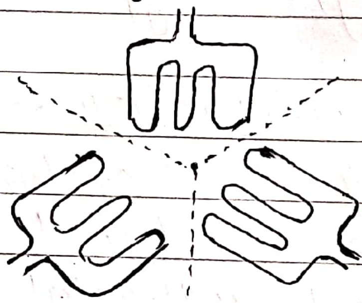
foil

Fig: Uniaxial Strail gauge

Simultaneous measurement of strain in more than one direction is obtained by placing single element gauge at proper location but it is more tedious work. In practice, the element may be subjected to stress in any direction and therefore the orientation of strain gauge along the direction of stress may not be known. Therefore to overcome that difficulty we use multielement gauge or rosette (The measurement of strain in more than one direction can be carried out by using rosette). Correspondingly we have 2 element rosette, 3 element rosette or multielement rosette.



~~Two element rosette~~
90° planar foil



Three element rosette
60° planar foil.

Unbonded Strain Gauge :-

The unbonded strain gauge is basically a free filament-sensing element where the strain is transferred to the resistance wire without any backing. It consists of a stationary frame and an armature that is supported in the centre of the frame. The armature can move only in one direction. Its travel in that direction is limited by four filaments of strain-sensitive wire, wound betn rigid insulators that are mounted on the frame and on the armature. The filaments are of equal length & arranged as in fig:

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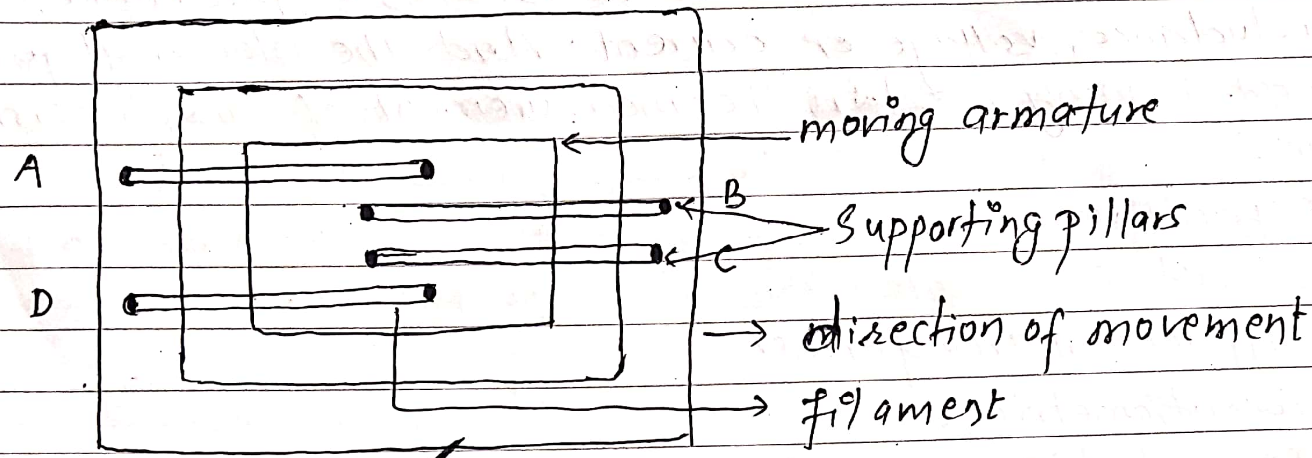
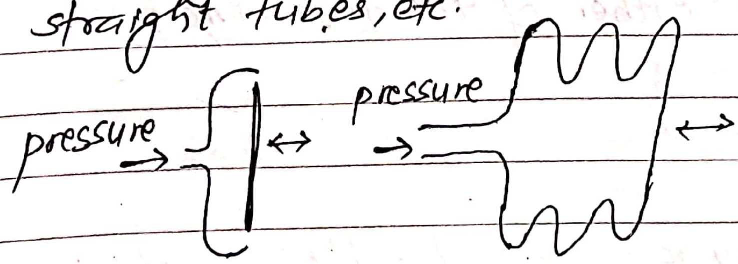


fig: Construction of Unbonded strain Gauge.

When an external force is applied to the strain gauge, the armature moves causing an increase in length of the wires and decrease in length of the other two. The resistance change of four wire filament is proportional to their change in length and this change can be measured with a wheatstone bridge.

Displacement Transducer :-

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 displacement are called force-summing devices. eg: diaphragm, bellows, bourdon tubes, straight tubes, etc.



Diaphragm Bellows

Displacement may be linear, non-linear or rotational. The displacement created by the action of the force-summing devices is converted into a change of some

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electrical parameters such as resistance, capacitance, inductance, voltage or current. And the electrical principles most commonly used in the measurement of displacement are:

- → Capacitive
- → Inductive
- → Differential Transformer
- → Potentiometric
- → Piezo electric.

Capacitive Transducer :-

The principle of operation of capacitive transducer is based on the simple eqn of parallel plate capacitor.

$$\text{Capacitance } (C) = \epsilon \frac{A}{d} = \epsilon_0 \epsilon_r \frac{A}{d} \quad \text{——— (1)}$$

where, A = overlapping area of the plates

d = distance betn 2 plates.

$\epsilon = \epsilon_0 \epsilon_r$ = permitivity of the medium

ϵ_0 = absolute " (i.e. of free space).

ϵ_r = relative "

The capacitive transducer works under the principle of change in capacitance which may be due to either of the following:

(i) Change in area

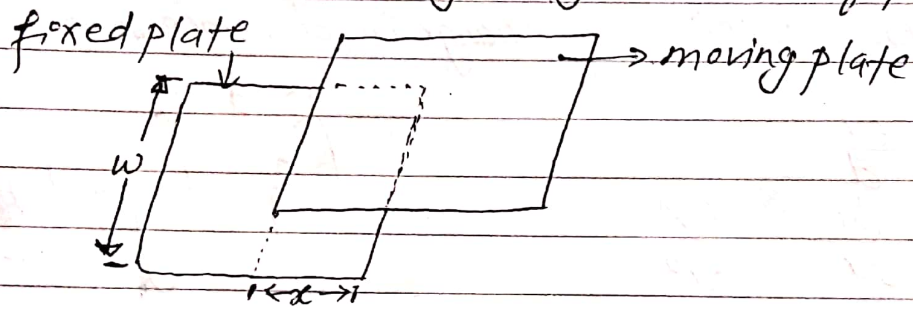
(ii) Change in distance

(iii) Change in dielectric.

These changes are due to the physical variables like displacement, force, pressure in most of the cases. The change in capacitance is measured by the bridge ckt.

Capacitive transducer can be used to measure linear as well as angular displacement and in level measurement. They can also be used for the measurement of force and pressure. The force and pressure to be measured are first converted into displacement which causes change in capacitance. They can be used for the measurement of humidity in gases since the dielectric constant of gases changes with humidity thereby producing the change in capacitance.

(i) Capacitive transducer using change in area of plates :-

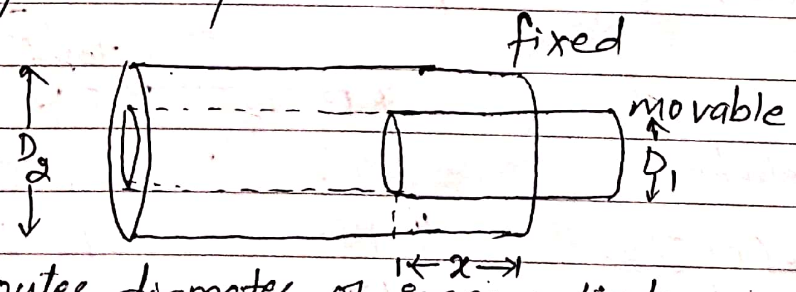


$$C = \frac{\epsilon A}{d} = \frac{\epsilon x w}{d}$$

$$\text{Sensitivity } (S) = \frac{\partial C}{\partial x} = \frac{\epsilon w}{d} \quad (F/m)$$

This type of capacitive transducer is suitable for the measurement of linear displacement ranging from 1 mm to 10 mm. The accuracy is upto 0.005%.

For cylindrical Capacitors:



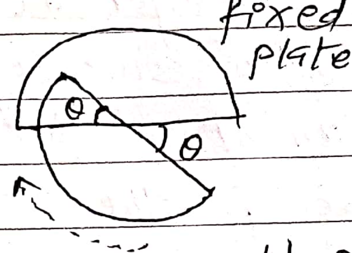
D_1 = outer diameter of inner cylinder
D_2 = Inner " " outer "
x = overlapping part of cylinders.

$$C = \frac{2\pi\epsilon x}{\log_e (D_2/D_1)}$$

$$\therefore S = \frac{\partial C}{\partial x} = \frac{2\pi\epsilon}{\ln (D_2/D_1)}$$

For angular displacement:

$$C = \frac{\epsilon A}{d} = \frac{\epsilon \pi r^2}{2d}.$$

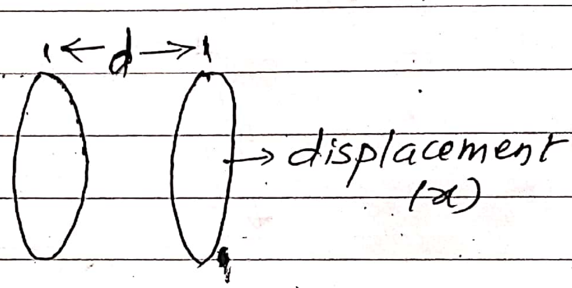


For angle 'θ',

$$C = \frac{\epsilon \theta r^2}{2d}$$

$$\& \; S = \frac{\epsilon r^2}{2d}$$

(ii) Capacitive transducer using change in distance :-

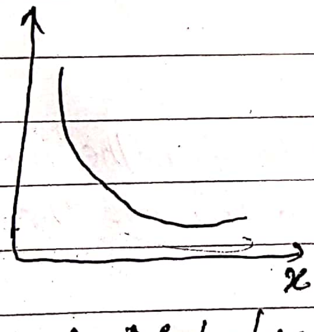


$$C = \frac{\epsilon A}{d}$$

$$\text{or, } S = \frac{\partial C}{\partial x} = \frac{\epsilon A}{x^2}$$

∴ C decreases when d increases
& C increases when d decreases

The relation betn C & x is as:



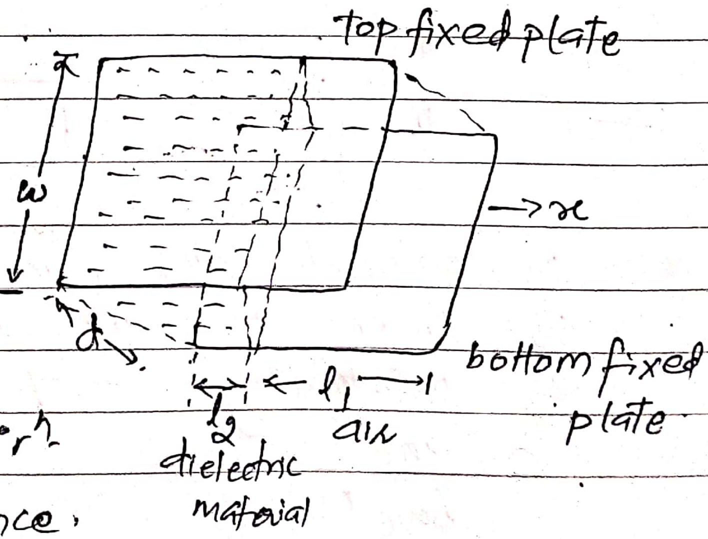
which is non linear i.e. hyperbolic.

(iii) Variation of Dielectric Constant for the measurement of displacement :-

$$C = C_{air} + C_{dielectric}$$

$$\text{or, } C = \frac{\epsilon_0 w l_1}{d} + \frac{\epsilon_0 \epsilon_r w l_2}{d}$$

$$\text{or, } C = \frac{\epsilon_0 w}{d}\left[l_1 + \epsilon_r l_2\right] \quad \text{—(i)}$$



Let the dielectric moves in the dirn of x, there is change in capacitance,

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

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

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

$$\therefore C+\Delta C = \frac{\epsilon_0 w}{d}(l_1 + \epsilon_r l_2) + \frac{\epsilon_0 w x}{d}(\epsilon_r - 1) \quad \text{--- (II)}$$

Comparing with eqⁿ (1), we get

$$\Delta C = \frac{\epsilon_0 w x}{d}(\epsilon_r - 1)$$

$\therefore$ Change in capacitance $\boxed{\Delta C = \frac{\epsilon_0 w x}{d}(\epsilon_r - 1)}$

Hence, the change in capacitance is proportional to the displacement 'x'.

Inductive Transducer

The inductive transducers are based on the principle of variation of self inductance or mutual inductance as a function of displacement. They can be used to measure either linear or angular displacement.

Self inductance can be changed either by changing the number of turns, changing the permeability and changing the reluctance of the magnetic ckt by introducing an air gap.

The device operating on the principle of variation of mutual inductance are variable differential transformer

eg: LVDT → Linear Variable differential transformer

RVDT → Rotary " " "

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Linear Variable Differential Transformer (LVDT)

LVDT consists of a primary coil and two identical secondary coils, axially spaced and wounded on a cylindrical coil former with a rod-shaped magnetic (ferromagnetic material) core positioned centrally inside the coil assembly providing a preferred path for the magnetic flux linking the coil. The displacement to be measured is transferred to the magnetic core thru suitable linkages.

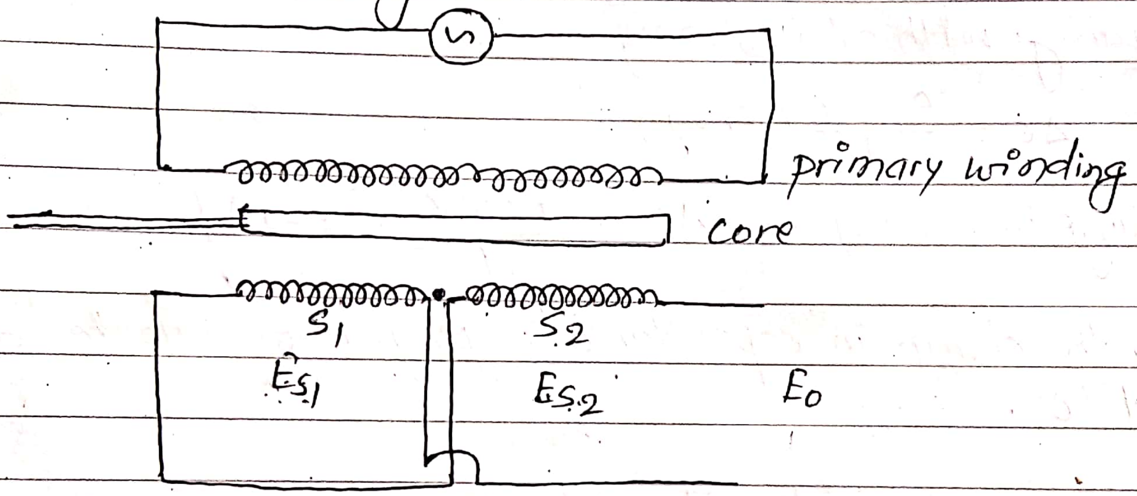

Fig: CKt of LVDT

when the primary coil is energized by ac carrier wave signal (range: 50Hz to 20KHz). Voltages are induced in primary section, exact depending upon the position to the magnetic core with respect to the secondary coils. If the core is symmetrically placed (electrically) w.r.to the two secondary coils, o/p voltages are induced in the two coils. Since the two secondary coils are connected in phase opposition (series) and o/p voltage of the transducer is the difference betn these two voltages, the o/p voltage $E_0 = 0$. Such a balance point is known as the NULL POSITION. [In practice, a residual voltage is always present at a Null Position due to the presence of harmonics in the excitation signal and stray capacitance coupling betn the primary and secondary windings.]

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i.e. when the core is at center, the o/p voltage is

$$E_o = E_{S_1} - E_{S_2} = 0 \quad \text{———— (i)}$$

If the core is moved to the left of the Null position, more flux links with secondary winding S_1 and less with S_2. Therefore the o/p voltage E_{S_1} of the secondary winding S_1 is greater than the o/p voltage E_{S_2} of the secondary winding S_2. The magnitude of the resultant o/p voltage is in phase with E_{S_1}.

$$E_o = E_{S_1} - E_{S_2} \quad \text{———— (ii)}$$

Similarly, if the core is moved to the right of the null position, the flux linking with the S_2 is greater than that of S_1. This results in secondary voltage E_{S_2} being greater than that of E_{S_1}. So the o/p voltage is in phase with E_{S_2}

$$E_o = E_{S_2} - E_{S_1} \quad \text{———— (iii)}$$

Thus the amount of o/p voltage is either of the secondary windings is proportional to the movement of the core and gives the ~~di~~ indication of amount of linear motion. The direction of the motion can be determined by noting down which o/p is increasing or decreasing.

Resistive Transducer

These types of transducers are based on the principle of measurement of change in resistance caused by the quantity being measured. They are most widely used and are more preferred because both ac and dc are suitable for resistance measurement.

we know, $R = \rho \frac{l}{A}$

The variation in any one of the quantities in the right side of the above eqn forms the basis of the electrical resistance transducer.

Eg: Potentiometric device [change in resistance with change in length of the conductor]

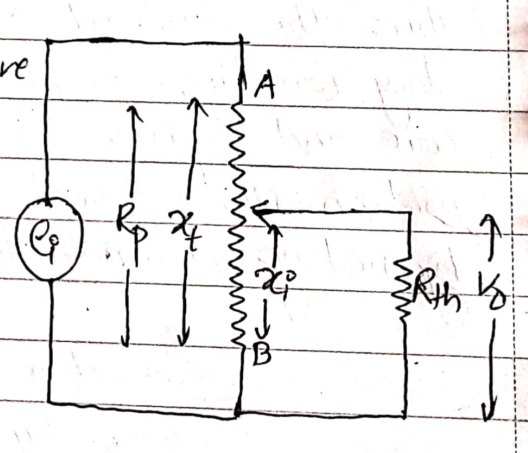
Resistance Strain Gauge [change in resistance of a conductor with strain]

Resistance Temperature detector [change in resistivity of the material with change in temperature].

Potentiometric Device :-

Potentiometric Devices are passive transducer based on the principle of change in resistance of a conductor as a result of change in length. The sensing element is basically a resistance potentiometer with a movable wiper contact attached to an insulated plunger type shaft, mechanically linking the point under measurement.

The displacement causes the wiper to move thereby changing the effective length of the wire. The change in length causes the proportional change in resistance and hence the change in voltage. The change in voltage may be calibrated in terms of displacement.



Let e_i = i/p voltage

e_o = o/p voltage

x_t = total length of translational potentiometer

x_i = displacement of the wiper from its zero position.

R_p = total resistance of the potentiometer.

If the distribution of the resistance w.r.to translation movement is linear, the resistance per unit length is R_p/x_t.

The o/p voltage under this condition is:

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$$e_o = \left(\frac{\text{resistance at the o/p terminals}}{\text{resistance at the i/p terminals}}\right) \times \text{i/p voltage}.$$

$$\text{or } e_o = \frac{R_p\,(x_i/x_t)}{R_p} \times e_i$$

$$\text{or } e_o = \left(\frac{x_i}{x_t}\right) \times e_i$$

$$\therefore e_o = K \times e_i \quad \text{——— (i)}$$

$$\text{where } K = \frac{x_i}{x_t}$$

If the voltmeter or recorder or meter is attached at o/p then,

R_m = resistance of meter.

In actual condition R_m is not infinite and this causes non-linear relationship between o/p and the i/p voltage (due to loading effect). The resistance of the parallel combination of the load resistance and the portion of the resistance of the potentiometer is

$$R_{th} = \frac{(x_i/x_t)R_p \cdot R_m}{(x_i/x_t)R_p + R_m} = \frac{KR_pR_m}{KR_p + R_m}$$

Total resistance seen by the source

$$R = R_p(1-K) + R_{th}$$

$$\text{or } R = R_p(1-K) + \frac{KR_p \cdot R_m}{KR_p + R_m}$$

$$\text{or } R = \frac{R_p(1-K)(KR_p + R_m) + KR_p \cdot R_m}{KR_p + R_m}$$

$$\text{or } R = \frac{KR_p^2(1-K) + R_pR_m}{KR_p + R_m} \quad \text{——— (ii)}$$

we know that,

$$\text{Current } i = \frac{e_i}{R} \quad \text{——— (iii)}$$

$$\text{or } i = e_i\left(\frac{KR_p + R_m}{KR_p^2(1-K) + R_pR_m}\right)$$

o/p voltage under this condition

$$e_0 = e_i\left(\frac{KR_p + R_m}{KR_p^2(1-K) + R_pR_m}\right) \times \left(\frac{KR_pR_m}{KR_p + R_m}\right) \quad [\because e_0 = i \times R_{th}]$$

$$\boxed{e_0 = \frac{e_i K}{K(1-K)R_p/R_m + 1}}$$

Error = o/p voltage with load − o/p voltage without load

ie. Error $= \dfrac{e_i K}{K(1-K)\dfrac{R_p}{R_m} + 1} - e_i K$

$$\therefore \boxed{\text{Error} = \frac{e_i K^2(K-1)}{K(1-K) + R_m/R_p}}$$

The error is always negative except for two end positions ie. at $K=0$ (or $x_i = 0$) and $K=1$ (or $x_i = x_t$).

Temperature Measurement

Depending upon construction and operating principle, there are various temperature sensors or transducers:

(i) Mechanical sensor: eg: liquid in gases, bimetallic thermometer
- mercury
- organic (alcohol)
- vapour

(ii) Electrical Sensor: eg: Thermocouple, Thermister, RTD

(iii) Optical Sensor: eg: Spectral pyrometer
Band radiation pyrometer
Fiber optic temp. sensor

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Temperature Transducers:

Thermocouple :-

It is based on the seebeck effect which states that when two junctions formed by the different materials are placed at two different temperature levels, emf is generated and magnitude of emf depends on the metals used and the temperature of the junction. The emf generated is thermoelectric emf and is the function of temp. difference of the two junctions.

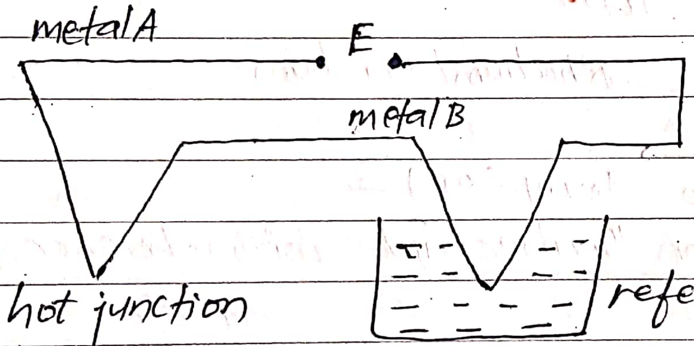

Fig: thermocouple

If the reference junction is maintained at constant temperature, the emf set up will give a measure of temp. of hot junction. So for accurate measurement, it is maintained at a constant temperature.

The relation betn the emf set up and the temp. difference of hot and cold junction is given by the expression,

$$E = \alpha_0(T-T_0) + \alpha_1(T-T_0)^2 + \alpha_2(T-T_0)^3 + \dots + \alpha_{n-1}(T-T_0)^n$$

where,

E = thermoelectric emf

T = Temp. of hot junction

T_0 = Temp. of cold "

$\alpha_0 > \alpha_1 > \alpha_2 \dots\dots$ are the constants whose value depend upon the metals used.

→ The emf generated by the thermocouples is directly proportional to the temp. difference betn the two junctions

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and is very small (in μV to few 100 mV).

- In fact, there are other voltages due to a peltier and Thompson's effect. But these voltages are very small and are neglected.

the curve in which thermoelectric emf varies with temp. for some commonly used thermocouple is as shown below:

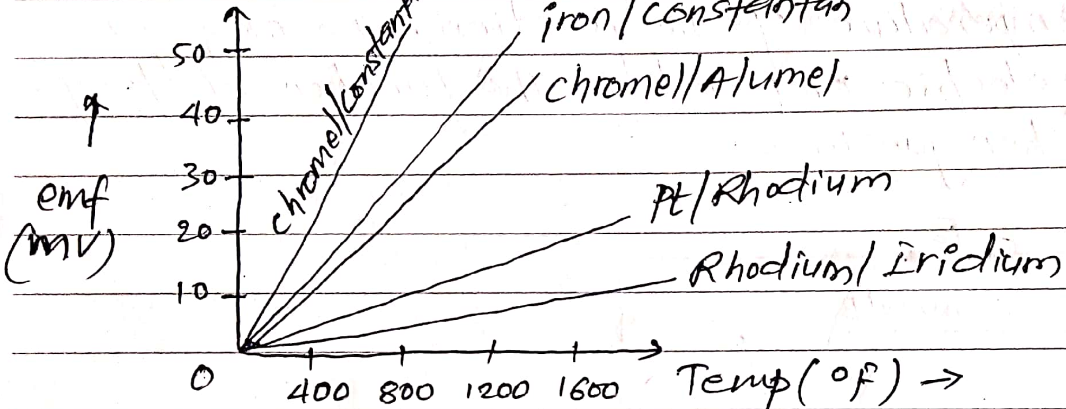
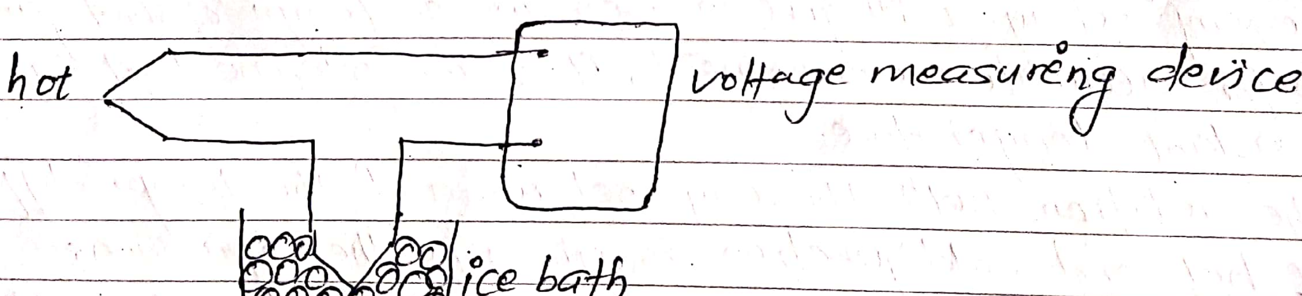


Fig: Temp-emf curve for thermocouples with reference junction at 0°C

Establishing Reference Junction :-



while making measurements, it is necessary that the reference junction be kept at a constant temp. One method is to use an ice bath to keep the reference junction at a constant known temp. (0°c) as shown above.

If the extension wire of different materials are used in the thermocouple then the new junction formed should be kept at constant temp. as shown in fig below:

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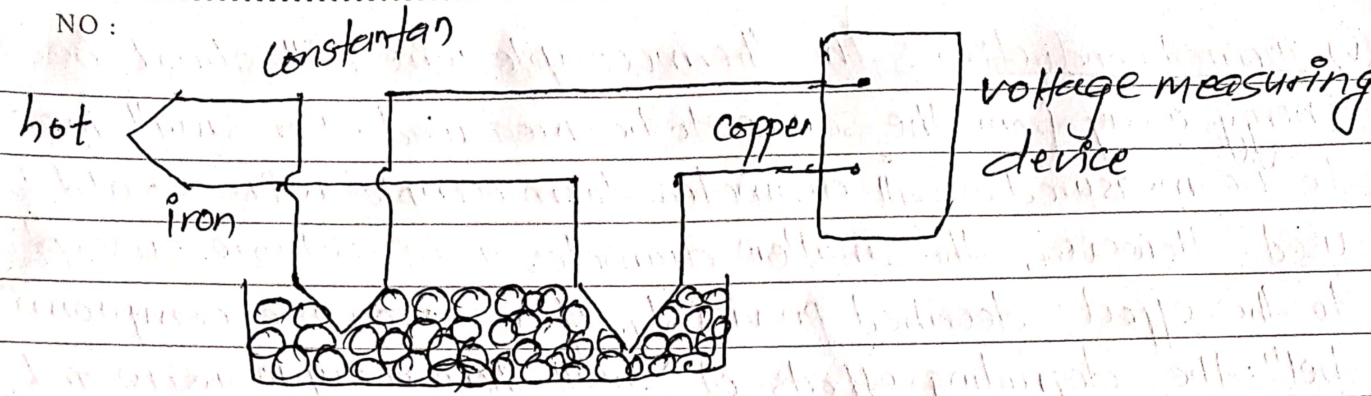

Thermocouple Error Sources:

During construction or measurements, following errors can be occurred in thermocouples:

(i) Open Junction:- Sometimes the junction of a thermocouple may break due to being exposed to a very high temperature than it is designed for, such type of error can be detected simply measuring the resistance.

(ii) Decalibration: It is due to altering the characteristics of the thermocouple wire thus changing the seebeck voltage. This can be caused by subjecting the wire to successively high temp, diffusion of particles from the atmosphere into the wire takes place.

(iii) Insulation Degradation:- In some cases the insulation can breakdown and cause a significant leakage resistance which will cause an error in the measurement of the seebeck voltage. Sometime chemicals in the insulation can diffuse into the thermocouple wire and cause decalibration.

(iv) Galvanic Action:- Chemicals coming in contact with the thermocouple wire can cause galvanic action. The resulting voltage can be as much as 100 times the seebeck voltage causing an extreme error.

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(v) 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 effect decribed previously. If a reasonable compromise betn the degrading effects of small thermocouple wire and the loss of the thermal energy and the resultant temperature is made, error cannot be found. Thermocouple extension wire can be used.

Resistance Temperature Detector (RTD):-

→ It is also known as Resistance Thermometer.

→ It is based upon the principle of variation of resistance with temperature.

→ Change in resistance is proportional to change in temperature.

→ For most metals, the resistance increases with temperature and are called positive temperature coefficient device (PTC-device). The range of temperature over which it is valid is determined by the temperature coefficient of resistance, chemical inertness and its structure.

→ The relation betn resistance and temperature for most metallic material is given by

$$R_T = R_0(1+\alpha_0 T+\alpha_1 T^2+\alpha_2 T^3+\dots+\alpha_{n-1}T^n)$$

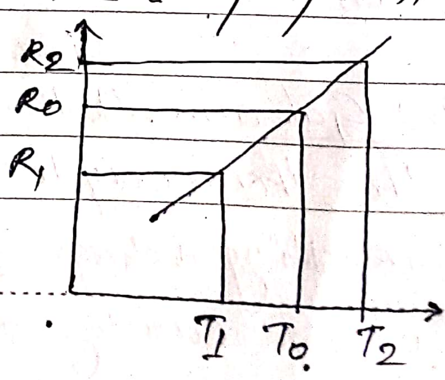
where, R_T = resistance at temp. T

R_0 = resistance at some temp. T_0 (say)

and $\alpha_0 > \alpha_1 < \alpha_2$ are temp. coefficient determined on the basis of two or more known resistance temp. points.

In general,

$$\alpha_0 = \frac{1}{R_0} \times \text{Slope at } T_0$$



from fig,

$$\alpha_0 = \frac{1}{R_0}\left[\frac{R_2-R_1}{T_2-T_1}\right].$$

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→ But for narrow range we expect the device to operate linearly and so we choose linear approximation.

$\therefore R_T = R_0(1+\alpha_0 T)$

For temperature change;

$R_T = R_0(1+\alpha_0 \Delta T)$ where $\Delta T = (T - T_0)$

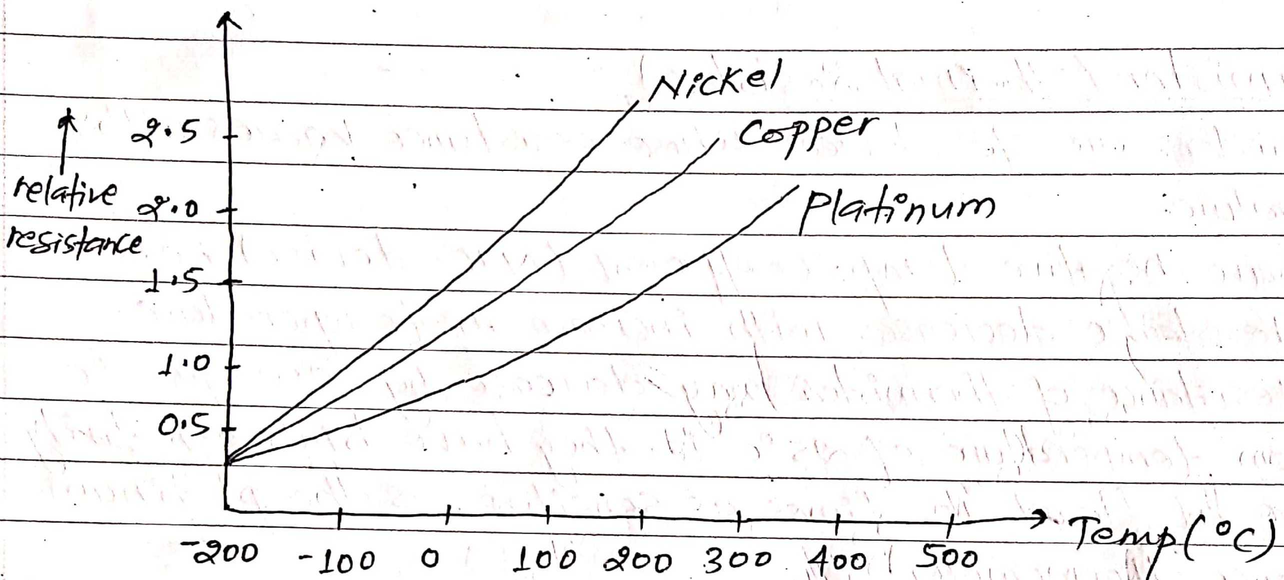

Fig: Resistance Variation with temp. for Pt, Ni, Cu

→ RTD is applicable for measurements of small temperature differences as well as wide range of temperature.

→ The main drawback of RTD lies in its large size.

→ RTD doesnot generate its own voltage so a voltage source is required to be incorporated into the measuring ckt.

→ Wheatstone bridge is usually employed for the measurement of variation in resistance, owing to changes in temperature.

→ The requirements for the resistance materials used in RTD are:

(i) high temp. coefficient of resistance in order to give substantial change in resistence for a relatively small change in temperature i.e. larger sensitivity.

(ii) high resistivity to ensure small wire length for high resistance.

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(iii) linearity of relation betn resistance and temperature.
(iv) Sufficient mechanical strength.

→ Platinum, Nickel, & Copper are the most commonly used resistance materials.

Thermistor (Thermal Resistor)

→ Thermistors are s/c devices whose resistance varies with temperature.

→ They have negative temp. Coefficient (NTC-device) i.e. their resistance decreases with increase in temperature.

→ The resistance of thermistor may decrease by 0.04 per °C at room temperature of 25 °C ie. they have high sensitivity and are at least 10 times as sensitive as the platinum resistance thermometer.

→ Thermistors are highly non-linear in their characteristics ie. their resistance temp. relation.

→ The resistance - temp. characteristics for thermistor is exponential type and is given by

$$R_T = R_0 e^{\beta(1/T - 1/T_0)}$$

where R_T = resistance at temp. T

R_0 = " " reference temp. T_0

β = Experimentally determined constant for given thermistor material typically betn 3500K to 4000K.

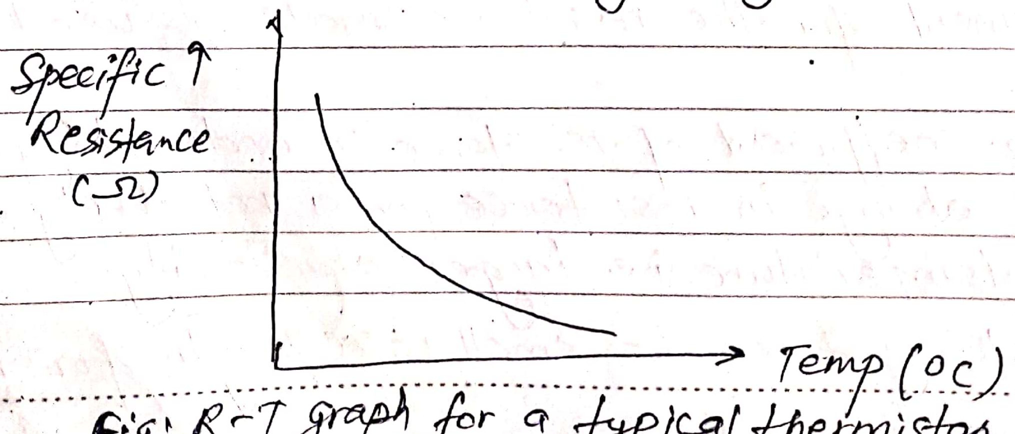
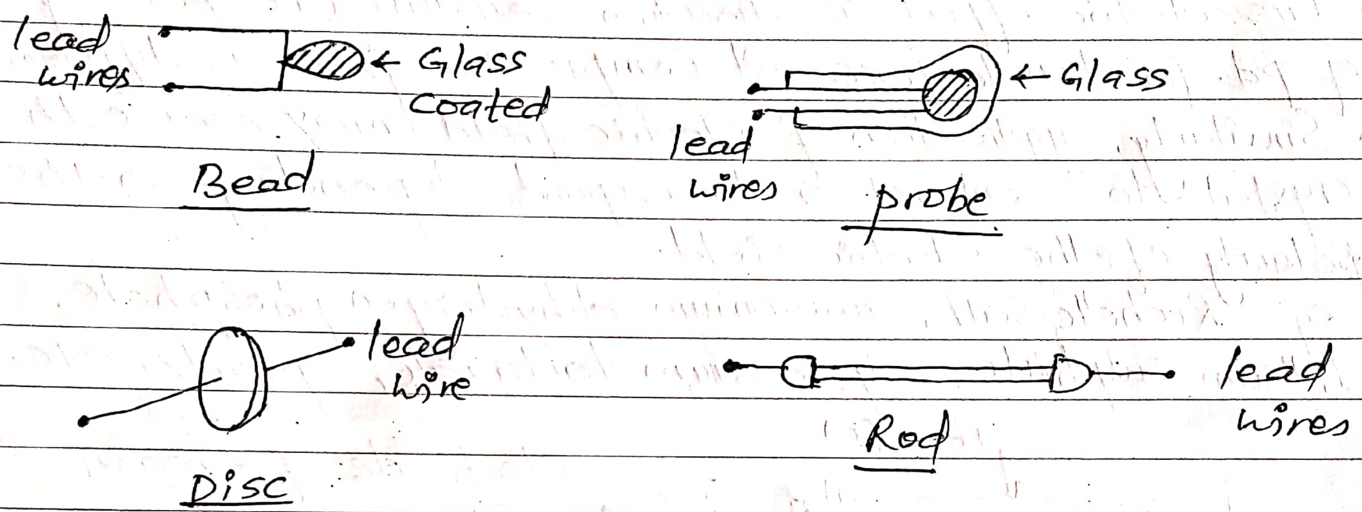


Fig: R-T graph for a typical thermistor.

→ Thermistors are composed of a sintered mixture of metal oxide such as nickel, cobalt, copper, iron, magnesium, titanium, Uranium, etc.

→ they are available in variety of shapes and sizes (such as beads, discs, rods, probes, etc).



→ They can provide good accuracy when used for the measurement of temperatures between $-100°C$ to $+300°C$.

Piezoelectric Transducer :

→ In certain solid materials an electric field appears across surfaces of crystal structures, when mechanical force is applied.

→ The arrangement of +ve and -ve ions are not symmetrical in piezoelectric material.

→ Application of force results in a change in the arrangement of ions to produce a net displacement of charge so that one ~~plac~~ face of the material becomes +vely charged and the other -vely charged.

→ The net charge 'Q' on a surface is proportional to the amount 'x' by which the charges have been displaced.

→ This effect is reversible and is known as piezoelectric effect.

→ This piezoelectric effect can be defined as the phenomenon seen in some crystalline or ceramic materials in which a potential difference appears across the opposite faces of the material as a result of dimensional changes when a mechanical force is applied to it.

→ Piezoelectric effect is direction sensitive (ie. polarity of pd. for tensile force and compressive force is different).

→ Similarly, application of electric field may cause the crystal to contract or to expand depending on the polarity of the electric field.

eg: Rochelle salt, ammonium dihydrogen phosphate, lithium sulphate, dipotassium tartarate, quartz, etc.

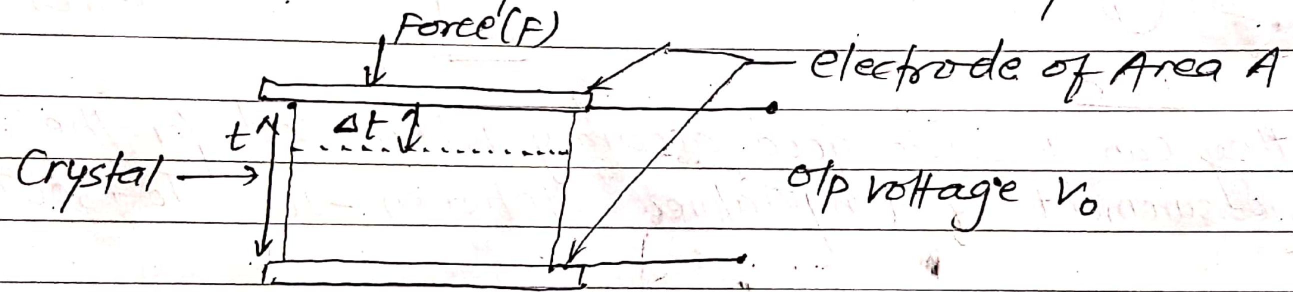


Fig: Piezoelectric transducer

We know,

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

ie. $Q \propto F$

or $Q = dF$ —— (1)

where, d = charge sensitivity in Coulombs per newton (C/N) and is constant for a given crystal.

we have,

Young's Modulus of elasticity $(E) = \frac{\text{Stress}}{\text{Strain}}$

or $E = \frac{F/A}{\Delta t/t}$ [if the force causes the change in thickness by Δt]

where t = thickness of the piezoelectric crystal.

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Now, $F = EA\frac{\Delta t}{t}$ —— (II)

Now from eqn (I) and (II)

$$\frac{Q}{d} = EA\frac{\Delta t}{t}$$

$$or,\ Q = EA\frac{\Delta t}{t}.d$$

The charge at the electrodes gives rise to an o/p voltage 'V' and is given by

$$V = \frac{Q}{C} = \frac{Q}{\epsilon_0\epsilon_r A/t} = \frac{Qt}{\epsilon_0\epsilon_r A} \quad \left[\because C = \frac{\epsilon_0\epsilon_r A}{d} = \epsilon_0\epsilon_r\frac{A}{t}\right]$$

$$or,\ V = \frac{dFt}{\epsilon_0\epsilon_r A}$$

$$or,\ V = \frac{dFt}{\epsilon_0\epsilon_r A}$$

$$\therefore V = gPt \quad \text{—— (III)}$$

where, $g = \frac{d}{\epsilon_0\epsilon_r}$ = crystal voltage sensitivity in Vm/N.

$P = F/A$ = pressure in Pascals applied on the crystal

eqn (III) can be written as,

$$g = \frac{V/t}{P} = \frac{\text{Electric Field}}{\text{Stress applied on crystal}} \quad \text{—— (IV)}$$

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Hall Effect Transducer :

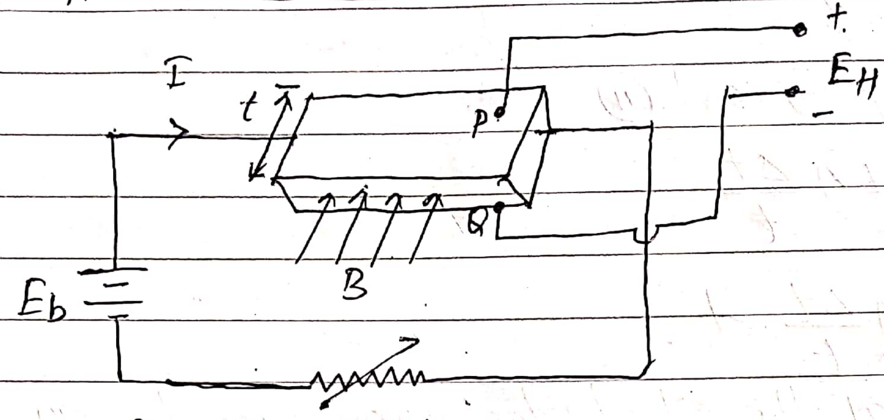

fig: Hall effect.

when a conductor is kept perpendicular to the magnetic field and a direct current is passed thru it, it results in an electric field perpendicular to the direction of both the magnetic field and current with a magnitude proportional to the product of the magnetic field strength and current. The voltage so developed is very small and it is difficult to detect. But in some s/c such as germanium, this voltage is enough for measurement with sensitive moving coil instrument. This phenomenon is called the Hall Effect.

Let us consider a slab of conducting material (N-type Germanium) connected to a battery so that a current I flows thru the slab as shown in fig. The electrons constituting the flow of current I actually flow in the direction opposite to that of conventional current. No potential difference exists betn the top and bottom of the slab because no transverse magnetic field passes thru the slab.

when the magnetic field is applied so that it is perpendicular to the slab of Hall Crystal, the electrons are acted on by a force because of magnetic field. The electrons are forced or drifted towards the top of the slab. This results in an excess of electrons near the top of the slab and deficiency of electrons near the bottom. Thus a potential difference is created betn the top & bottom of the slab. The magnitude of this voltage is proportional to the product of strength of the magnetic field and current flowing thru the slab and is given by

$$E_H = \frac{K_H I B}{t} \text{ volts.}$$

where, K_H = Constant called Hall Coefficient
B = magnetic flux density
I = Current thru the slab
t = thickness of the slab
K_H depends upon the no. of free charge carriers per unit volume.

Application:

Measurement of Current
To distinguish betn P-type & N-type S/C
Measurement of displacement.

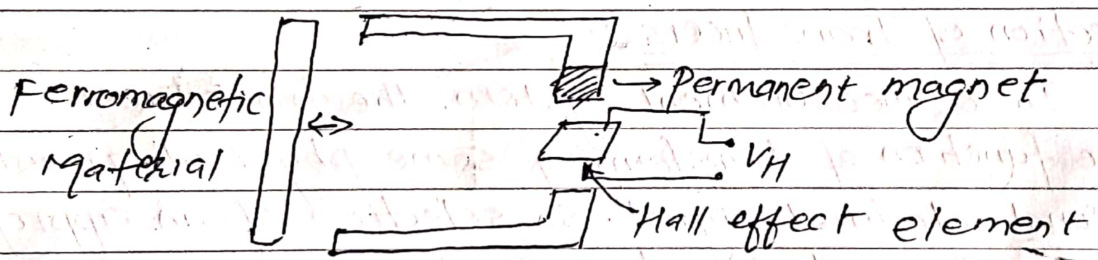

Fig: Hall effect displacement transducer.

Basic Requirements of transducers:-

Transducers should meet the following basic criteria:

(i) Ruggedness:- It should be capable of withstanding overload and some safety arrangement should be provided for overload protection.

(ii) Linearity:- The i/p - o/p characteristics should be linear and it should produce these characteristics in symmetrical way.

(iii) Repeatability:- It should reproduce same o/p signal when the same i/p signal is applied again and again under fixed environmental condition.

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(iv) High o/p Signal Quality :- The quality of o/p signal should be good i.e. the ratio of the signal to noise should be high and the amplitude of the o/p signal should be enough.

(v) High reliability and Stability :- It should give minimum error in measurement for temp. variations, vibrations & other various changes in surroundings.

(vi) Good Dynamic Response :- Its o/p should be faithful to i/p when taken as a function of time.

(vii) No Hysteresis :- It should not give any hysteresis during measurement while i/p signal is varied from its low value to high value & vice-versa.

(viii) Residual Deformation :- There should be no deformation on removal of local after long period of application.

Selection of Transducers :-

In a measurement system, the transducer performs the function of transforming some physical quantity to proportional electrical signal. So selection of an appropriate transducer is most important for having accurate result.

The first step in the selection procedure is to clearly define the nature of quantity under measurement and know the range of magnitudes and frequencies that the measurand is expected to exhibit. Next step will be to determine the available transducer principles for measurement of desired quantity. The type of transducer selected must be compatible to the type and range of the measurand and the o/p device. The points to be considered in determining a transducer suitable for a specific measurement are as follows:-

(i) Range :- The range of the transducer should be large enough to encompass all the expected magnitudes of the measurand.

(ii) Sensitivity :- The transducer should give a sufficient o/p signal per unit of measurand i/p in order to yield meaningful data.

(iii) Electrical o/p characteristics :- The electrical characteristics the o/p impedance, the frequency response and the response time of the transducer o/p signal should be compatible with the recording device and the rest of the measuring system equipment.

(iv) Physical Environment :- The transducer selected should be able to withstand the environmental conditions to which it is likely to be subjected while carrying measurement. Such parameters are temperature, shock, vibration, moisture and corrosive chemicals might damage some transducers but not others.

(v) Errors :- The errors inherent in the operation of the transducer itself or those caused by environmental conditions of the measurement, should be small enough or controllable enough that they allow meaningful data to be taken.

Characteristics & Choice of Transducer :-

When choosing a transducer, the i/p, o/p and transfer characteristics have to be taken into account.

(i) Input characteristics :-

* Type of i/p and operating Range :-

The type of i/p, which can be any physical quantity, is generally determined in advance. A physical quantity may be measured thru the use of a number of transducers. However, the choice of a particular transducer that is selected for the purpose,

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depends upon the useful range of i/p quantity over which the transducer can be used. The useful operating range of the transducer may be a decisive factor in the selection of transducer.

* **Loading Effect :-**

The magnitude of loading effect can be expressed in terms of force, power or energy extracted from the quantity under measurement. Therefore, the transducer, that is selected for a particular application should ideally extract no force, power or energy from the quantity under measurement for the accurate measurement.

(ii) **Transfer Characteristics :-**

↓ 3 separate elements

- Transfer function
  → gives relation betⁿ i/p & o/p
  $q_o = f(q_i)$
- Error
- Response of transducer to environmental influences

* **Error :** The error in transducers occurs because they donot follow the i/p - o/p relationship given by

$$q_o = f(q_i)$$

Any departure from the above relationship results in errors. For eg: the o/p in account of i/p q_i has to be q_o but in practice an o/p q_o' is obtained, then the error is

$$E = q_o' - q_o$$

The error can be expressed in terms of either i/p or o/p.

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* Transducer Response :-

The performance of a transducer is fully defined by its transfer function and errors, provided that the transducers are in constant environments and not subjected to any disturbances like stray electromagnetic fields, mechanical shocks and vibration, temp. changes, pressure and humidity changes, change in supply voltage, etc. If the transducer is subjected to the above environmental disturbances, errors may take place. Therefore, the transducer selected must be gaurded against the interfering and modifying inputs.

(iii) O/p characteristics :-
- → type of Electrical o/p
- → o/p impedance
- → Useful Range.