Electronics Measurement & Instrumentation
4EC3-06
Unit -5
Transducers

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4EC3-06: Electronics Measurement & Instrumentation

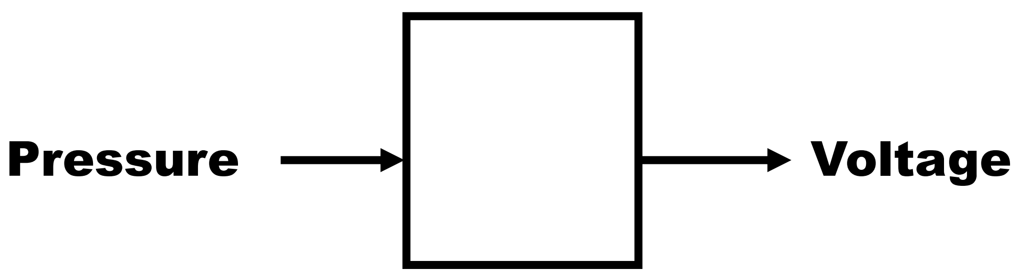
Credit: 3 | **Max. Marks: 150(IA:30, ETE:120)**

3L+0T+0P | **End Term Exam: 3 Hours**

6	**TRANSDUCERS** - Classification, Selection Criteria, Characteristics, Construction, Working Principles and Application of following Transducers:- RTD, Thermocouples, Thermistors, LVDT, Strain Gauges, Bourdon Tubes, Seismic Accelerometers, Tachogenerators, Load Cell, Piezoelectric Transducers, Ultrasonic Flow Meters.	**8**

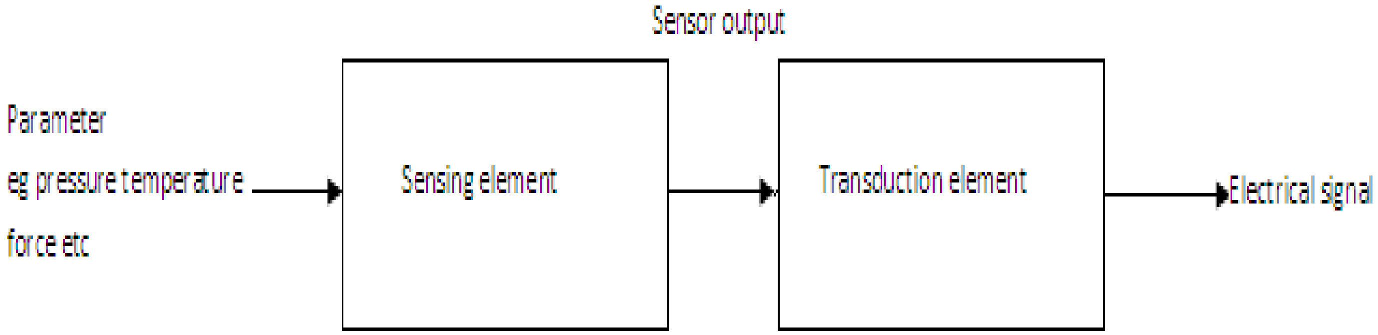
INTRODUCTION OF TRANSDUCERS

- A transducer is a device that convert one form of energy to other form. It converts the measurand to a usable electrical signal.
- In other word it is a device that is capable of converting the physical quantity into a proportional electrical quantity such as voltage or current.



BLOCK DIAGRAM OF TRANSDUCERS

- Transducer contains two parts that are closely related to each other i.e. the sensing element and transduction element.
- The sensing element is called as the sensor. It is device producing measurable response to change in physical conditions.
- The transduction element convert the sensor output to suitable electrical form.



CHARACTERISTICS OF TRANSDUCERS

1. Accuracy
2. Resolution
3. Linearity
4. Repeatability
5. Precision
6. Range
7. Dynamic Response
8. High stability and reliability
9. Speed of response
10. Sensitivity
11. Small size
12. Cost

TRANSDUCERS SELECTION FACTORS

1. **Operating Principle:** The transducer are many times selected on the basis of operating principle used by them. The operating principle used may be resistive, inductive, capacitive , optoelectronic, piezo electric etc.

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

3. **Operating Range:** The transducer should maintain the range requirement and have a good resolution over the entire range.

4. **Accuracy:** High accuracy is assured.

5. **Cross sensitivity:** It has to be taken into account when measuring mechanical quantities. There are situation where the actual quantity is being measured is in one plane and the transducer is subjected to variation in another plan.

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

7. **Transient and frequency response :** The transducer should meet the desired time domain specification like peak overshoot, rise time, setting time and small dynamic error.

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

9. **Environmental Compatibility:** It should be assured that the transducer selected to work under specified environmental conditions maintains its input- output relationship and does not break down.

10. **Insensitivity to unwanted signals:** The transducer should be minimally sensitive to unwanted signals and highly sensitive to desired signals.

CLASSIFICATION OF TRANSDUCERS

The transducers can be classified as:

I. Active and passive transducers.
II. Analog and digital transducers.
III. On the basis of transduction principle used.
IV. Primary and secondary transducer
V. Transducers and inverse transducers.

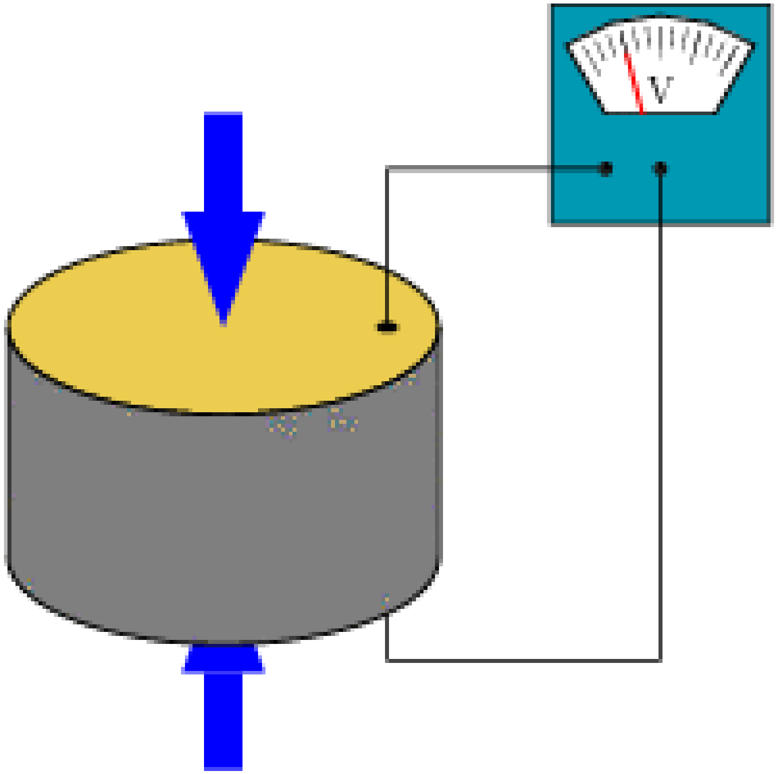
ACTIVE AND PASSIVE TRANSDUCERS

- **Active transducers :**
- These transducers do not need any external source of power for their operation. Therefore they are also called as self generating type transducers.

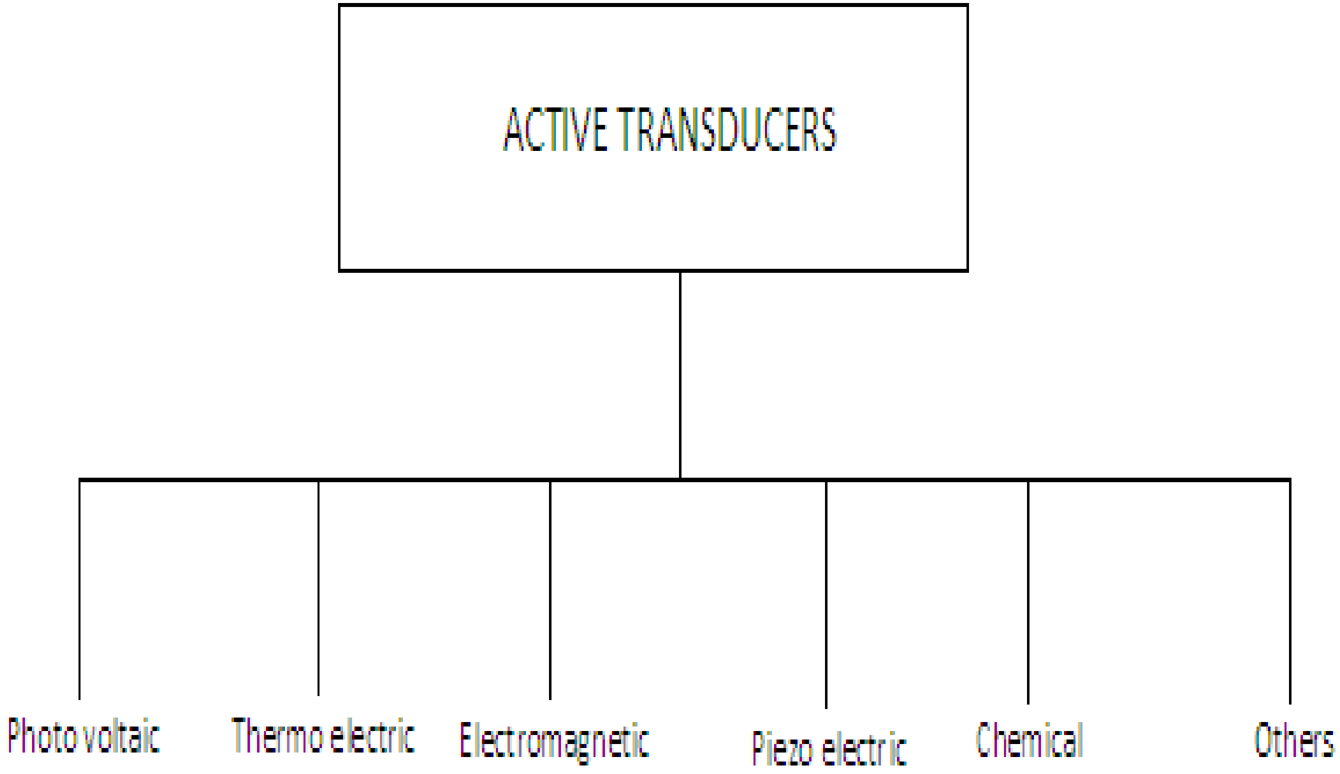
I. The active transducer are self generating devices which operate under the energy conversion principle.

II. As the output of active transducers we get an equivalent electrical output signal e.g. temperature or strain to electric potential, without any external source of energy being used.

Piezoelectric Transducer



CLASSIFICATION OF ACTIVE TRANSDUCERS



PASSIVE TRANSDUCERS

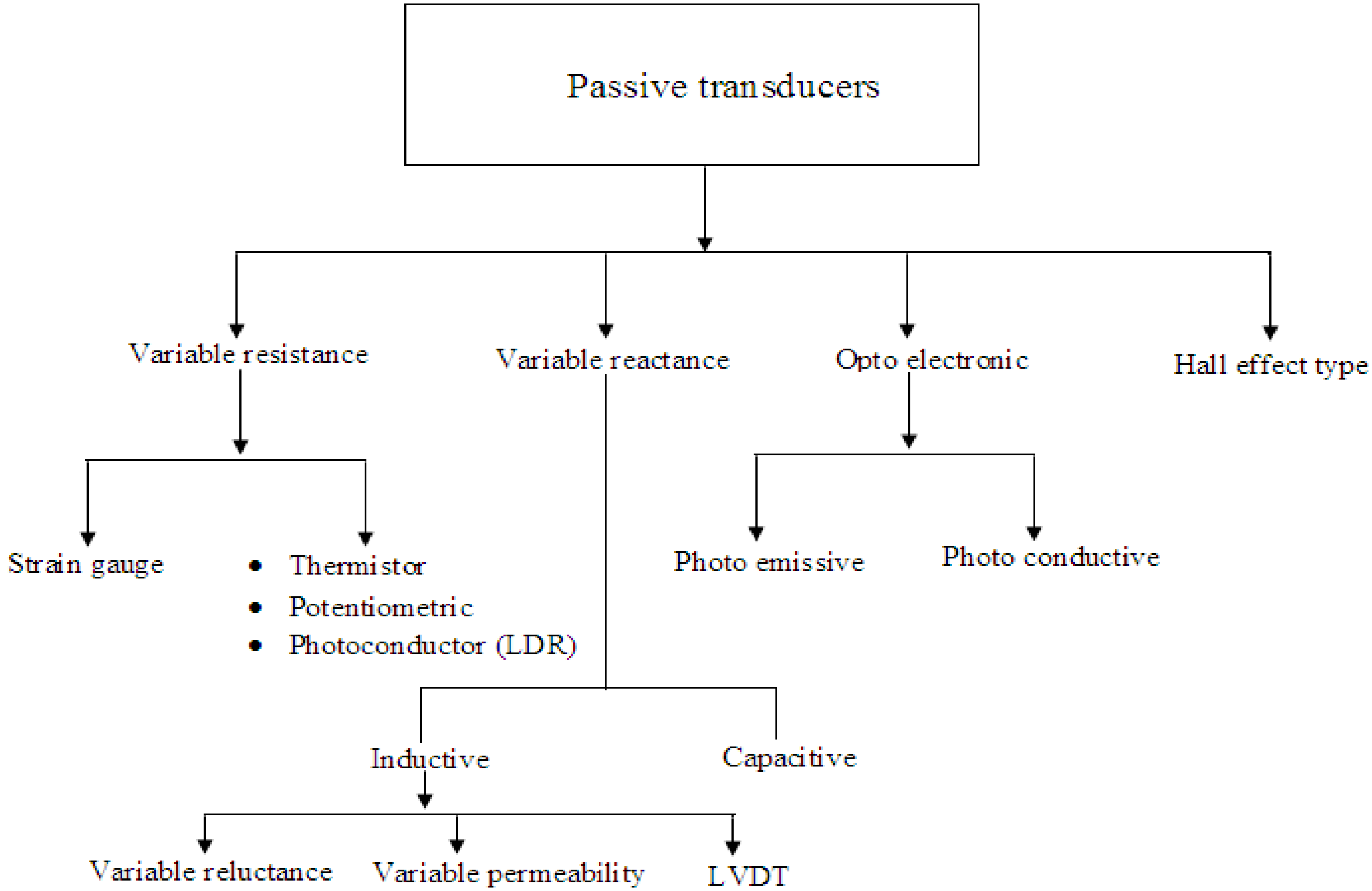
- **Passive Transducers :**

I. These transducers need external source of power for their operation. So they are not self generating type transducers.

II. A DC power supply or an audio frequency generator is used as an external power source.

III. These transducers produce the output signal in the form of variation in resistance, capacitance, inductance or some other electrical parameter in response to the quantity to be measured.

CLASSIFICATION OF PASSIVE TRANSDUCERS

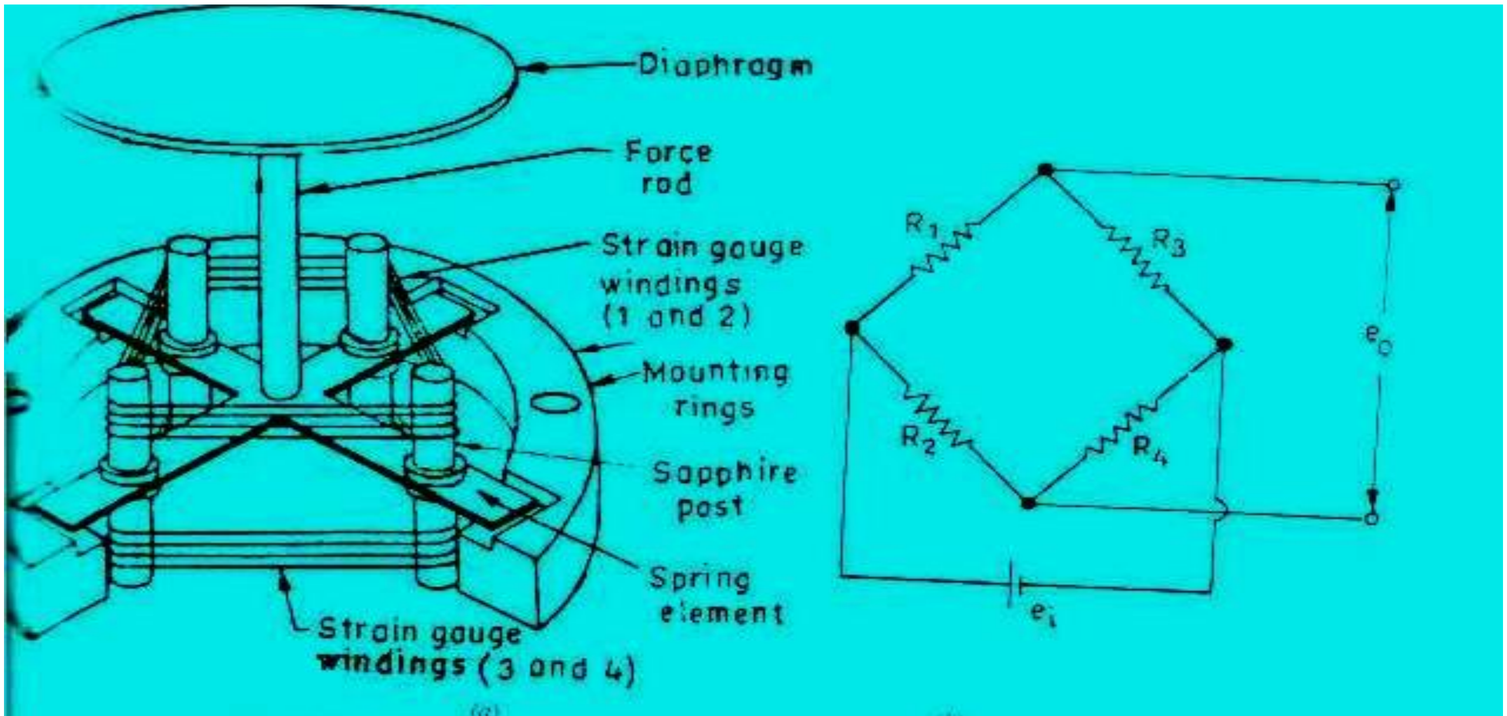


PRIMARY AND SECONDARY TRANSDUCERS

- Some transducers contain the mechanical as well as electrical device. The mechanical device converts the physical quantity to be measured into a mechanical signal. Such mechanical device are called as the primary transducers, because they deal with the physical quantity to be measured.

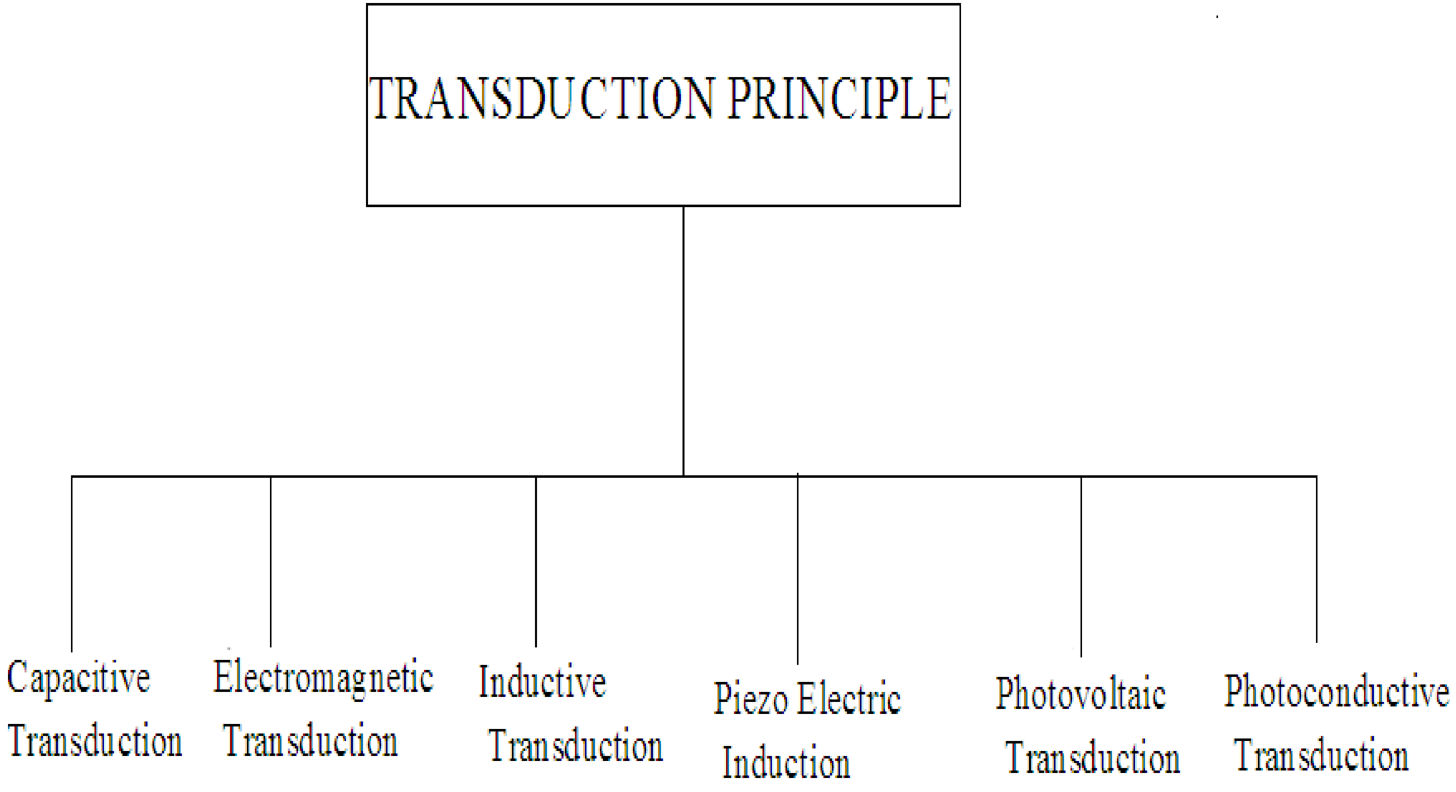
- The electrical device then convert this mechanical signal into a corresponding electrical signal. Such electrical device are known as secondary transducers.

•Ref fig in which the diaphragm act as primary transducer. It convert pressure (the quantity to be measured) into displacement(the mechanical signal).
•The displacement is then converted into change in resistance using strain gauge. Hence strain gauge acts as the secondary transducer.



Set up of a unbonded strain gauge and measurement with a wheatstone bridge

CLASSIFICATION OF TRANSDUCERS
According to Transduction Principle



CLASSIFICATION OF TRANSDUCERS
Transducer and Inverse Transducer

TRANSDUCER:

- Transducers convert non electrical quantity to electrical quantity.

INVERSE TRANSDUCER:

- Inverse transducers convert electrical quantity to a non electrical quantity

Resistive Temperature Detectors (RTDs)

→ It based on the principle of change in resistance of a conductor when its temperature changes.

→ When a metal wire is heated the resistance increases, so temprature can be measured by using the relation between resistance of wire & tempr.

→ The relation between resistance & temperature is given as

$$R_t = R_0(1 + \alpha \Delta t)$$

R_t = Resistance of wire at t°C

R_0 = wire resistance at 0°C

Δt = tempr difference

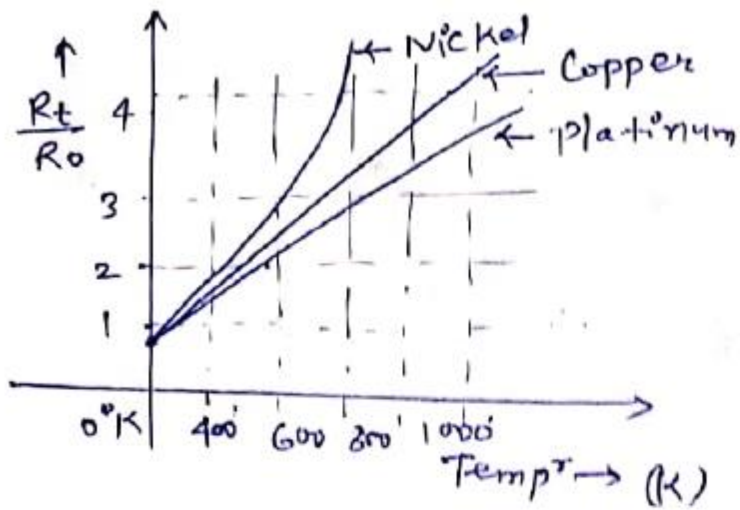
α = tempr co-efficient of resistance

In general

$$R_t = R_0(1 + \alpha_1 \Delta t + \alpha_2 \Delta t^2 + \dots + \alpha_n \Delta t^n)$$

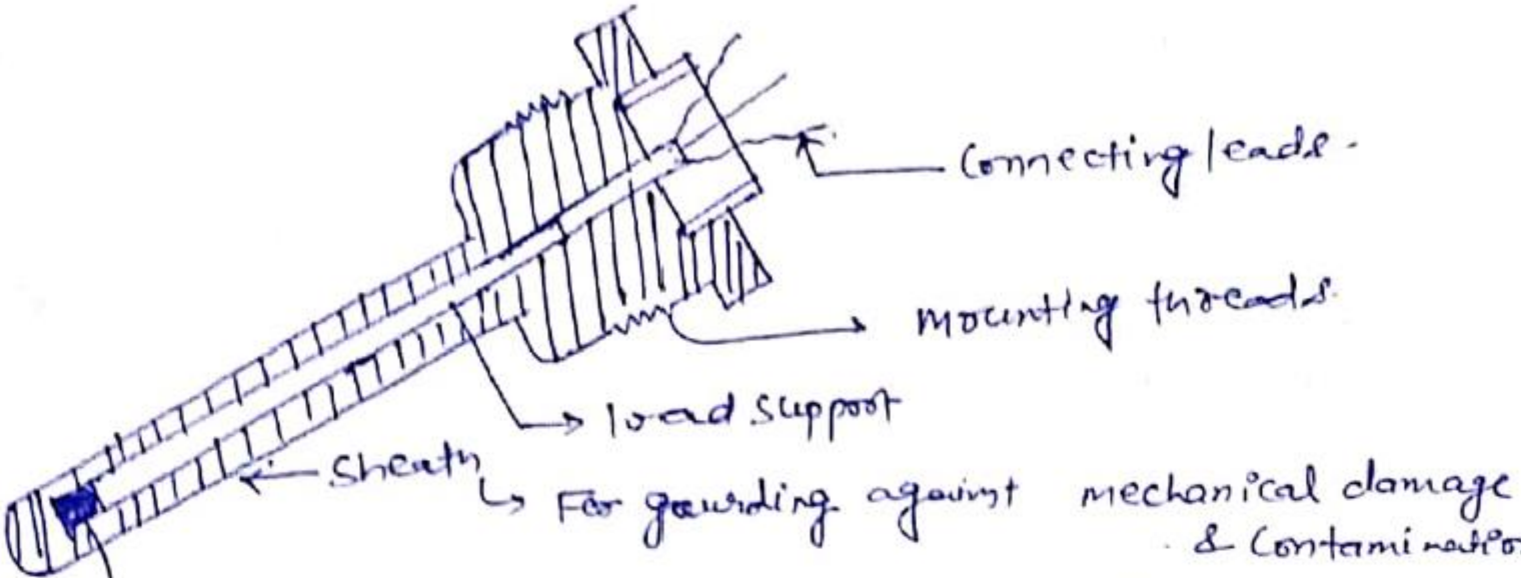
Material	Tempr. Range (°C)	Typical Resistance (Ω)
1. Platinum	−200 − +800	100
2. Nickel	−80 − +300	120
3. Copper	−200 − +260	10

→ Characteristics of various materials;



$$\frac{R_t}{R_0} = 1 + \alpha \Delta t$$

Construction & Working of RTD :-

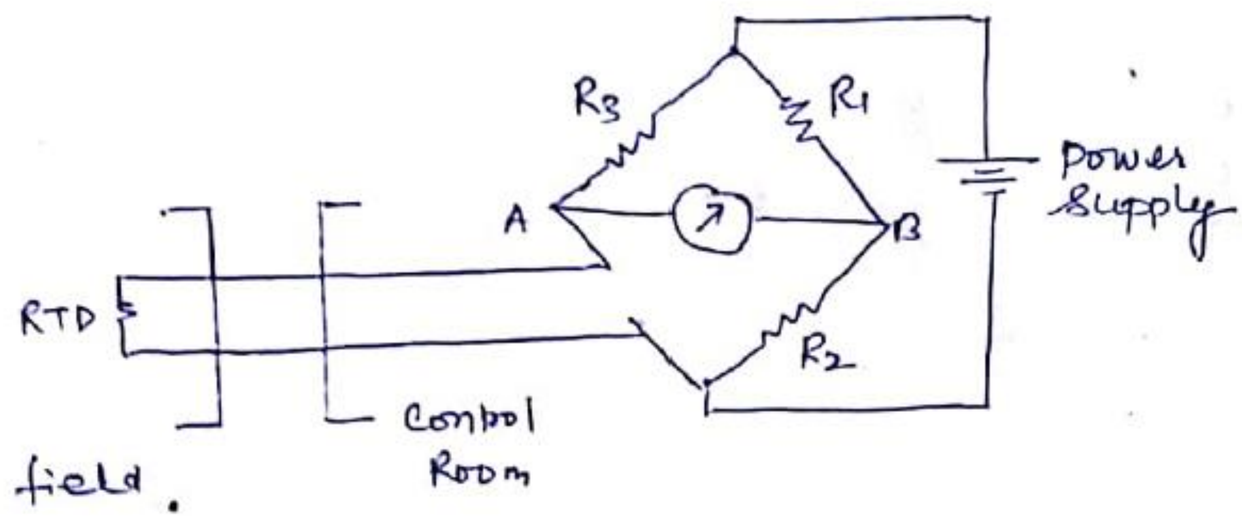


sensing element [platinum, nickel or Copper]

The RTD should posses 2 Characteristics.

(i) Change in Resistance per unit change in tempr must be large

(ii) Resistance of wire should have a Continuous & stable relationship with tempr.



Circuit Diagram

Thermocouples :-

↳ It changes the thermal energy into electric voltage.

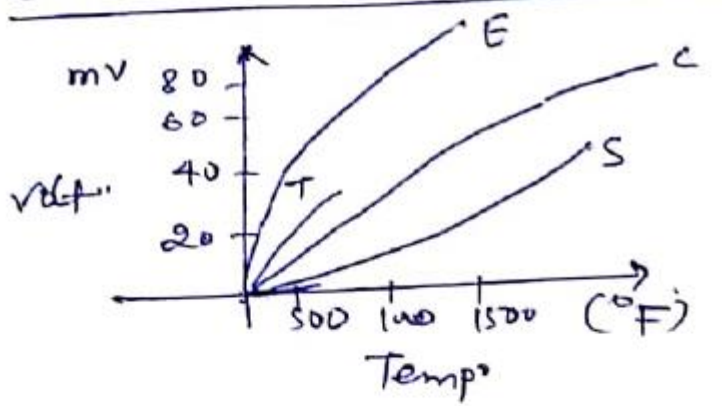
↳ Active transducer, used for high tempr range

↳ It is based on principle of ~~seebec~~ "Seabeck" effect

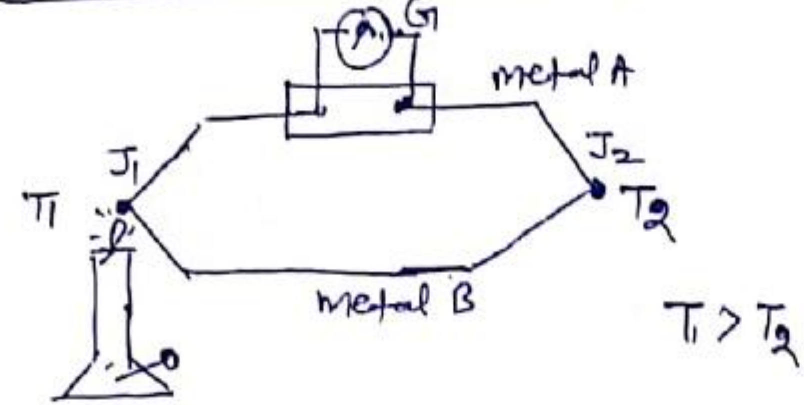
" If two different metals are joined together so as to form a closed loop then there will be two junctions formed. If both junctions are kept at different tempr then a current will flow in the closed loop circuit.

Material	ANSI	Tempr Range °F	Voltage Range (mV)
copper/constantan	T	-200 to 400	-5.60 to 17.82
chromel/constantan	E	-200 to 900	-8.82 to 68.78
Platinum rhodium/ 10% platinum	S	0 to 1450	0 to 14.97
tungsten 5% tungsten 26%	C	0 to 2760	0 to 37.07

Characteristics of thermocouple.

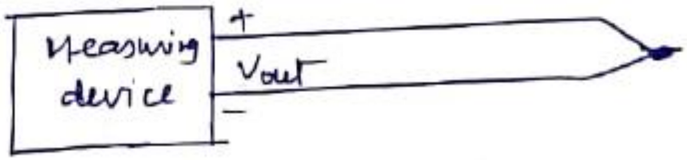


Construction & working:



→ when two different conductors are joined, electrons will diffuse across the junction from conductor having high ele. density

→ Conductor who looses ele. acquire positive voltage w.r.t other conductor. It is called 'Peltier emf'



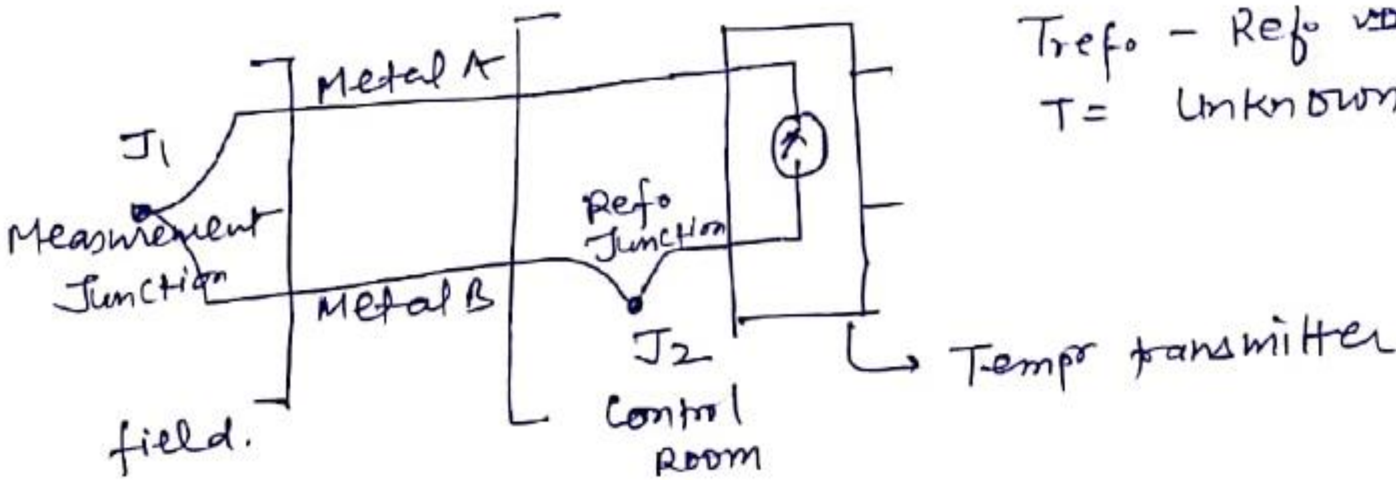
$$V_{out} = \alpha (T - T_{ref.})$$

$$\Rightarrow T = \frac{V_{out}}{\alpha} + T_{ref.}$$

α = Tempr Cont. $= 50 \frac{\mu V}{^{o}C}$

$T_{ref.}$ − Ref. ~~voltage~~ Tempr

T = Unknown Tempr.



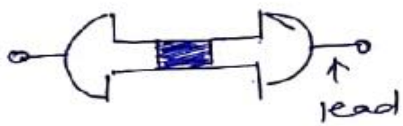
Thermistors : (Thermal resistor)

↳ It is a thermally sensitive variable resistor made of a ceramic like semiconductor material

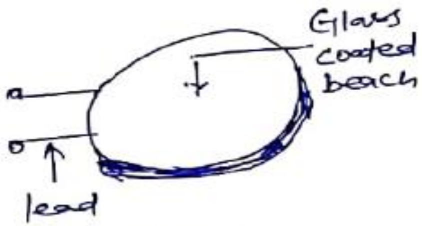
→ The tempr co-efficient for termistor is negative means its resistor decreases if tempr increases Hence it is also known as "NTC" (Negative tempr co-efficient device).

→ It is composed of oxides of magnese, nickle & cobalt having resistivity range → 100 to 450000 Ω cm

Construction & Working



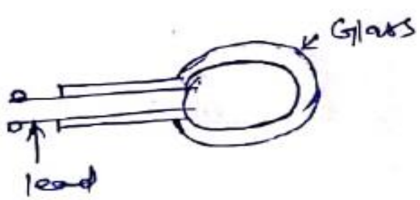
(a) Rod Type ; length from ·6mm to ·50mm



(b) Bead Type ; glass coated for potection
dia – 0.15mm to 2.5mm

(c) Washer Type ; Can be used in series of parallel

(d) Disc Type :



(e) Probe Type ; dia: ·up to 25mm

Working of thermistor :

Resistance at tempr t can be given by eqn.

$$R_t = R_0 e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

β = (negative) tempr coeff

T_0 = ref° tempr

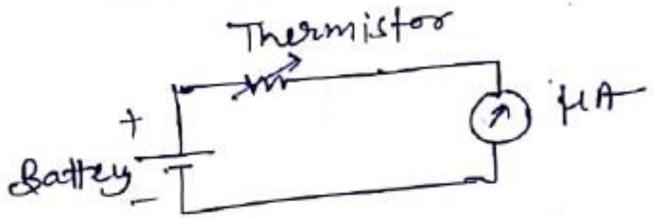
since thermistor is a non linear device.

$$\Rightarrow \frac{R_t}{R_0} = e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

$$\Rightarrow \beta\left(\frac{1}{T} - \frac{1}{T_0}\right) = \ln\left(\frac{R_t}{R_0}\right)$$

$$\Rightarrow \frac{1}{T} - \frac{1}{T_0} = \frac{1}{\beta} \ln\left(\frac{R_t}{R_0}\right) \quad \Rightarrow \frac{1}{T} = \frac{1}{T_0} + \frac{1}{\beta} \ln\left(\frac{R_t}{R_0}\right)$$

$$\Rightarrow \boxed{T = \frac{1}{1/T_0 + \frac{1}{\beta} \ln\left(\frac{R_t}{R_0}\right)}}$$

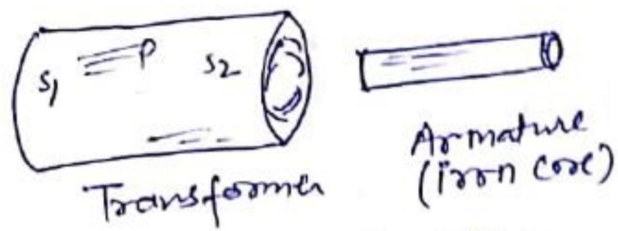


The 'μA' can be calibrated to read tempr directly in case of using constant emf battery & limited current

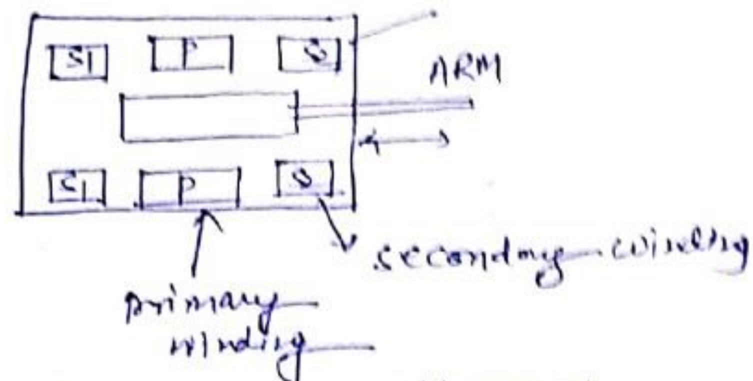
LINEAR VARIABLE DIFFERENTIAL TRANSDUCER '(LVDT)'

- It is a variable inductance transducer to produce AC output, which is proportional to the relative displacement of transformer & armature.
- electromechanical device.
- passive transducer.

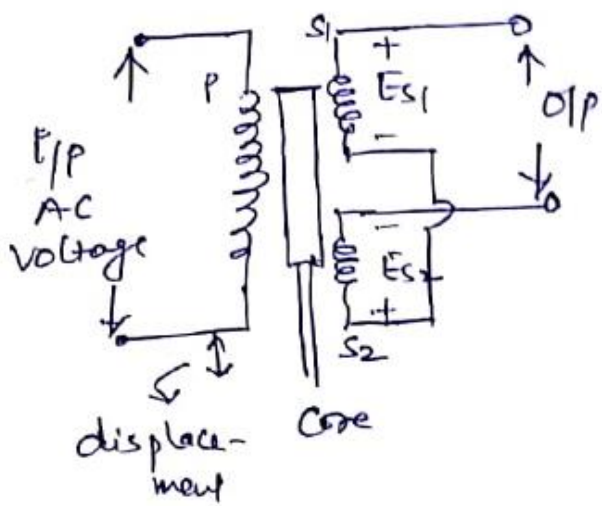
Construction & Working principle :-



(i) actual construction.



(ii) Schematic diagram



$E_0 = E_{s1} - E_{s2}$

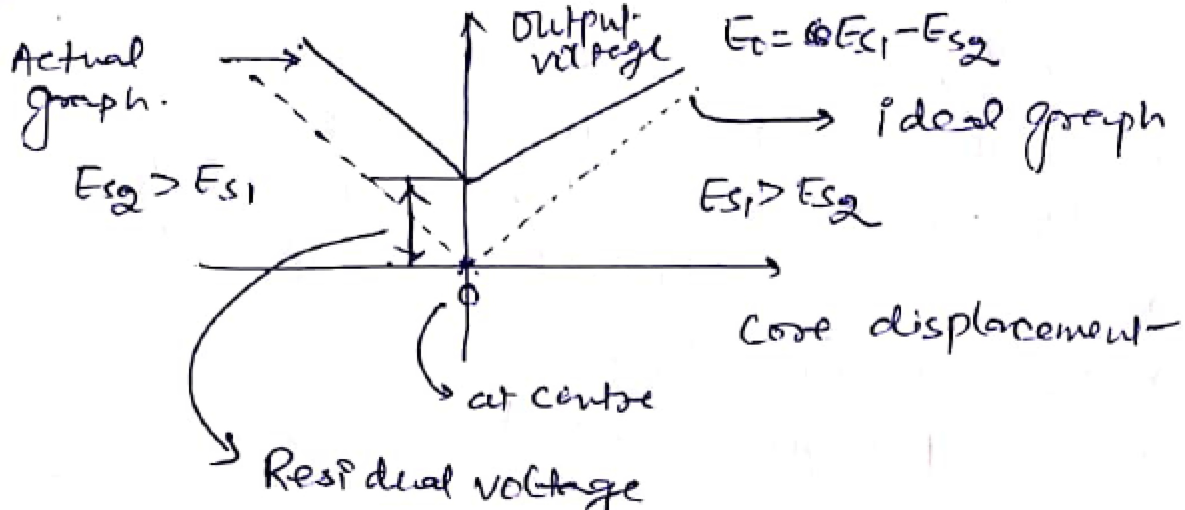
(iii) circuit diagram.

There are 3 cases; Case I; When core is at centre
flux linking with both secondry is equal E_{s1} & E_{s2} are equal
Hence $E_0 = E_{s1} - E_{s2} = 0$

Case II; if core is moved towards 'S_1'
In this case flux links with S_1 is more compared to S_2 Hence $E_{s1} > E_{s2}$
so $E_0 = E_{s1} - E_{s2} > 0$ $E_0 = +ive$

Case III; If core is moved towards 'S_2'
If core is moved towards 'S_2' Hence flux links with S_2 is more compared to 'S_1' Hence
$E_{s2} > E_{s1}$ so $E_0 = E_s - E_{s2} < 0$
$E_0 = -ive$

- The Difference of output voltage of secondary windings give the amount of displacement following a linear law.



→ Ideally output voltage should be zero at null position

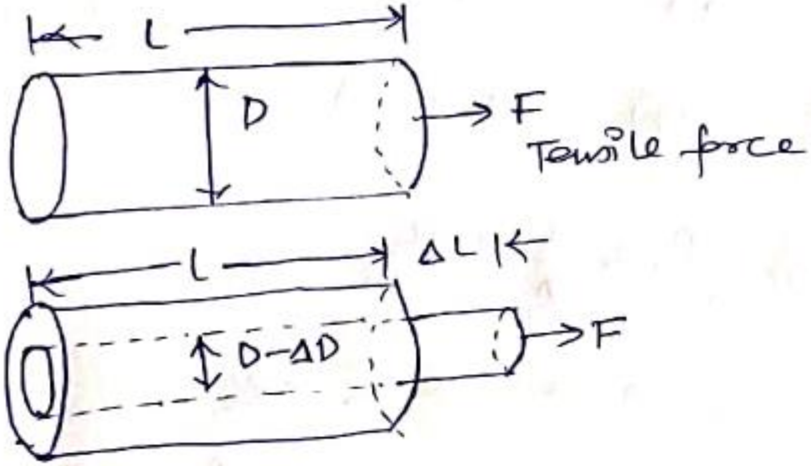
→ Practically there is small voltage at output which is known as residual voltage.

→ Residual voltage is because of magnetic unbalance or due to electrical unbalance.

→ It can be overcome by magnetic ~~shif~~ shield

Strain gauge :-

- It is a passive transducer.
- It works on the principle that the resistance of a conductor or a semi conductor changes when strained.
- This property can be used for measurement of displacement, force and pressure.
- The resistivity of materials also changes with change of temp^r thus causing a change of resistance.



Original Resistance

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

ρ = Resistivity
L = length
A = Area $= \pi\left(\frac{D}{2}\right)^2$

~~log~~

longitudenal strain $= \frac{\Delta L}{L}$

principle of working:

↳ change in resistance is proportional to strain applied

↳ sensitivity of strain gauge is defined in terms of gauge factor 'G_f'. It is defined as

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

R = initial resistance
ΔR = change in initial resistance
Δl = change in length in meter
l = initial length .. " "

To derive the expression for Gf let's assume that

applied stress = S

as we know Resistance $R = \frac{\rho L}{A}$

partial diff. w.r.t stress 's'

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

divide both sides with R

$$\frac{1}{R}\frac{\partial R}{\partial S} = \frac{1}{L}\frac{\partial L}{\partial S} + \frac{1}{\rho}\frac{\partial \rho}{\partial S} - \frac{1}{A}\frac{\partial A}{\partial S} \quad \text{—} (1)$$

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

so $\frac{\partial A}{\partial s} = \frac{\pi}{4}(2D)\cdot\frac{\partial D}{\partial s}$

$\frac{\partial A}{\partial s} = \frac{\pi D}{2}\frac{\partial D}{\partial s}$ — ② put in eqn ①

$\Rightarrow \frac{1}{R}\frac{\partial R}{\partial s} = \frac{1}{L}\frac{\partial L}{\partial s} + \frac{1}{\rho}\frac{\partial \rho}{\partial s} - \frac{\pi D}{2A}\frac{\partial D}{\partial s}$

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

$\Rightarrow \frac{1}{R}\frac{\partial R}{\partial s} = \frac{1}{L}\frac{\partial L}{\partial s} + \frac{1}{\rho}\frac{\partial \rho}{\partial s} - \frac{2}{D}\frac{\partial D}{\partial s}$ — ③

Now we know poisson's ratio $\nu = \frac{\text{lateral strain}}{\text{longitudinal strain}} = \frac{-\partial D/D}{\partial L/L}$

$\Rightarrow \partial D/D = -\nu\frac{\partial L}{L}$ — ④ put in ③

$\frac{1}{R}\frac{\partial R}{\partial s} = \frac{1}{L}\frac{\partial L}{\partial s} + \frac{1}{\rho}\frac{\partial \rho}{\partial s} + 2\nu\frac{\partial L}{L\partial s}$

for small variation $\frac{\partial R}{\partial s} \to \Delta R$

$\frac{\partial L}{\partial s} \to \Delta L$, $\frac{\partial \rho}{\partial s} \to \Delta \rho$

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

$$\Rightarrow \frac{\Delta R/R}{\Delta L/L} = 1 + 2\nu + \frac{\Delta \rho/\rho}{\Delta L/L} \qquad \because \frac{\Delta R/R}{\Delta L/L} = G_f$$

$$\Rightarrow G_f = 1 + 2\nu + 0 \qquad \because \Delta\rho/\rho \ll \frac{\Delta L}{L}$$

$\frac{\Delta \rho}{\rho} / \frac{\Delta L}{L}$ can be neglected

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

→ ν for a wire is 0.3

→ ν for metals is between 0 to 0.5

Numericals:

Q1. A strain gauge bounded to steel beam of 0.20 m long and has a cross sectional area of $0.4 \times 10^{-3} m^2$. Young's modulus of elasticity for steel is 200 GN/m^2. The strain gauge has a unstrained resistance of 120 Ω & a gauge of 2. When load is applied the gauge resistance changes by 0.012 ohm. Calculate the change in length of steel beam & amount of force applied to the beam.

Sol^n. Given: $L = 0.20\,m$, $A = 0.4 \times 10^{-3}\,m^2$ $Y = 200\,GN/m^2$.

$R = 120\,\Omega$, $G_f = 2$, $\Delta R = 0.012\,\Omega$

To calculate: $\Delta L = ?$, & $F = ?$

as we know $G_f = \dfrac{\Delta R/R}{\Delta L/L}$

$$\Rightarrow \frac{\Delta L}{L} = \frac{\Delta R}{R} \times \frac{1}{G_f}$$

$$\Rightarrow \Delta L = \frac{\Delta R}{R} \times \frac{1}{G_f} \times L$$

$$= \frac{0.012}{120} \times \frac{1}{2} \times 0.2 = 10^{-5}\,m$$

also we know

$$Y = \text{stress}/\text{strain} = \frac{F/A}{\Delta L/L}$$

$$\Rightarrow F/A = Y \times \Delta L/L$$

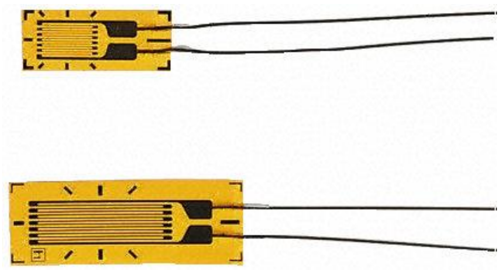
$$\Rightarrow F = Y \times \frac{\Delta L}{L} \times A = \frac{200 \times 10^9 \times 10^{-5}}{0.2} \times 0.4 \times 10^{-3}$$

$$\boxed{F = 4 \times 10^3\,N}$$

Q2; The output of an LVDT is connected to a 5V voltmeter through an amplifier whose amplification factor is 250. An amount of 2mV appears across the terminals of LVDT when the core moves through a distance of 0.5mm. Calculate the sensitivity of the LVDT and that of the whole setup. The millivoltmeter scale has 100 divisions. The scale can be read to 1/5 of a division. Calculate the resolution of the instrument in mm.

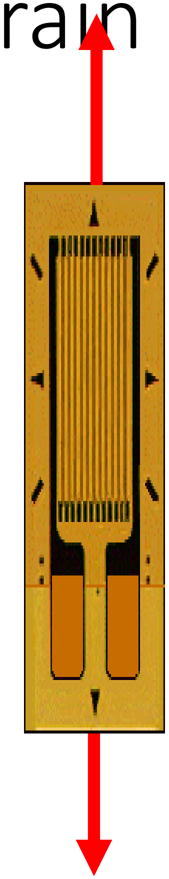
Strain Gauge

- A **strain gauge (or strain gage)** is a device used to measure strain on an object. It is also termed as Load cell
- The most common type of strain gauge consists of an insulating flexible backing which supports a metallic foil pattern.

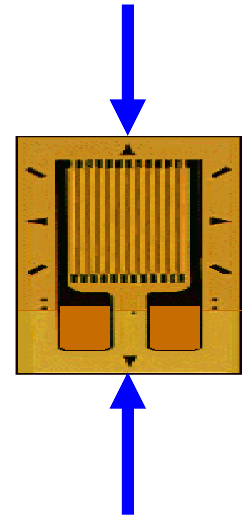


Strain Gauge

Tension



Compression



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

$R =$ Resistance

$\rho =$ Property of material

$l =$ Length of wire

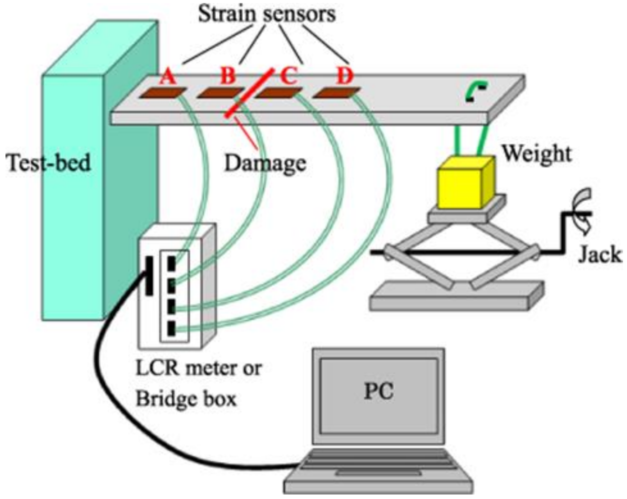
$A =$ Effective cross sectional area of wire

Tension: $l \uparrow$, $R \uparrow$

Compression: $l \downarrow$, $R \downarrow$

Strain Gauge Applications

- Measurement of pressure
- Measurement of force
- Measurement of small displacement
- Measurement of Torque
- Measurement of Load etc.

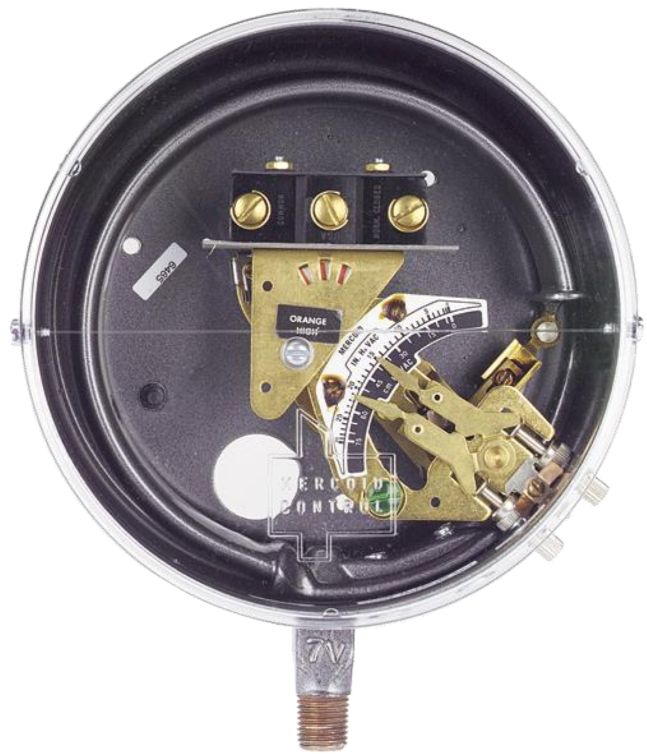


BOURDON TUBES

- Invented by Eugene Bourdon in the year 1849.
- Bourdon tubes are an elastic type pressure transducer.
- Used for very high range pressure measurement of almost 1,000,000 Psi (700MPa)

Working Principle

- The cross-sectional of the Bourdon tubing when deformed in any way will tend to regain its circular form under the action of pressure.



TYPES OF BOURDON TUBES

C-Type Bourdon tube

- The C-shaped Bourdon tube has a hollow, elliptical cross section. It is closed at one end and is connected to the fluid pressure at the other end.
- When pressure is applied, its cross section becomes more circular, causing the tube to straighten out.

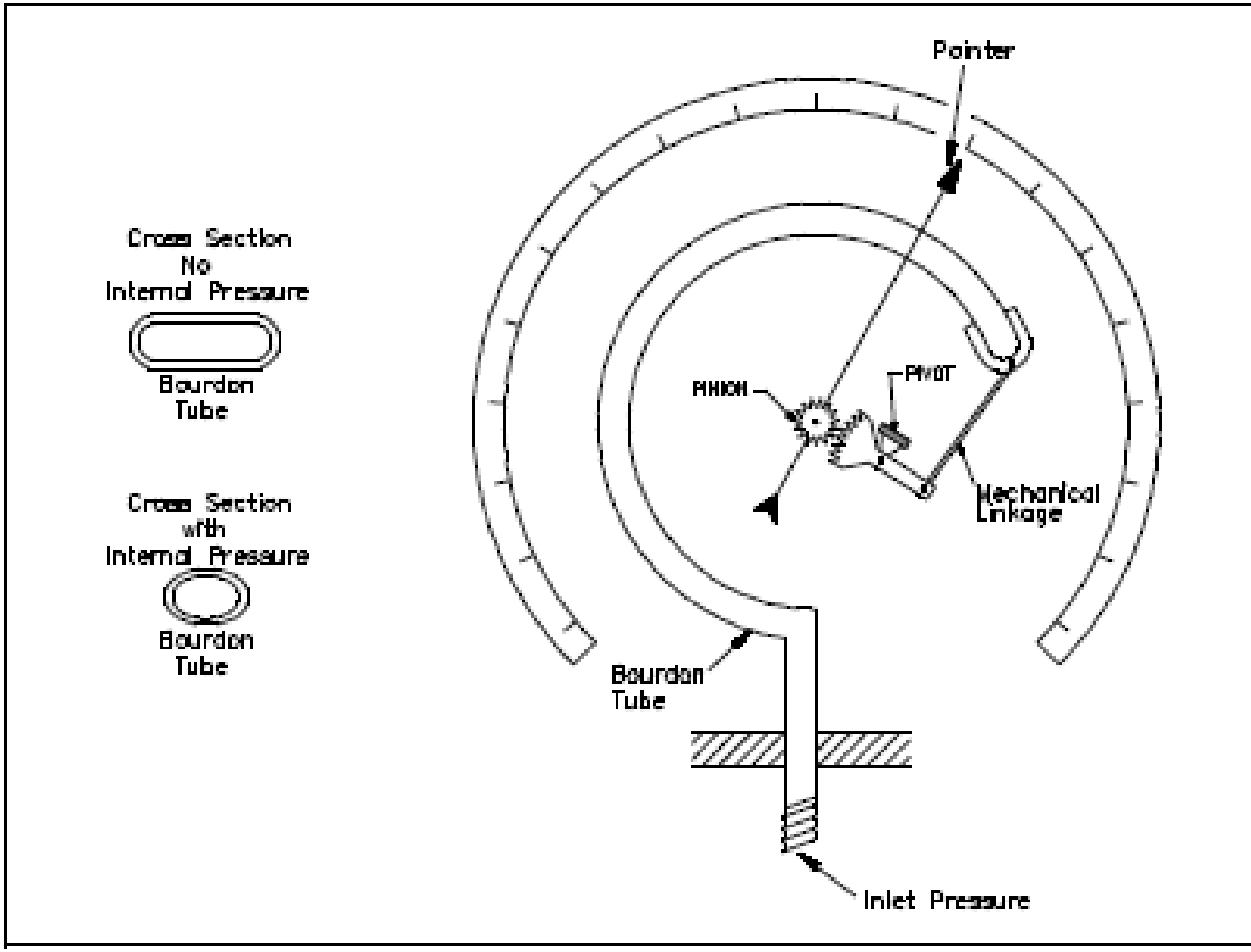
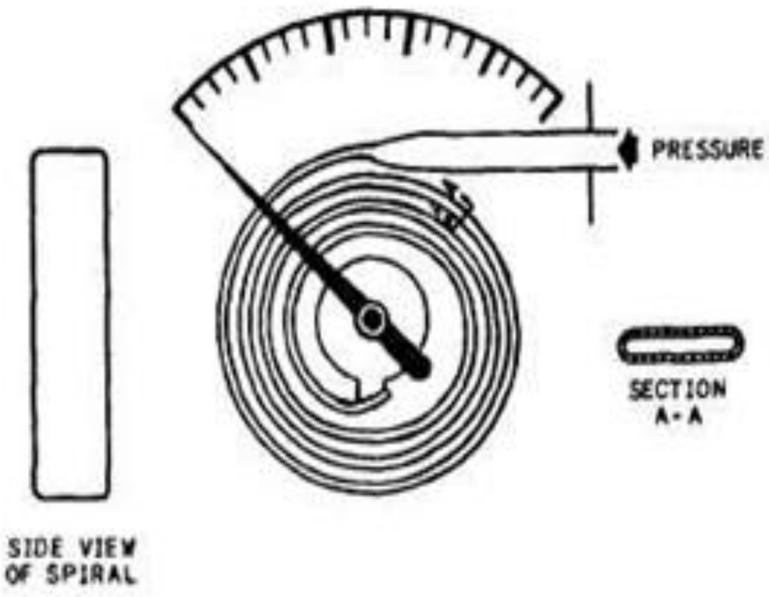
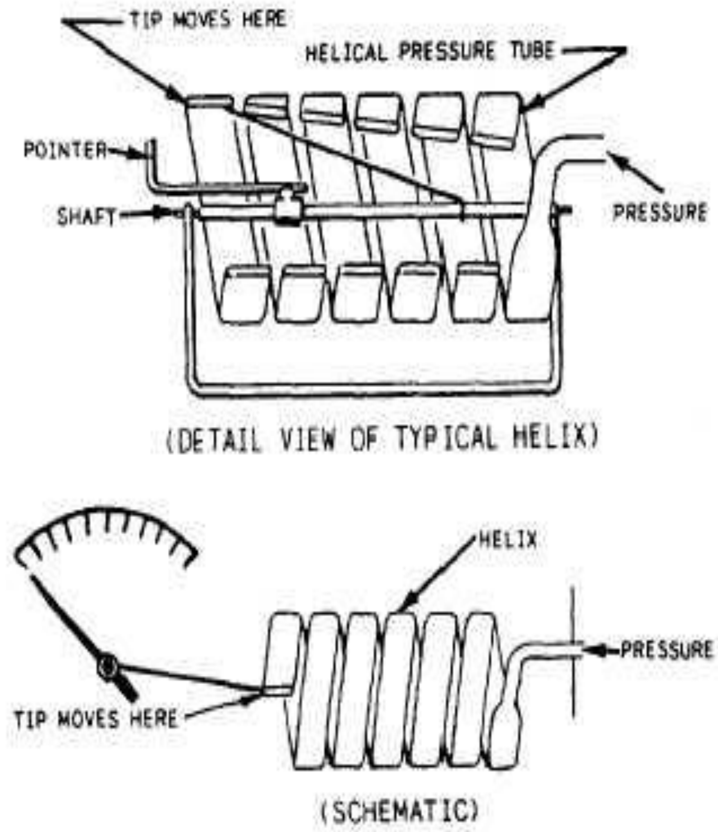


Figure 2 Bourdon Tube

Spiral type Bourdon tube



Helical type Bourdon tube



ADVANTAGES OF BOURDON TUBE PRESSURE GAUGES

- These Bourdon tube pressure gauges give accurate results.
- Bourdon tube cost low.
- Bourdon tubes are simple in construction.
- They can be modified to give electrical outputs.
- They are safe even for high pressure measurement.
- Accuracy is high especially at high pressures.
- Their greatest advantage is that they are easily adapted for designs for obtaining electrical outputs.

LIMITATIONS OF BOURDON TUBE PRESSURE GAUGES

- They respond slowly to changes in pressure.
- They are subjected to hysteresis.
- They are sensitive to shocks and vibrations.
- Amplifications is a must as the displacement of the free end of the bourdon tube is low.
- It cannot be used for precision measurement.

TACHOMETERS

- A **Tachometer** is an instrument used to measure the rotation speed of a shaft or disk, as in a motor or other machine.
- Measurement unit : Revolution per Minute {RPM}.
- Linear speed is measured in m/s ξ Angular speed in rad/s or rpm.

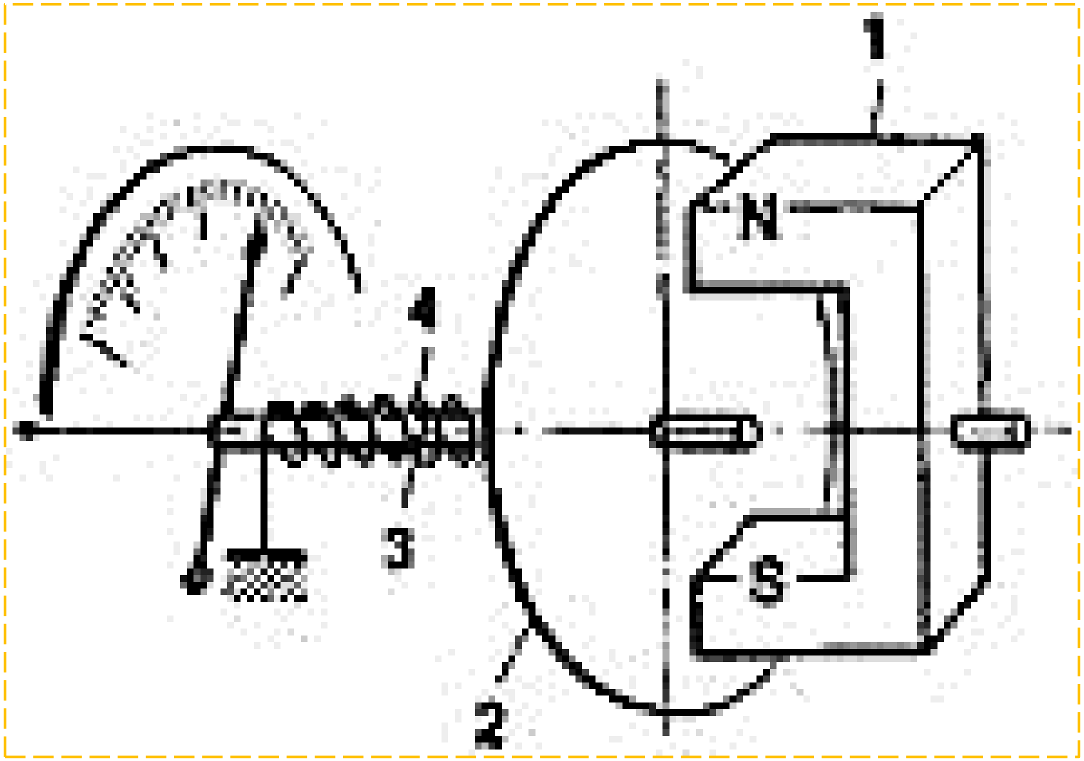
TACHOMETERS CLASSIFICATIONS

- Mechanical Tachometers
  - Revolution Counter.
  - Hand speed Indicator.

- Electrical Tachometers
  - Eddy current tachometer.
  - Magnetic pickup tachometer.

Eddy current/Drag cup tachometer

Electrical Tachometers



- Parts: Permanent magnet within aluminium cup, spindle connected to cup to which a pointer is fixed by spiral spring.

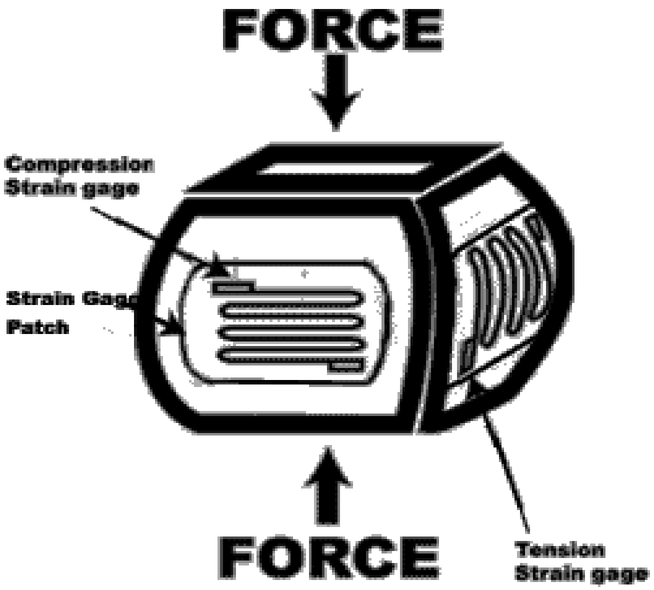
- Principle: When the permanent magnet rotates in a drag cup close to magnet , the eddy current is induced which produces a torque in drag cup.

- Now, the deflection of cup due to torque is indicated by pointer representing speed of shaft & it’s measured upto 12000 rpm.

- **Advantage:** Less maintenance, ripple free output , Inexpensive.
- **Dis-advantage:** Hard to calibrate.
- **Application**: Automobile speedometer, Locomotive speed.

LOAD CELL

- Load cell is an electromechanical device.
- A load cell is a force transducer that converts force or weight acting on it into an electrical signal.
- Load cell can be used to measure force, torque and pressure.
- Load cell can measure a wide range of force, from 25grams to 3,000,000lbs.



CLASSIFICATION AND APPLICATION

Mechanical type load cell

- ❑ Hydraulic
- ❑ Pneumatic

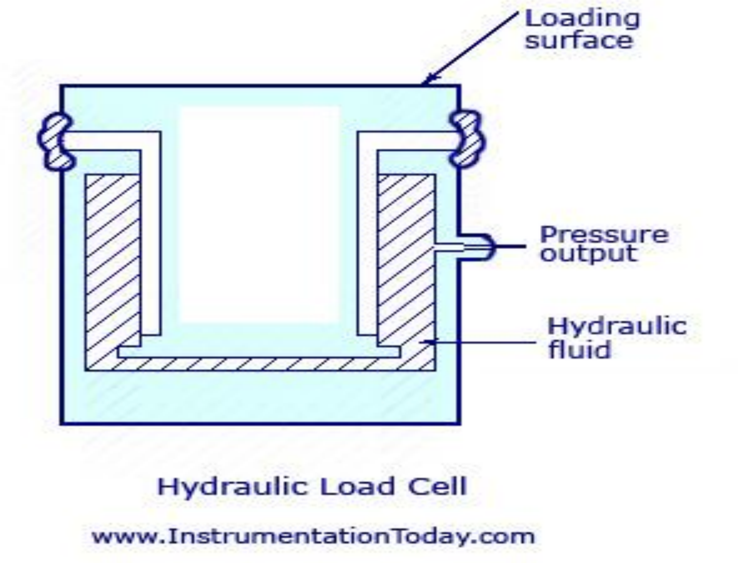
Electrical type load cell

- ❑ Resistance based (strain gauge load cell)
- ❑ Capacitance based
- ❑ Inductance based (LVDT load cell)

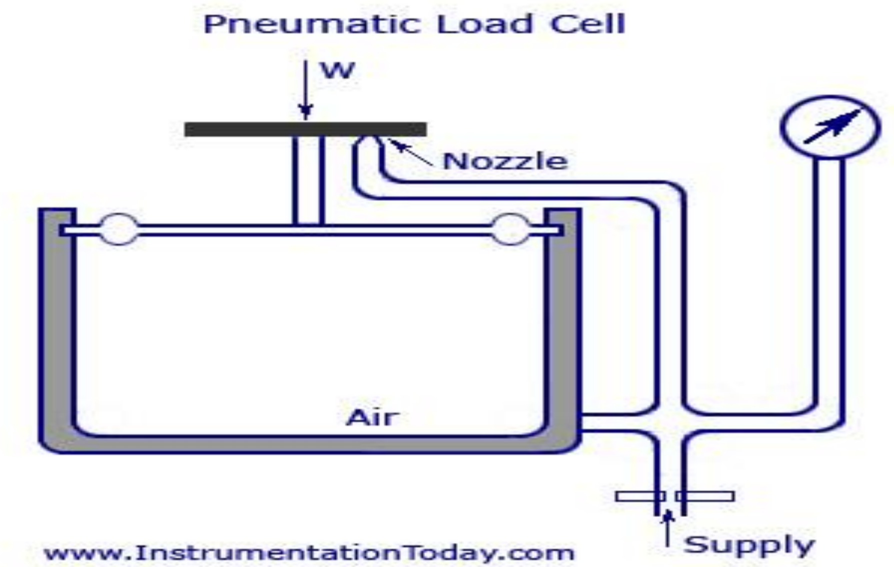
Among the many kinds of load cell the most common type is strain gauge load cell.

Mechanical Load Cell

Hydraulic load cells are force balance-devices, measuring weight as a change in pressure of the internal filling fluid. It is ideal for use in hazardous areas as there are no any electrical component in it.



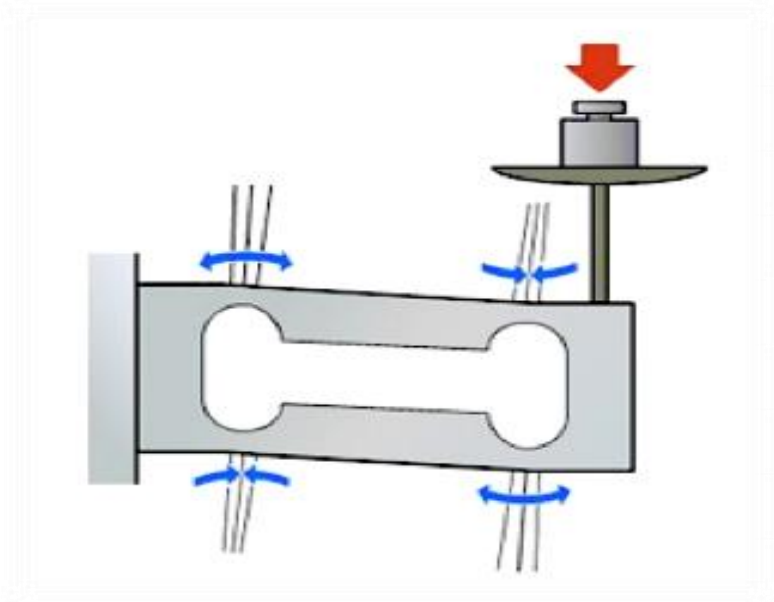
Pneumatic Load Cells also operate on the force-balance principle. These devices use multiple dampener chambers to provide higher accuracy than hydraulic load cell. Pneumatic load cells are often used to measure relatively small weights in industries where cleanliness and safety of prime concern.



Electrical Load Cell

<u>Strain Gauge Load Cell</u>

- ❑ A strain gauge is a device used to measure the strain of an object and convert the load acting on them into electrical signals.
- ❑ Due to application of load, strain changes the electrical resistance of the gauge in proportion to the applied load.
- ❑ Strain gauge shows a very high accuracy of 0.03%.



LOAD CELL APPLICATION

1. All types of textile testing (Instron).

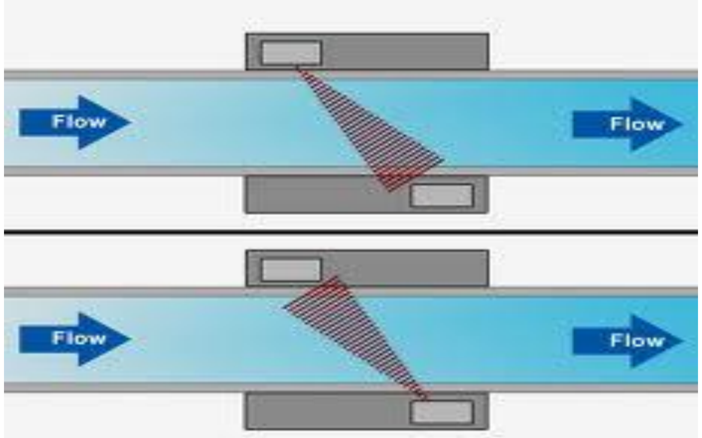
2. Measurement of weight (Moisture regain testing).

3. Online measurement of tension during various process (like printing).

Ultrasonic flow meter

- Sound generated above the human hearing range (typically 20- 20KHz) is called ultrasound .

- The ultrasonic flow meter operates on the principle that the velocity of the sound in a fluid in motion is the resultant of the velocity of sound in the fluid at rest plus or minus the velocity of the fluid



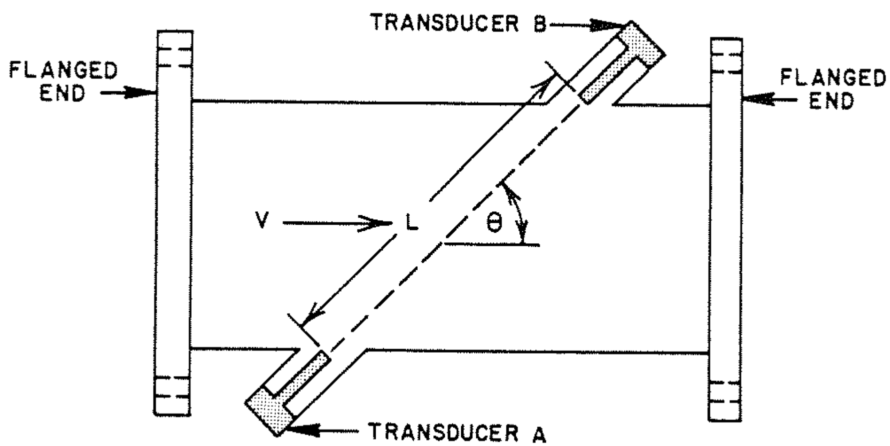
Time of Flight Flow Meter

TYPES

ULTRASONIC FLOWMETER

- TRANSIT-TIME ULTRASONIC FLOWMETER
- DOPPLER FLOWMETER

TRANSIT-TIME FLOWMETER



The time(T_{BA}) for the ultrasonic energy to go from transducer B to transducer A is given by the expression

$$T_{BA} = \frac{L}{C - V\cos\theta}$$

The time (T_{AB}) to go from A to B is given by

$$T_{AB} = \frac{L}{C + V\cos\theta}$$

The differential transit time is given by

$$\Delta T = T_{BA} - T_{AB}$$

$$\Delta T = \frac{2.L.V\cos\theta}{C}$$

The differential transit time ΔT is proportional to fluid velocity V

FREQUENCY DIFFERENCE TYPE

- The pulse repetition frequency in the forward propagating loop is $1/t_1$ while in the backward loop is $1/t_2$

The frequency difference is

$$\Delta f = 1/t_1 - 1/t_2$$

$$= \frac{C + V\cos\theta}{L} - \frac{C - V\cos\theta}{L}$$

$$= \frac{2V\cos\theta}{L}$$

ADVANTAGE

- No obstruction in the flow path, no pressure drop
- No moving parts, low maintenance cost
- Multi-path models have higher accuracy for wider ranges of Reynolds number
- Portable models available for field analysis and diagnosis

DISADVANTAGE

- Higher initial set up cost
- Single path (one-beam) models may not be suitable for flow velocities that vary over a wide range of Reynolds number