Unit 5 : Sensors and Transducers

* **Transducers :** A transducer is a device that transforms a non-electrical physical quantity (like sound, light, temperature) into an electrical signal (like voltage, current, R, L, C)

Physical quantity to be sensed → [sensor] $\xrightarrow[\text{(non-electrical)}]{\text{detected quantity}}$ [signal conditioning unit] $\xrightarrow{\text{Electrical quantity}}$ [Data representation]

$\underbrace{\text{sensor} \rightarrow \text{signal conditioning unit}}_{\text{Transducer}}$

* Classification of Transducers

Transducers
- Active / Passive
- Analog / Digital
- Primary / Secondary
- resistive / capacitive / inductive — Based on Transduction
- Transducer / Invers Transduc

(1) Primary and Secondary Trans~~formers~~ducers

primary transducer → elements that makes direct contact to the physical quantity, converts the physical quantity into a mechanical signal.

secondary transducer → converts output of primary transducer (mechanical signal) into an electrical signal.

For eg. In a Bourbon Tube Pressure Gauge Device,
primary transducer = Bourbon Tube
secondary transducer = LVDT

(2) Active and Passive Transducer

Active Transducer → does not require external power source

eq. accelerometer

(An accelerometer has a piezoelectric transducer, wherein, when a force is applied to a crystal, a voltage is induced. The induced voltage provides a proportional acceleration).

Passive Transducer → requires power from an external supply source

eq. resistive, inductive & capacitive transformers

(3) Analog and Digital Transducers

Analog Transducer → changes the output into a continuous function, ie an analogous fn.

eq → LVDT, thermistor, thermocouple

Digital Transducer → converts a continuous input quantity into a digital (electrical) signal. eq. encoders

(4) Transducers and Inverse Transducers

Transducers → converts non-electrical quantity to an electrical quantity

(consider a microphone, amplifier and loudspeaker setup)

Inverse Transducers → converts an electrical quantity into a physical quantity

(audio casettes, turn electric signals to magnetic fluctuations on the tape head)

* Basic requirements of a good transducer

(i) Linearity : I/P & O/P characteristics must be linear

(ii) Ruggedness : should be able to withstand and handle overloads

(iii) Repeatibility: should provide identical o/p signals when the same input is given repeatedly in the same environmental conditions.

(iv) Reliability : should not be affected by temperature, vibration

(v) Good dynamic response : should respond quickly to changes in input

(vi) Convenient instrumentation: should produce sufficiently high analogue o/p that can later be amplified.

(vii) Good mechanical characteristics : should not deform & hinder performance

* Resistive Transducer

→ converts the change in resistance to an electrical signal w.r.t environmental conditions

→ change in resistance is measured by ac or dc measuring devices.

→ used to measure physical quantities like temperature, displacement, vibration etc.

→ Principle: $R = \frac{\rho l}{A}$ $R \propto l$ & $R \propto 1/A$

There are different types of resistive transducers :

(i) Potentiometric transducer (ii) Strain gauges

(iii) Resistance Thermometers (iv) Thermistors

Potentiometric Transducer

→ consists of a resistance element that is in contact with a movable slider.

→ The movement of the slider by a force-summing member changes the value of resistance, which is measured by the voltage source E.

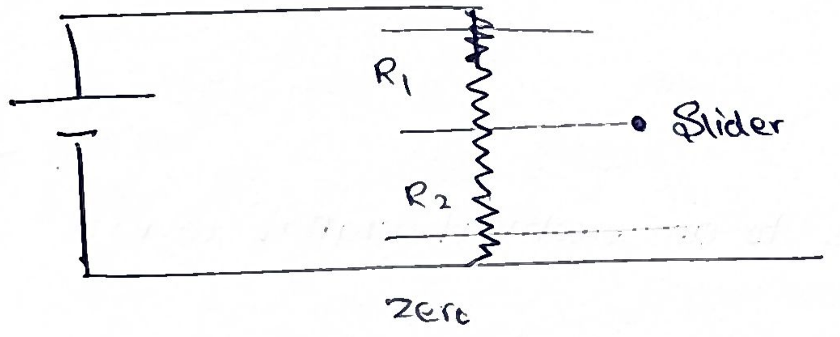
→ The displacement of the slider is converted into an electrical signal.

→ This type of transducer is used as :

(i) as a voltage divider to obtain an adjustable o/p voltage

(ii) in TVs to control brightness, contrast.

(iii) to measure the displacement.



Advantages → cheap, simple
→ measure large amplitude, displacement
→ used in control applications

Disadvantages : → needs large force
→ limited life time

Strain Gauges

Principle: If a metal conductor is stretched or compressed, its resistance changes because of dimensional changes. If a wire is under tension and its length increases from l to $l + \Delta l$, then the strain is $S = \frac{\Delta l}{l}$, then the resistance changes from R to $R + \Delta R$.

There are 2 types of strain gauges: bonded and Unbonded strain gauges

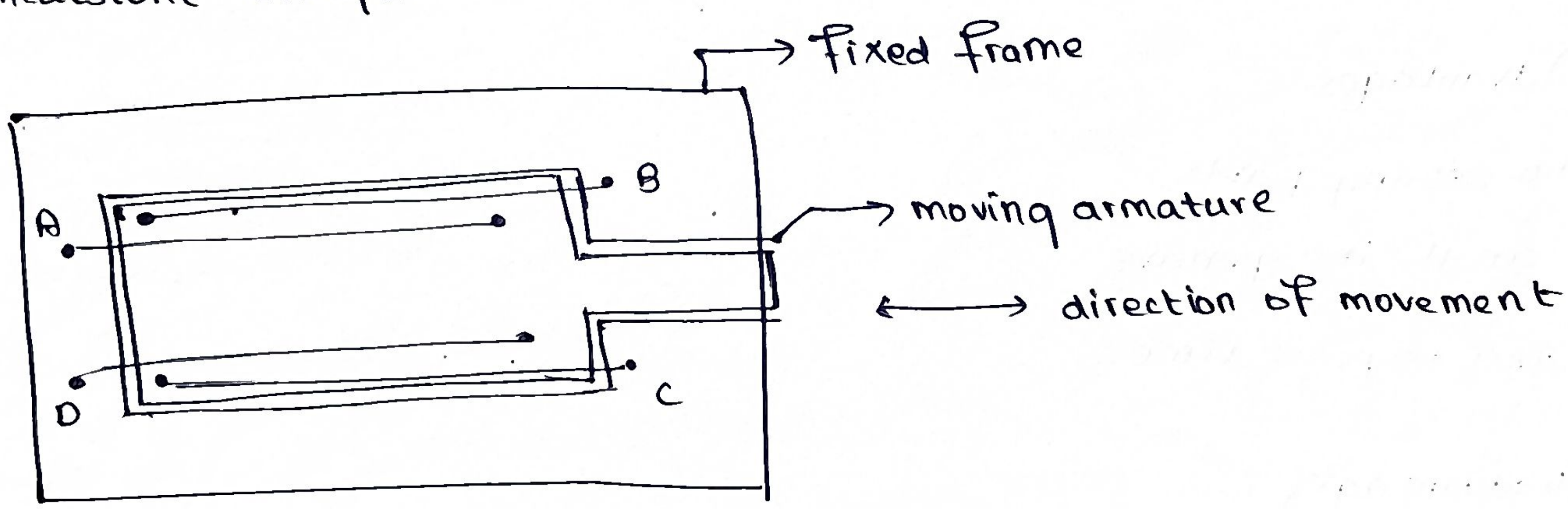
(i) Unbonded Strain Gauges

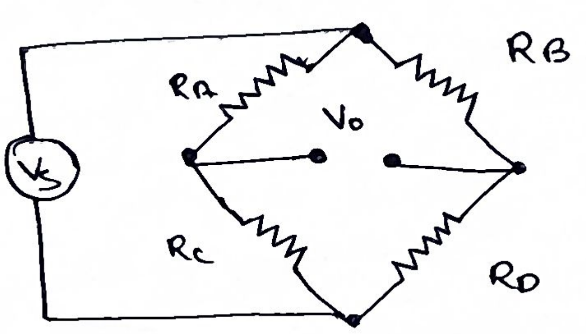
→ A force rod transmits force onto a platform containing an unbonded wire structure.

→ When the external force is applied, the armature moves in a specific direction.

→ The length of elements A and D increases, whereas the length of elements B and C decrease.

→ The change in resistance of the four wires is proportional to their change in length and this change can be measured using a Wheatstone bridge.





(ii) Bonded Strain Gauge

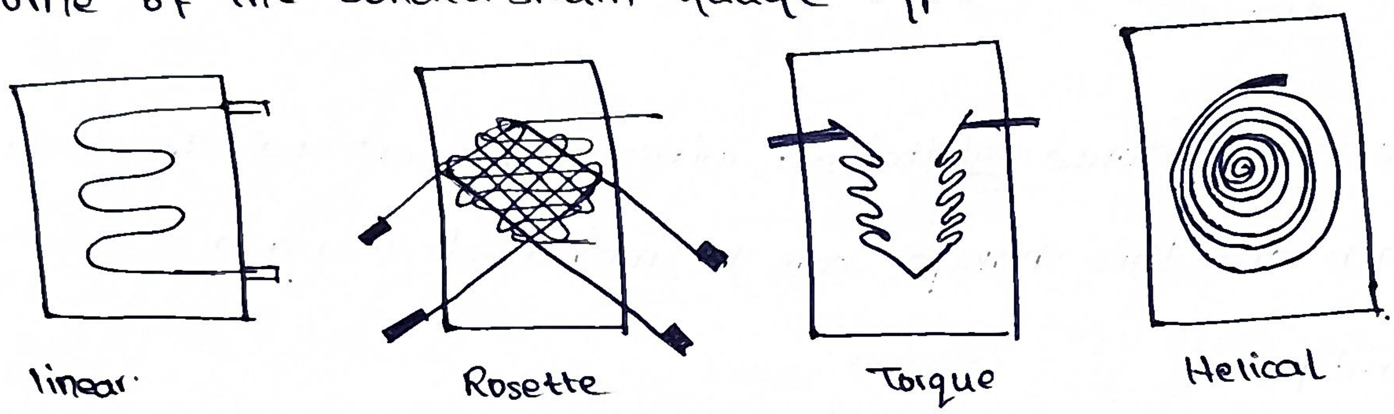
→ has a grid of fine resistance wire

→ the wire is cemented to a base

→ the base is bonded to the structure under study with an adhesive material

→ This acts as a bonding material, transfers strain from base to wires

Some of the bonded strain gauge types are:



Advantages

→ no moving parts

→ small, inexpensive

→ fast response time

Disadvantages

→ has non-linear characteristics

→ very sensitive

→ needs calibration

Applications

→ measure normal strain in any direction

→ measure shear strain

→ measure static & dynamic strain

Resistance Thermometers

Principle: resistance of a conductor varies with temperature according to the relation

$$R = R_0(1 + \alpha T + \beta T^2 + \dots)$$

R_0 = resistance at T_0 (at 0°C)

R = resistance at temp T

α, β are constants

Over a small temperature range, the equation reduces to:

$$R = R_0(1+\alpha T)$$ α = temp. coeff of resistance

Properties of materials required to make an RTD

(i) high temperature coefficient

(ii) stable properties so that R does not vary w/ repeated heating / cooling

(iii) high resistivity

Materials used to make an RTD

(i) copper → used in applications where sensor size is not restricted.

(ii) platinum & nickel → easy to obtain in the pure state.

(Note: platinum > nickel, as the temp coeff. of R is linear over a larger range)

Resistance - Temperature relationship for Platinum

= Callendar equations

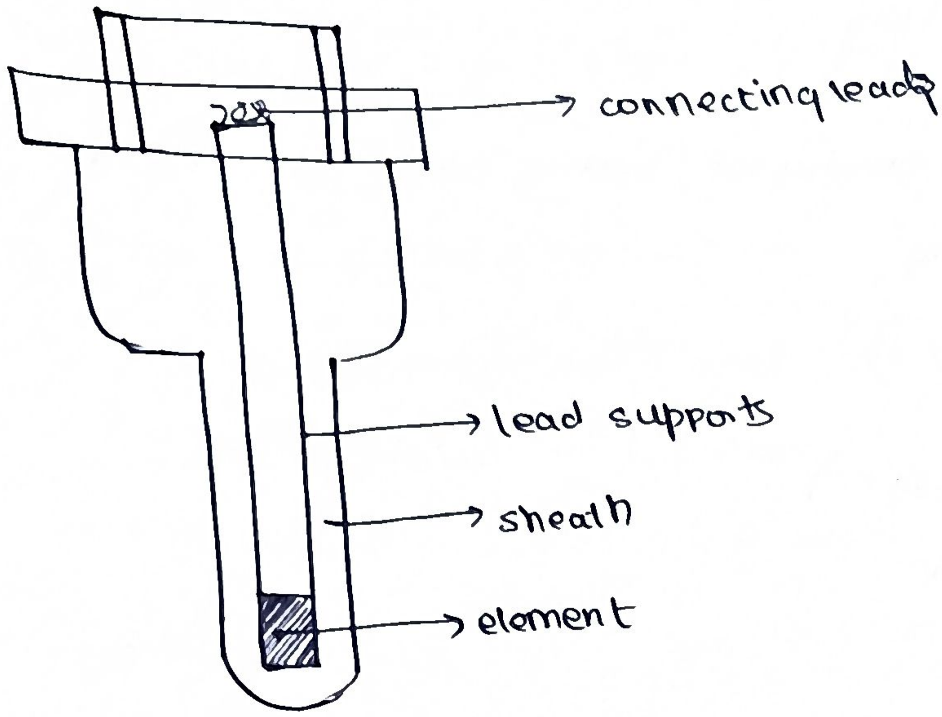
$$T = \frac{100(R_T - R_0)}{R_{100} - R_0} + d\left(\frac{T}{100} - 1\right)\frac{T}{100}$$

R_T = R at temp T

R_0 = R at 0°C

R_{100} = R at 100°C

d = Callendar constant = 1.5



Platinum resistance thermometer

Advantages

→ accurate measurement is possible

→ easy to install and replace

→ measure differential temperature

→ wide range of temp. measurement

Disadvantages

→ external power source needed

→ expensive

→ self-heating issues

Applications

→ aerospace

→ Food-service equipment

→ analytical equipment

* Thermistor

→ Thermistor or thermal resistor is a 2 terminal semiconductor device.

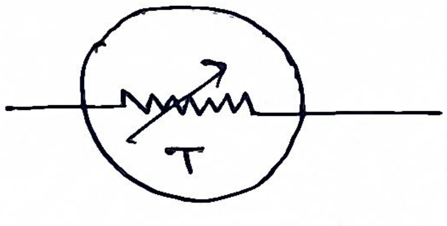
→ Principle: temperature coefficient of the thermistor material varies with resistance.

→ Resistance decreases with an increase in temperature (prop. of semiconductors)

→ Expression for the resistance is:

$$R_T = R_0 \exp \beta \left(\frac{1}{T} - \frac{1}{T_0} \right).$$

Symbol



Characteristics

Parameters used to characterize thermistors

(i) Time constant : time taken for the resistance to change by 63% of the original value, for zero power dissipation

(ii) Dissipation constant : Power need to increase temp. of thermistor by 1°C.

(iii) Resistance ratio : ratio of resistance at 25°C to that at 125°C

Advantages

→ compact, low cost

→ fast response

→ sensitive

Disadvantages

→ requires shielding

→ not suitable for a large temp range

→ non-linear characteristics

Applications

→ measuring temperature

→ controlling temperature

→ temperature compensation

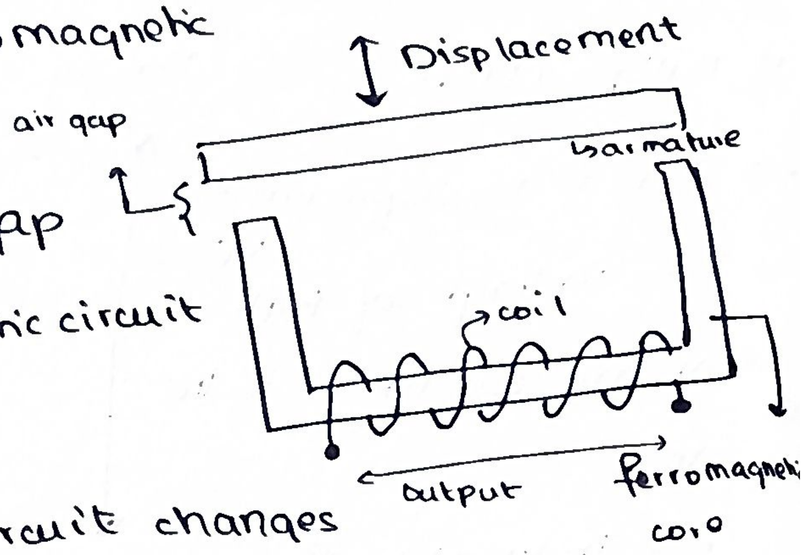
* Differences between RTD and Thermistor

RTD	Thermistor
1. made of metals	1. made of semiconductors
2. has a +ve temp. coeff	2. has a −ve temp coeff
3. $R \propto T$	3. $R \propto 1/T$
4. has linear resistance-temp characteristics	4. non-linear resistance-temp. char
5. less sensitive to temp	5. highly sensitive to temp
6. larger in size	6. smaller in size
7. Expensive	7. Cheaper
8. used in laboratory & industrial applications	8. used in dynamic temp. measurement

* Inductive Transducers

Principle : a change in inductance when there is an appreciable change in the physical quantity to be measured.

Working : → force is applied on a ferromagnetic armature



→ there is a change in the air gap

→ the reluctance of the magnetic circuit changes

∴ → inductance of the magnetic circuit changes

→ Thus, the applied force is measured by the change in inductance in a single coil

Inductive transducers all work on one of the following principles:

(i) change of self inductance
(ii) change of mutual inductance
(iii) production of eddy current

* Linear Variable Differential Transformer (LVDT)

→ one of the most widely used inductive transducers, that converts linear motion into electrical signals.

Construction → has a primary coil and 2 identical secondary coils

→ a rod shaped magnetic core is placed centrally

Working → primary coil is connected to an AC source, generates flux across primary

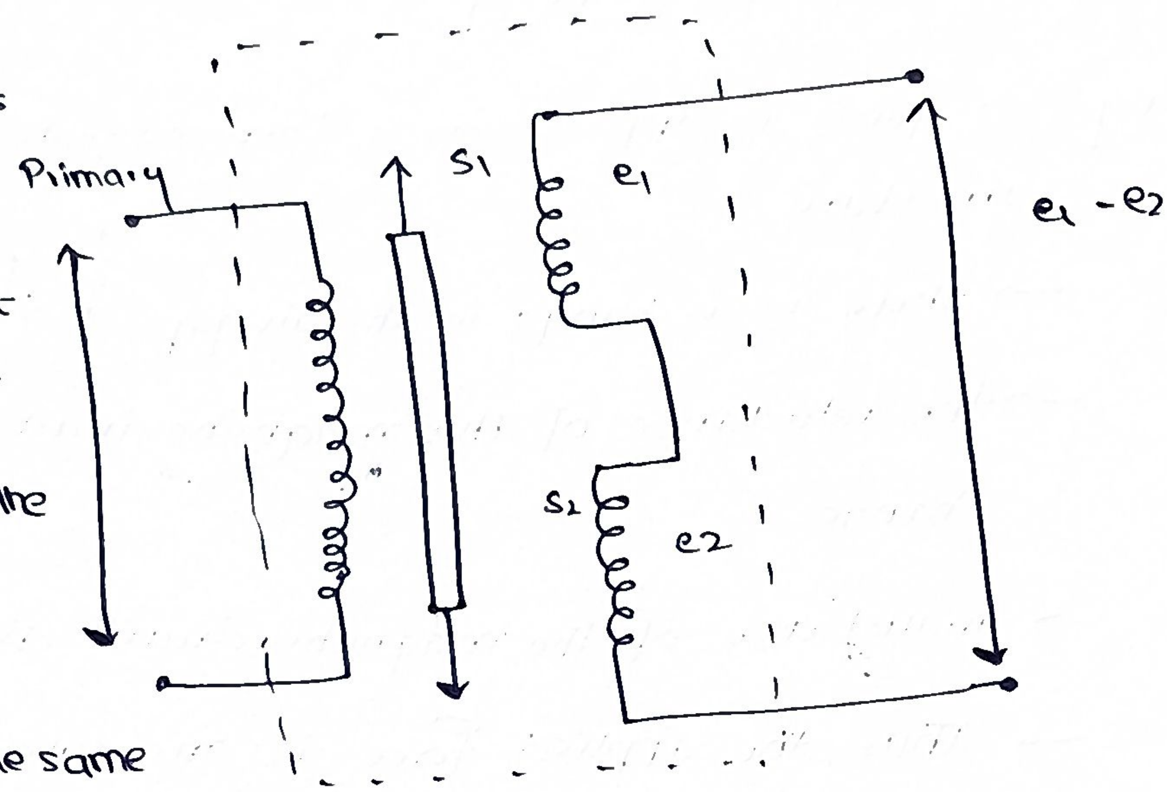
→ an induced emf is produced across the 2 secondary coils due to a change in the magnetic flux

→ emf induced across $S_1 = e_1$

emf induced across $S_2 = e_2$

The differential output is $e_1 - e_2$

Case 1: when the core is at null position



→ There is no displacement

→ flux linkage w/ both secondary windings is the same

→ net induced emf across S_1 & S_2 is the same

⇒ $e_1 - e_2 = 0$

→ This shows that no displacement took place.

Case 2: when the core is moved upwards

→ flux linking with $S_1 > S_2$

→ emf $e_1 > e_2$

⇒ output emf $e_1 - e_2$ is positive

Case 3: when the core is moved downwards

→ flux linking with $S_2 > S_1$

→ emf $e_2 > e_1$

→ output emf $e_1 - e_2$ is negative

Advantages

→ linear relationship

→ high sensitivity

→ low hysteresis

→ low frictional losses

Disadvantages

→ Needs large displacement to get a considerable o/p.

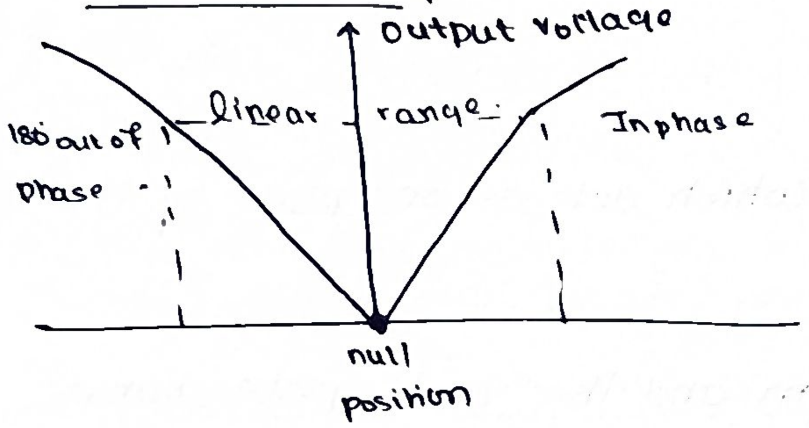
→ Temperature and vibrations influence o/p

Applications

→ used to measure displacement

→ used w/ Bourdon tube to measure pressure.

Characteristics



* Capacitive Transducers → used to measure displacement, pressure and other physical quantities

→ a type of passive transducer (requires external power for operation)

Principle: physical quantities are measured by the changes in capacitance. The change in C may occur due to

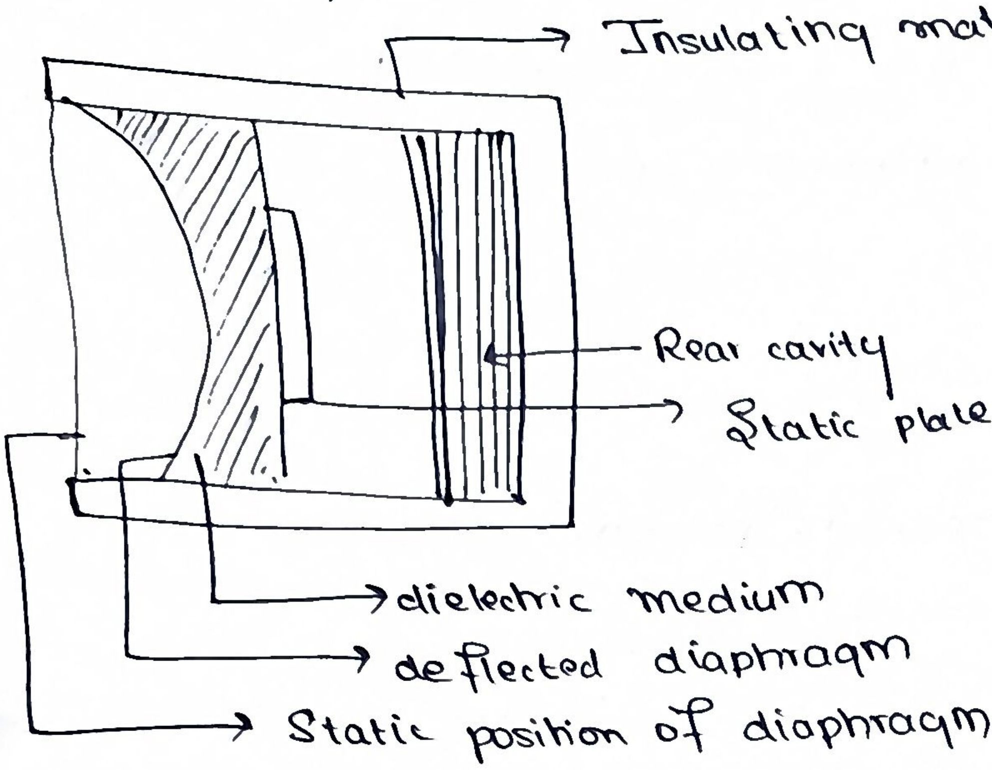
(i) overlapping of plates

(ii) dielectric medium

(iii) change in distance between plates

$$C = \frac{A\varepsilon}{d} \quad \text{or} \quad C = \frac{A\varepsilon_0\varepsilon_r}{d}$$

Working

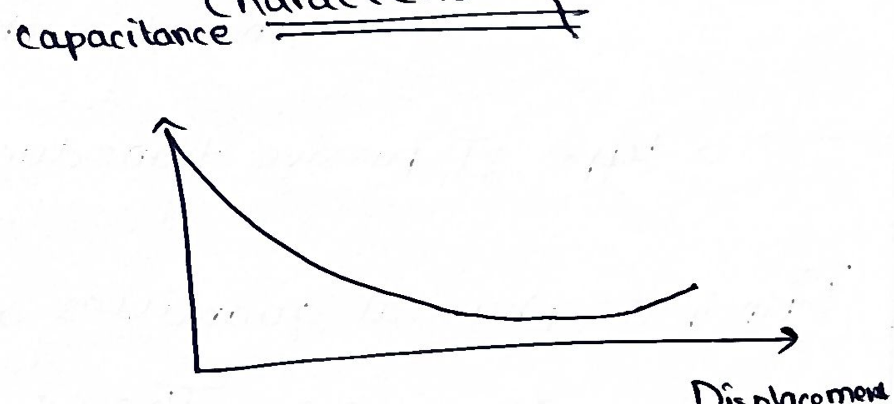


→ Force is applied to a diaphragm, which acts as one plate of the parallel plate capacitor.

→ The distance between the diaphragm and the static plate changes

→ The resulting change in capacitance is measured an AC bridge or an oscillator circuit.

Characteristics



Advantages → highly sensitive,
→ requires small power

Disadvantages → requires insulation
→ non linear characteristics
→ sensitive to temp. change

Applications → measures linear & non linear displacement
→ measures force and pressure.

* Thermoelectric Transducer – Thermocouples

→ A transducer that converts thermal energy into electric energy

→ A thermocouple is a type of thermoelectric transducer.

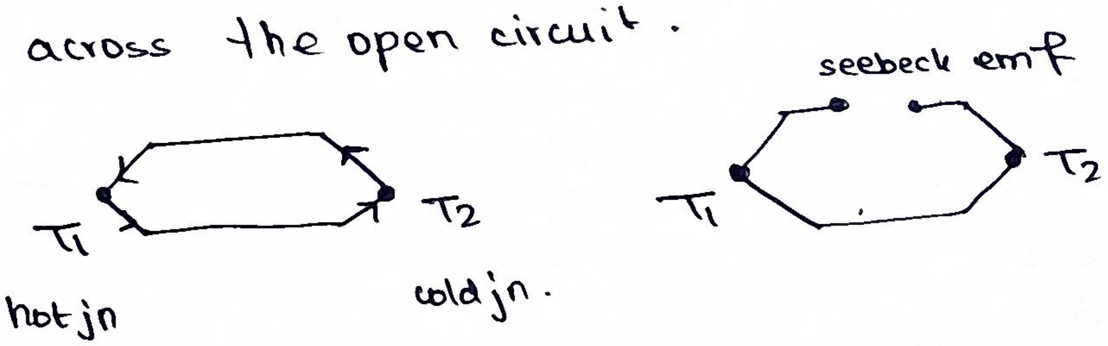
→ A change in temperature arising from two dissimilar metals is converted into electrical energy

→ This can be used to measure temperature.

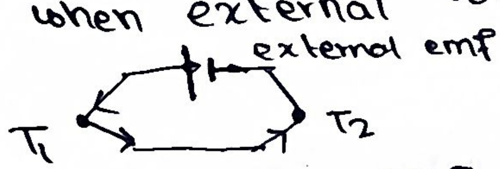
Principle: Whenever two metals are connected together maintained at diff. temps, a thermoelectric potential is generated across the two free ends of the metal, This emf is a function of junction temperature.

Thermoelectric Phenomena governing Thermocouple behaviour

① Seebeck Effect : If 2 wires of diff metals are joined to form a closed circuit with two junctions, and if those jns are maintained at diff. temps, an electric current would flow through the closed circuit. It also states that an emf, called the Seebeck emf which is directly proportional to the change in temperature, appears across the open circuit.



② Peltier Effect : If 2 wires of dissimilar metals form 2 jns, when external voltage is connected, current flows through the jn.



③ Thompson Effect : When current flows through a copper conductor w/ a thermal gradient across its length, heat is released at a jn, where current & heat flow are in the same direction, and heat is absorbed where heat & current are in the opp. dir.

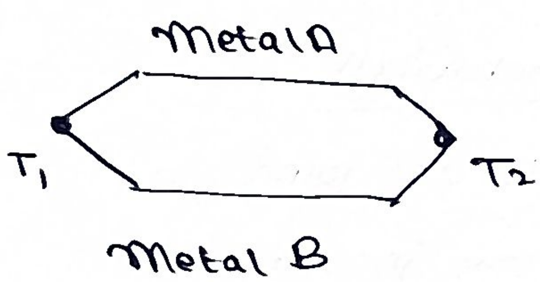
Construction of a Thermocouple

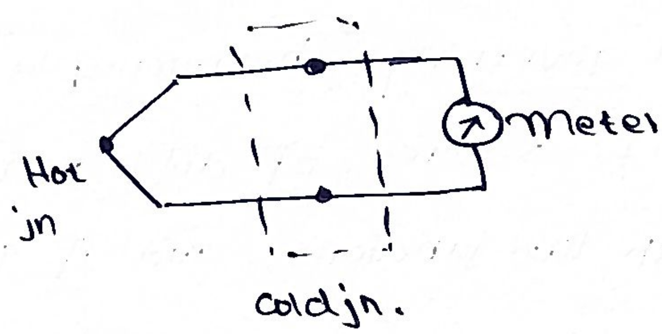
→ Two dissimilar metals are joined to form 2 junctions to form a thermocouple

→ T_2 is kept at a constant reference temperature, called the cold jn or the reference jn.

→ Temperature is measured at T_1, called the hot jn. or the measuring jn.

→ A temp. diff. between T_1 & T_2 generates an emf that is proportional to the temp gradient, which is measured using a meter





Advantages

→ wide temp. range measurement

→ cheap

→ good reproducibility

→ good response, good accuracy

Disadvantages

→ non linear characteristics

→ signal amplification is needed

Applications

→ used in low temp. & cryogenic applications

→ testing temps in diff. process plants., chem production, food industries etc.

* Piezoelectric Transducer

→ Piezoelectric transducer = an electro acoustic transducer, converts physical quantity into an electric voltage.

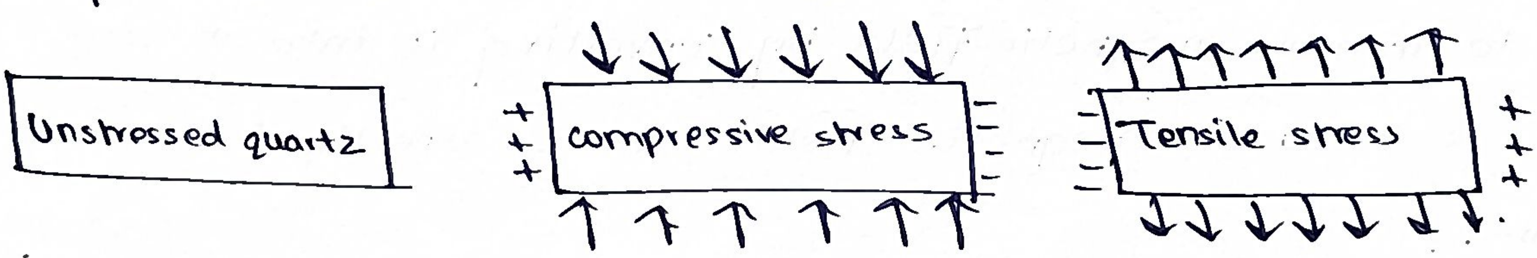
→ Uses piezoelectric materials, such materials induce voltage when pressure or stress is applied on it. Such materials are called electro - resistive elements.

piezoelectric materials = quartz, Rochelle's salt

quartz → natural; Rochelle's salt → man-made

<u>Working Principle</u> - Piezoelectric effect : When a mechanical stress or force is applied on a quartz crystal, electrical charge / emf is induced on the surface of the quartz crystal. The emf produced is directly proportional to the magnitude of applied pressure / force.

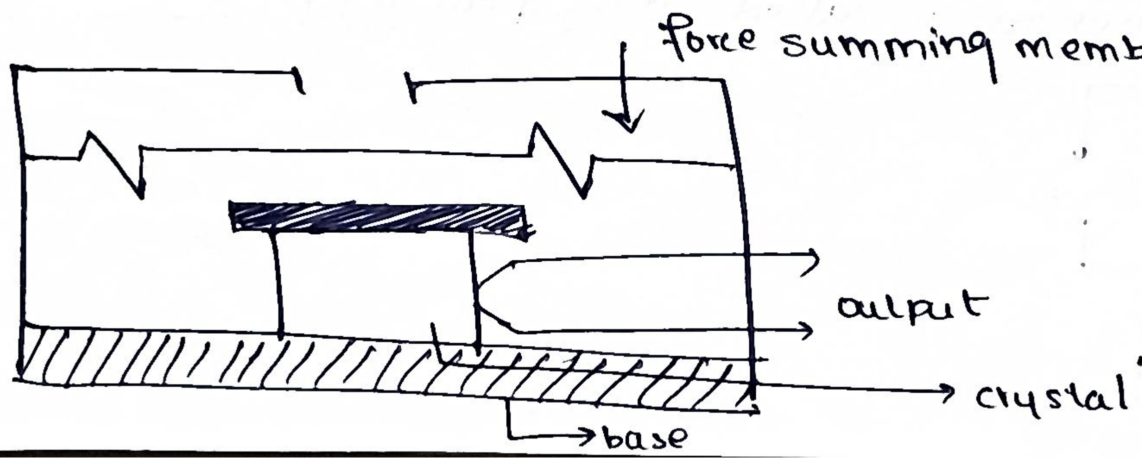
Note that when compressive stress is applied, charges are induced in one way, while tensile stress causes a reversal in polarity.



<u>Construction</u> : → a crystal is placed between a solid base and a force - summing member.

→ external pressure is applied to the top of the crystal.

→ a proportional emf is induced.



Advantages: → no external power source needed

→ easy to handle (small dimensions)

→ high frequency response

Disadvantages: → not suitable to measure static conditions

→ temperature sensitive

→ low output

Applications : → stabilizing electronic oscillators

→ measure surface roughness

→ spark ignition (cigarette lighters)

→ ultrasound imaging

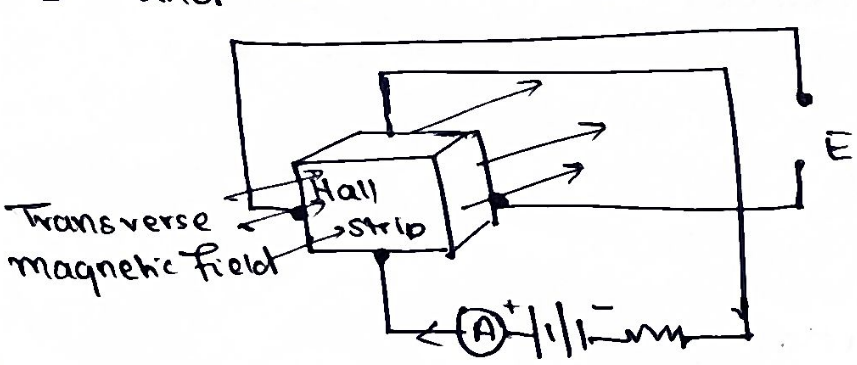
* Hall Effect Transducers

→ used to measure magnetic field by converting it into an emf

→ This is because magnetic field cannot directly be measured.

→ The transducer converts the magnetic field

Principle : → When a transverse magnetic field B is applied to a thin strip of metal / semiconductor, carrying a current I, an electric field E is induced in the direction perpendicular to both B and I. This phenomenon is called the Hall Effect.



Under equilibrium conditions:

Electric field intensity $= qE$ — (1)

Magnetic Force : Bqv_d — (2) $\quad v_d$ = drift velocity

(1) = (2)

$$qE = Bqv_d \quad -(3)$$

Electric field intensity due to Hall Effect : $E = \dfrac{V_H}{d}$

d: distance between 2 surfaces of metal / semiconductor

V_H : Hall voltage between the 2 surfaces

Current density $= J = \rho v_d = \dfrac{I}{A} = \dfrac{I}{wd}$ (w = width of specimen)

$\rho v_d \rightarrow (4)$, $\dfrac{I}{wd} \rightarrow (5)$

$$V_H = Ed$$

From (3), $V_H = Bv_d d$

From (4) $V_H = Bd \cdot \dfrac{J}{\rho}$

From (5) $V_H = Bd \cdot \dfrac{I}{wd\rho}$

$$V_H = \frac{BI}{\rho w}$$

$$\boxed{V_H = \frac{BI}{\rho w} = R_H \cdot \frac{BI}{w}}$$

where R_H = Hall coefficient $(1/\rho)$

gives sign of charge carriers & their concentration

Working of Hall Effect Transducers in different Applications

1. Magnetic to Electric Transducer:

→ used to measure magnetic field strength

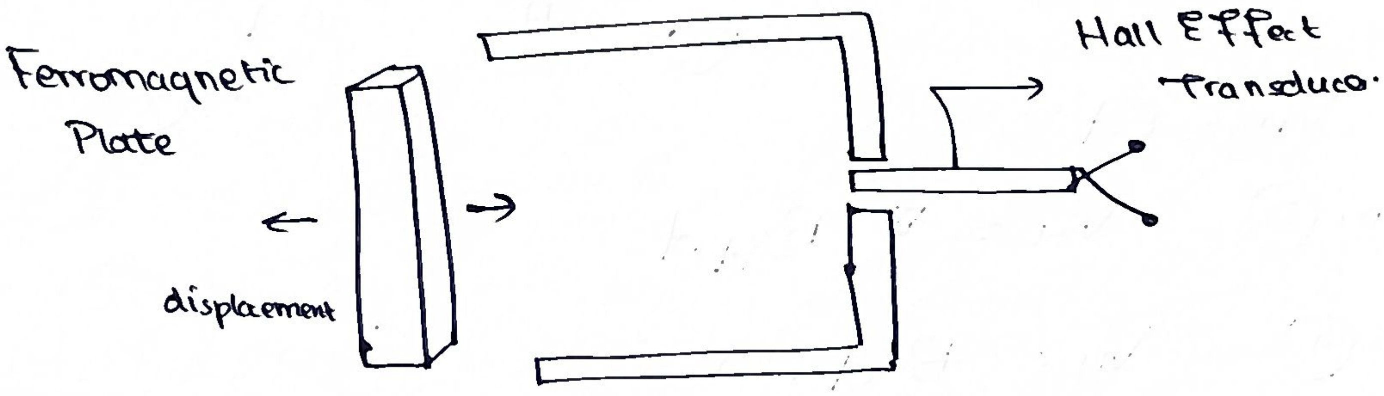
→ a ~~current carrying~~ semiconductor is placed in the magnetic field to be measured

→ a voltage develops across the end of the semiconductor chips

→ this voltage is directly proportional to magnetic field density

2. Measurement of displacement:

→ used to measure the displacement of a structural element



→ A Hall Effect Transducer is placed between the poles of a permanent magnet.

→ The magnetic field strength across the hall effect element changes by changing the position of the ferromagnetic field

3. Measurement of Current:

→ to measure current w/o any physical connection between the circuit & meter.

→ current is applied across the conductor → a magnetic field is produced

→ mag. field $\propto$ current, mag field induces emf, emf $\propto$ mag. field

The emf is then measured.

4. Measurement of Power:

Similar to (3) $P \propto V$, find emf, then power

Advantages

→ high speed operation
→ Repeatability
→ Can measure large current

Disadvantages

→ affected by external mag. field
→ Temp. drift is large
→ Large offset voltage

Applications

→ mag. flux to electric transducer
→ Automotive fuel-level indicator
→ Spacecraft propulsion
→ Measure power, current & displacement

* Sensors

→ a device that detects and responds to electrical or optical signals

→ It converts a physical parameter into a signal which can be measured

Criteria to choose a sensor

(i) accuracy
(ii) range
(iii) resolution (to be able to detect even the smallest increments)
(iv) cost
(v) repeatability

Resistive and Capacitive Sensors

→ A resistive sensor measures change in electrical resistance caused by the application of force

→ A capacitive sensor measures the change in capacitance

Resistive and capacitive sensors are used in touch sensors, proximity sensors etc.

* Touch Sensors → A touch sensor detects touch or near proximity.

→ They can replace mechanical switches and buttons, as they do not have moving parts and hence, are more convenient

→ They also reduce overall cost of the system, and make the system look more appealing and contemporary.

Working Principle

→ Touch sensors are sensitive to touch, force or pressure.

→ The working is similar to that of a simple switch.

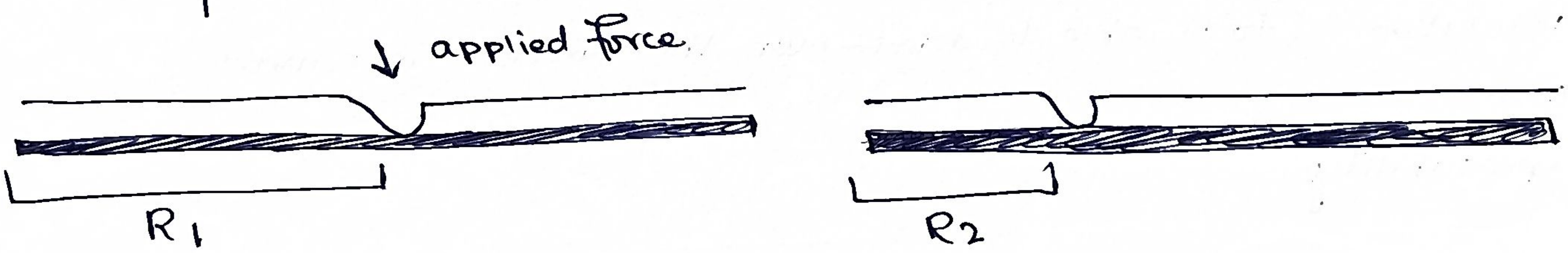
→ When there is contact with the surface of the touch sensor, the circuit is closed inside the sensor and there is a flow of current.

→ When the contact is released, the circuit is opened and no current flows.

Resistive Touch Sensors

→ Such touch sensors act as a variable resistor as per the location where it is touched.

→ A resistive sensor measures changes in electrical resistance caused by the application of force.



→ Such touch sensors have : (i) a fully conductive substance

(ii) insulated spacing material like foam or plastic

(iii) partially conductive material

→ The partially conductive material opposes the flow of current.

→ The main principle of a linear position sensor is that the current flow is more opposed, when the length of the material is more.

→ Resistance is varied by changing the point of contact.

→ Software is interfaced w/ touch sensors. The memory of the software stores the last touched position.

Applications : → Fluid level sensors
→ Appliances
→ Consumer Electronics

Capacitive Touch Sensors : → used in portable devices like MP3 players, mobile phones

→ has good durability, robustness, attractive product design

Principle: Capacitance is given by the expression $C = \frac{A\varepsilon_0}{d}$

Capacitive sensors measure changes in capacitance to trigger certain actions.

Construction : → Capacitors have 2 plates. In a touch sensor

(i) one plate is an electrode
(ii) the other plate is represented by 2 objects :
a) the environment of the sensor electrode, that forms a parasitic capacitor C_0
b) a conductive object, like a human finger, which forms touch capacitor C_T.

→ The sensor electrode is connected to a measurement circuit and C is periodically measured.
→ C increases if the sensor is touched, the measurement circuit

detects this change and converts it into a trigger signal.

→ C increases when A is large & d is small.

→ In capacitive touch sensors, a conductive material is enough to trigger a load and does not require any force.

→ This means that the risk of unintended triggers is high, and the sensor may be triggered by water, skin oils or sweat.

→ To distinguish between intented & false touches, additional sensing pads & algorithms are used.

Magnetic sensors

→ a sensor used to notice disturbances as well as changes within a magnetic field such as strength, direction & flux.

There are 2 types of sensors :

(i) to calculate total magnetic field

(ii) to calculate the vector components of the field

Working Principle : → the magnetic sensor has a chip with a magneto-resistive component, used to detect a magnetic vector.

→ changes in the magnetic vector result in a change in the resistance value of the magneto-resistive component.

→ This sensor comes into use as a compass, for navigation.

Types :(i) Low field sensors → detect low values of mag. field
→ used in nuclear & medical fields

(ii) Earth field sensors :→ ranges from 1μG to 1 G can be sensed
→ uses Earth's mag. field for navigation purposes

(iii) Bias Magnet Field Sensors → to sense mag. fields > 10G
→ used in hall devices, reed switches

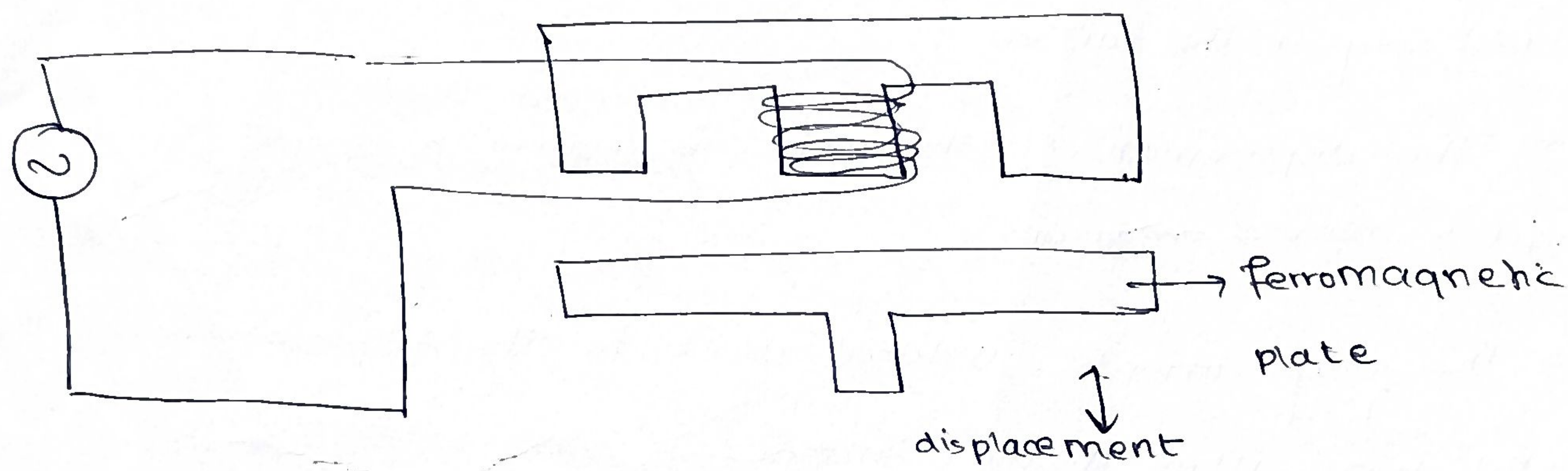
Magnetic Sensors (additional info)

→ Magnetic sensors use the concept of inductance, reluctance and eddy currents to indicate the value of a measured quantity.

→ Some types of magnetic sensors are:

① Inductive sensors

→ movement / displacement is translated into a change in mutual inductance. Consider the following set-up



~~→ displacement induces an emf~~

→ The E-shaped body is excited with an alternating voltage.

→ The displacement of the ferromagnetic plate changes the flux and thereby the current flowing through the coil.

→ $I = \frac{V}{R} = \frac{V}{L\omega}$

② Variable Reluctance Sensors

→ a coil is wound around a permanent magnet.

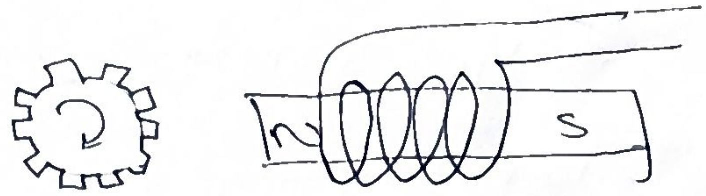
→ Such a setup is used to measure rotational velocity

→ a ferromagnetic gear is placed next to the sensor

→ as the teeth of the gearwheel moves towards / away from the sensor, there is a change in mag flux.

→ A voltage that is proportional to the rate of change of flux. is set up.

→ The o/p is a sequence of +ve and -ve pulses whose frequency is proportional to the rotational velocity.



③ Eddy current sensors

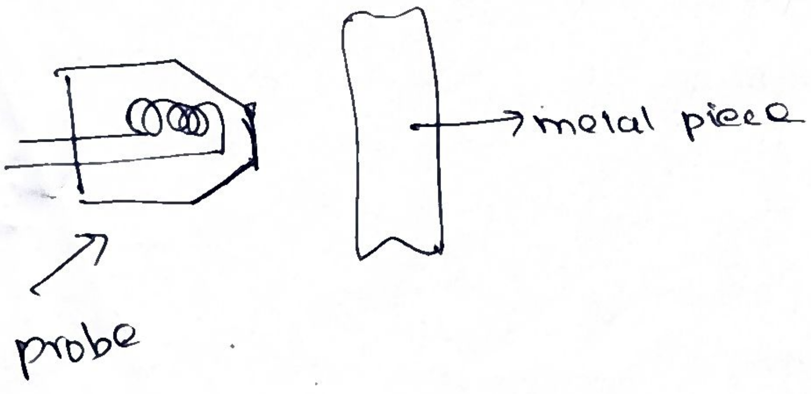
→ has a probe containing a coil

→ it is excited at a high frequency ⇒ eddy currents are induced only at the surface

→ The displacement of the probe is relative to a moving metal target is ~~moved~~ measured

→ The eddy currents induced w.r.t to the displacement of the metal strip alter the inductance.

→ This change in inductance can be translated into a dc voltage output, that is proportional to the distance between the probe and target.



computers

→ Xerox machines

→ light fixtures that turn on automatically

→ photographic flashes

* Ultrasonic Sensors

→ an instrument that measures the distance to an object using ultrasonic sound waves.

→ An ultrasonic sensor uses a transducer to send and receive ultrasonic pulses, that relay info about an object's proximity.

Working → The sensor sends out sound waves at a frequency > than the range of human hearing.

→ The transducer of the sensor acts as a microphone to send & receive ultrasonic sounds.

→ The sensor determines the distance to the target by measuring time lapses between the sending and receiving of the ultrasonic pulse.

Uses : → can be used to detect clear objects

→ can detect objects irrespective of color, surface or material.

→ used where other optical techniques fail.

* Microsensors

→ are millimeter size 2D & 3D structures that have smaller size improved performance, better reliability and lower production costs than other forms of sensors

→ used to measure temp, pressure, force, acceleration

→ made from silicon semiconductor material, also made of plastics, ceramics

→ Fabrication done using sensor growing & polishing, laser etching etc.

→ Microsensors also have forms like thin diaphragms, cantilever beams & bridges

→ small size is beneficial, but also leads to problems

for eg. microsensors have very low capacitance, o/p signals are prone to noise contamination.

→ o/p signals are also of very low magnitude & need to be amplified

<u>Working</u> : Many microsensors work based on a chip based technology called MEMS - called Micro Electro Mechanic System

→ The sensor has a suspended mass in between a pair of capacitive plates.

→ When a tilt is applied to the sensor, the suspended mass creates a diff. in electric potential.

→ This diff is measured as a change in capacitance.

→ Thus, parameters like torque, acceleration etc. can be measured

<u>Nuclear sensors</u>

→ radiation is transmitted between a source and a detector through a medium

Materials used: Caesium - 137 = Gamma Ray source
Sodium Iodide = gamma ray detector

Latter materials gives an o/p proportional to the incident radiation.

→ This technique can be used to measure the level of liquid in storage tanks