Unit - II

Inductive Sensors

Principle

utilizes principle that physical quantity, such as motion, to be measured can be made to vary the inductance of a coil, maintaining a relation between the two. This variation of inductance can be measured by ac bridge circuits, or can be made to produce a voltage if it is magnetically coupled to another coil carrying flux or voltage.

If a magnetostrictive core material is used, force and pressure can change the permeability which can be measured as a change in inductance of a coil around the core.

Methods of achieving variation in inductance

(i) by changing reluctance of magnetic path

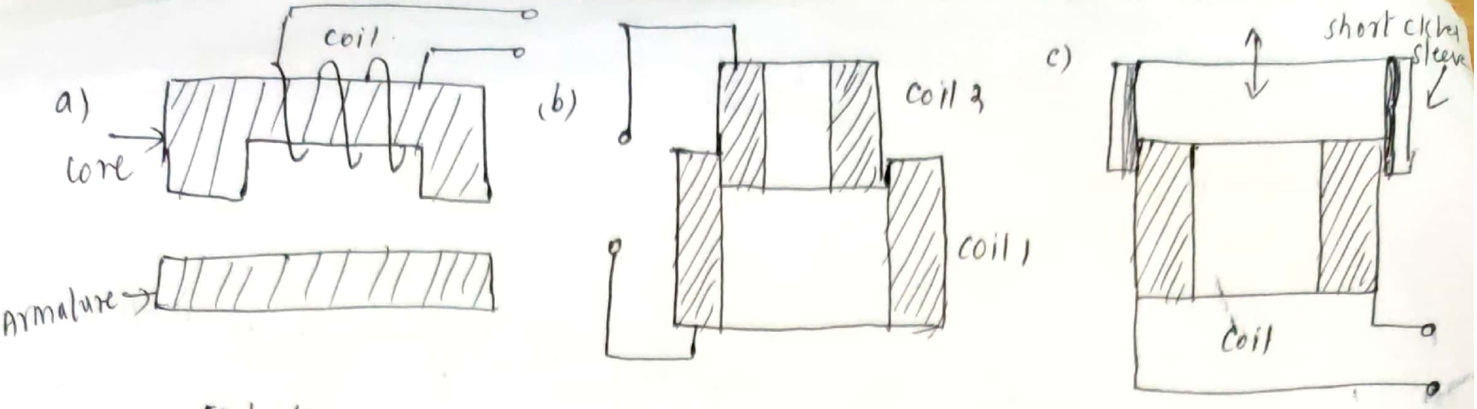
(ii) by coupling 2 or more elements.

- This technique works by

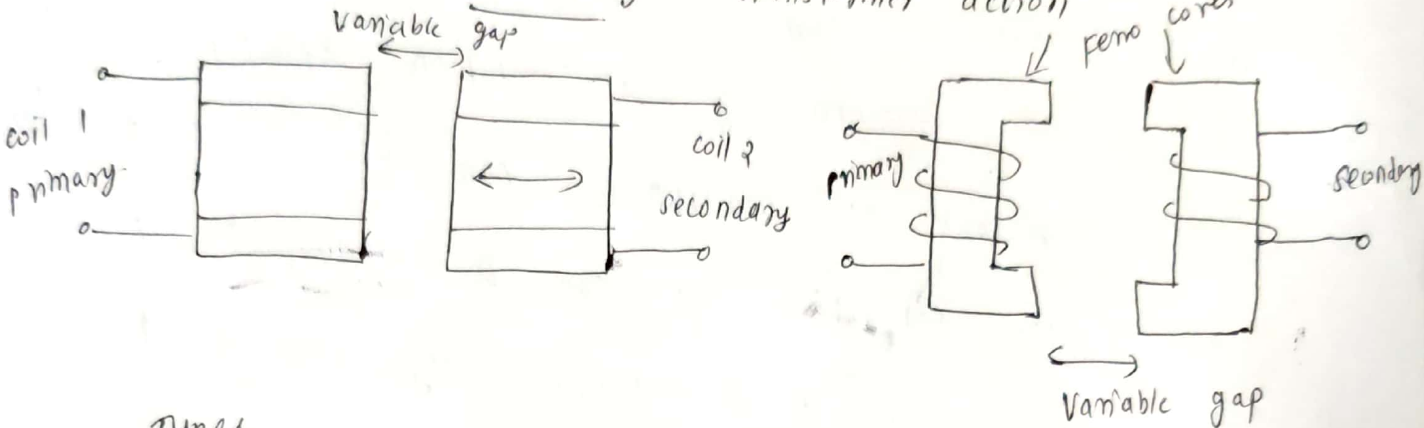
a) change of mutual inductance

b) change of eddy current when one element is short-circuited sleeve.

c) Transformer action.



Inductive sensors using transformer action



Types

(1) Electromagnetic type - Bilateral in operation with electrical and mechanical input / output relationship

(2) Magnetostrictive type.

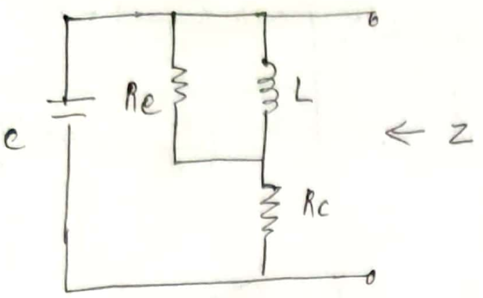
The coil is wound on a metal (iron) core or an air core.

In variable reluctance type, core is also a ferromagnetic material as armature. This is most widely used because i) most sensitive one

(ii) least affected by external fields as the air gap is least

(iii) requires less no. of turns than in air core design for same value of inductance.

Eq. ckt of a ferro magnetic coil



If a coil has n turns, a current I and the core length l, field strength H is,

$$H = \frac{nI}{l} \quad (A/m) \quad \text{—— (1)}$$

μ - permeability of core material

μ_r - relative permeability

μ_0 - permeability of free space or vacuum ($4\pi \times 10^{-7}$ H/m)

a - core section area

L - self inductance of coil

$$L = \frac{n\phi}{I} = n\frac{Ba}{I} = \frac{n\mu Ha}{I} \quad \text{—— (2)}$$

B - Tesla or wb/m²

ϕ - wb

sub. expr. of H,

$$L = \frac{\mu n^2 a}{l} \quad \text{(Henries)} \quad \text{—— (3)}$$

copper resistance R_c is easily calculated if the coil wire diameter d and copper resistivity ρ are known,

$$R_c = \frac{4\rho n l_t}{\pi d^2} \quad \text{—— (4)}$$

l_t - avg length per turn of the coil

coil dissipation factor $D_c = \frac{R_c}{\omega L}$ —— (5) decreases with increasing freq

For reducing eddy loss or core loss, the depth of penetration of eddy current, $d_p = \sqrt{\frac{\rho_e}{\pi\mu f}}$ —— (6)

ρ_e - resistivity of core material $f = \frac{\omega}{2\pi}$

Eddy loss resistance, $R_e = \left(\frac{2 d_p \omega L}{t_1}\right)\left[\frac{\cosh\left(\frac{t_1}{d_p}\right) - \cos\left(\frac{t_1}{d_p}\right)}{\sinh\left(\frac{t_1}{d_p}\right) - \sin\left(\frac{t_1}{d_p}\right)}\right]$ — (7)

(6) and (7) are valid only for low freq.

when $\rho_t = (t_1/d_p) \leq 2$.

(7) upon simplification, $R_e = \frac{6 \omega L}{(t_1/d_p)^2} = \frac{12 \rho_e a n^2}{(l\, t_1)^2}$ — (8)

Eddy loss dissipation factor is defined by,

$$D_e = \frac{\omega L}{R_e}$$

Magnetic material undergoes hysteresis and this causes dissipation or loss. The area within the hysteresis curve is given by,

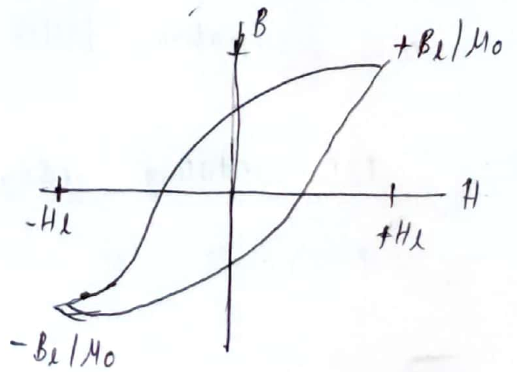
$$A_h = \int B \, dH$$

H - magnetic field strength

B - Magnetic induction.

Total hysteresis loss for a core of cross-sectional area a, length l,

$$P_h = \left(\frac{16\pi}{3}\right) a l \, \mu_r H_l^3 f \times 10^{-7} \text{ (watts)}.$$



Impedance calculation

$$Z = \frac{R + j\omega L}{(1 - \omega^2 LC) + j\omega RC}.$$

on rationalization,

$$Z = \frac{R}{(1-\omega^2 LC)^2 + (\omega^2 LC/\phi)^2} + j\omega L \frac{(1-\omega^2 LC) - (\omega^2 LC/\phi^2)}{(1-\omega^2 LC)^2 + (\omega^2 LC/\phi)^2}$$

where $\phi = L/R$

For good inductor with $\phi^2 >> 1$

$$Z = \frac{R}{(1-\omega^2 LC)^2} + \frac{j\omega L}{(1-\omega^2 LC)} = R_{eq} + j\omega L_{eq}$$

$$Q_{eq} = \frac{\omega L(1-\omega^2 LC)}{R}$$

Sensitivity and Linearity of the sensor

For a small air gap l_g and effective permeability of the core μ, inductance is given by,

$$L = \left[\frac{\mu_s}{\left\{1 + \left(\frac{l_g}{l}\right)\mu_s\right\}}\right]\left(\frac{n^2 a}{l}\right) \text{ (Henries)}$$

since n and a are constants, using

$$K_l = 4\pi \times 10^{-7} n^2 a$$

Now $$L = \frac{K_l}{\left(l_g + \frac{l}{\mu_s}\right)}$$

from which assuming $l >> l_g$, for any increase or decrease in gap l_g and δl_g,

$$\frac{dL}{L} = \frac{dl_g}{\left(l_g \pm dl_g + \frac{l}{\mu_s}\right)}$$

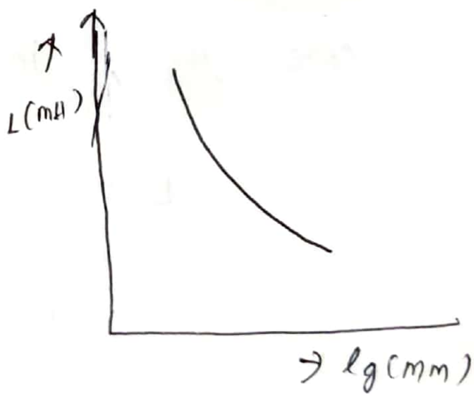
$$= \frac{dl_g/l_g}{1+\frac{1}{l_g \mu_s}} \cdot \frac{1}{1 \pm \frac{(dl_g/l_g)}{\{1 + l/(l_g \mu_s)\}}}$$

$$\frac{dL}{L} = \frac{dl_g/l_g}{1+\frac{l}{l_g \mu_s}} \left[1 \pm \frac{dl_g/l_g}{1+\frac{l}{l_g\mu_s}} + \left(\frac{dl_g/l_g}{1+\frac{l}{l_g\mu_s}} \right)^2 \pm \cdots \right]$$

There is a linear variation b/w L and l_g,

sensitivity $S_{l_g}^{L} = \frac{dL/L}{dl_g/l_g}$

$$S_{l_g}^{L} = \frac{1}{1 + l/(l_g \mu_s)}$$



Presence of higher order term increases non linearity.

It is possible to have 2 coils in the var. inductance transducer such that inductance in one coil increases and the other decreases. This can be adapted in plunger type design.

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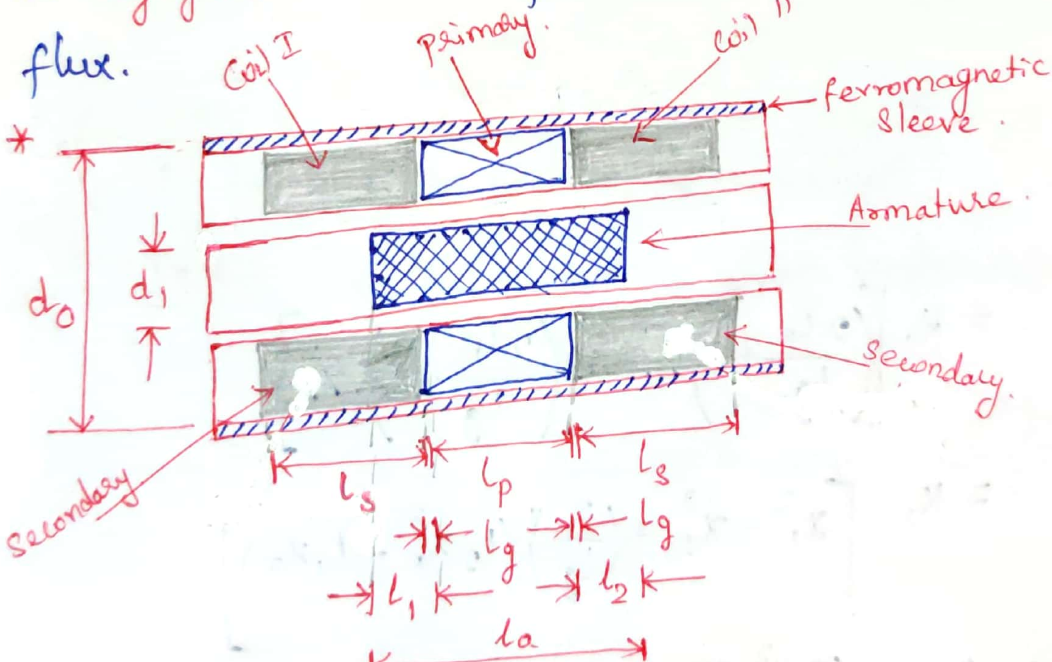
Transformer type Transducer

* Transformer type transducer – formed like a transformer with a variable iron core coupling between pair of coils.
* The transducer used most is linear variable differential transformer (LVDT)
* A plunger type armature moves into a pair of secondary coils and primary coil, secondaries being connected in differential mode.
* The properties of the magnetic circuit and flux leakages are considered.
* It is assumed that the mmf in ferromagnetic/iron is negligible when compared to air paths of the leakage flux.
*



* Assuming I_p (rms) – current in primary
n_p – no. of turns in primary
n_s – no. of turns in secondary

* The flux densities around the primary coil linking the secondaries is given as

$$\frac{B_{L_1}}{B_{L_2}} = \frac{-2l_2+l_g}{2l_1+l_g}$$

* Negative Sign – because of direction.

* Induced emfs in coil I & coil II for a supply freq ω

$$e_1 = \frac{2\pi^2 \omega I_p n_p n_s}{\ln(d_o/d_i)} \cdot \frac{2l_2+l_g}{l_s l_a} x_1^2 \times 10^{-7}$$

$$e_2 = \frac{2\pi^2 \omega I_p n_p n_s}{\ln(d_o/d_i)} \cdot \frac{2l_1+l_g}{l_s l_a} x_2^2 \times 10^{-7}$$

* x_1, x_2 → penetration of armature from nominal position beyond the primary coil length including the air gap.

* Differential Voltage.

$$e_o = e_1 \sim e_2 = \left[\frac{2\pi^2 \omega I_p n_p n_s}{\ln(d_o/d_i)} \times 10^{-7}\right] \frac{l_g}{l_s l_a}\left[\left(\frac{2l_2}{l_g}+1\right)x_1^2 - \left(\frac{2l_1}{l_g}+1\right)x_2^2\right]$$

$$= K_1\left[\left(\frac{2l_2}{l_g}+1\right)x_1^2 - \left(\frac{2l_1}{l_g}+1\right)x_2^2\right]$$

$$= K_1\left[x_1^2 - x_2^2 + \left(\frac{2}{l_g}\right)(l_2 x_1^2 - l_1 x_2^2)\right]$$

where $K_1 = \left(\frac{2\pi^2 \omega I_p n_p n_s}{\ln(d_o/d_i)}\right) \frac{l_g}{l_s l_a} \times 10^{-7}$

* In normal condition if $l_a = l_s$ then

$$e_o = K_1\left(1+\frac{2l}{l_g}\right)(x_1^2 - x_2^2)$$

* Linearization is done by making

$$(1/2)(x_1 + x_2) = x_0 \quad \text{constant}$$

$$(1/2)(x_1 - x_2) = x \quad \text{weighted differential movement.}$$

then

$$e_o = \left[4K_1\left(1+\frac{2l}{l_g}\right)x_0\right]x = K_2 x$$

* Rearrange & convert e_o in the form

$$e_o = K_3 x (1 - K_4 x^2)$$

where

$$K_3 = \frac{8\omega I_p n_p n_s (l_p + 2l_g + x_0)x_0 \times 10^{-7}}{\ln(d_o/d_i)\, l_s l_a}$$

$$K_4 = \frac{1}{(l_p + 2l_g + x_0)x_0}$$

* nonlinearity in the output is given by the relation

$$\eta_1 = K_4 x^2$$

* Assuming $2l_g << l_p$, even at maximum movement armature remains within the secondary coils. The simplified output relation is

$$\boxed{e_o = \left(\frac{8\pi^2 \omega I_p n_p n_s}{\ln(d_o/d_i)}\right)\frac{2l_p}{3l_s}\left(1 - \frac{x^2}{2l_p^2}\right) \times 10^{-7}}$$

Electromagnetic Transducer :-

* Bilateral double function type transducer that has
  → Mechanical input - electrical output
  → electrical input - mechanical output . construction .

* electromechanical energy converters - are governed by .
  (i) faraday's law of electrodynamics
  (ii) piezoelectric effect as postulated by curie .

* can be used as both generators and sensors and termed as Senders and Receivers . respectively .

* System Consists of a inductance coil wound on a ferromagnetic core and a variable gap provides the variation in output .

* Permanent Magnet is used as core .

* n - no of coil turns L - Inductance .
  ϕ - coil flux

Then $$L = \frac{\mu_0 a n^2}{d} \quad (H)$$

for cross section of coil a, the effective gap d is given by

$$d = x_1 + \left(\frac{\mu_1}{\mu_2}\right) l_1$$

μ_1 & μ_2 - relative permeabilities of air & core material

* μ_1 is unity & the magnetic energy stored in coil is

$$\mathcal{E}_m = \frac{1}{2}\frac{(n\phi)^2}{L}$$ if a current $I = \frac{n\phi}{L}$ flows in the coil

the stored energy is obtained by.

$$E_m = \frac{1}{2}\frac{\mu_0 I^2 a n^2}{d} \Rightarrow \frac{1}{2}LI^2$$

* The Energy develops a force f across the gap d as

$$f = \frac{\partial E_m}{\partial d} = \frac{1}{2}\frac{LI^2}{d}. \quad (N)$$

* If the bias magnetizing current or its equivalent is given by. I_0 and a sinusoidal current of amplitude of i and freq ω with $i << I_0$ energize the core then

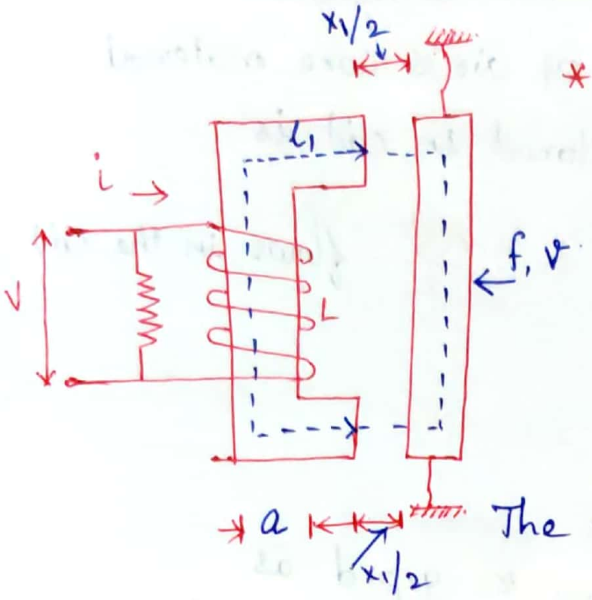
$$f = \left(\frac{L}{2d}\right)\left(I_0^2 + 2I_0 i\right)$$

if the coil resistance is negligible then, $i = \frac{V}{j\omega L}$ and the varying force term is $f_v = \frac{LI_0}{d} \cdot i$

$$f_v = \frac{I_0 V}{j\omega d}.$$

* The force f. is associated with a velocity v & analogy of electrical parameters.

$$f_m = Z_m V$$ where Z_m - mechanical Impedance.



* m - mass
k - stiffness.
δ - damping of transducer then

$$Z_m = \delta + j\left(\omega_m - \frac{k}{\omega}\right).$$

$$f_t = Z_m v\left(\frac{I_0 V}{j\omega d}\right).$$

The relation between voltage V, velocity v & X

Current i can be $V = \alpha_{vV} v + \alpha_{iv} i$

where α_{iv} - electrical impedance.

α_{vV} complex transducer co. eff.

* The receiver has voltage to force ratio.

$$\frac{V}{f} = \frac{I_0/j\omega d}{\left(\frac{I_0^2}{\omega^2 d^2}\right) + \left[\delta + j\left(\omega_m - \frac{k}{\omega}\right)\right]\left(\frac{1}{R} + \frac{1}{R_0} + \frac{1}{j\omega L}\right)}$$

where R_0 - load indicator Resistance → large.

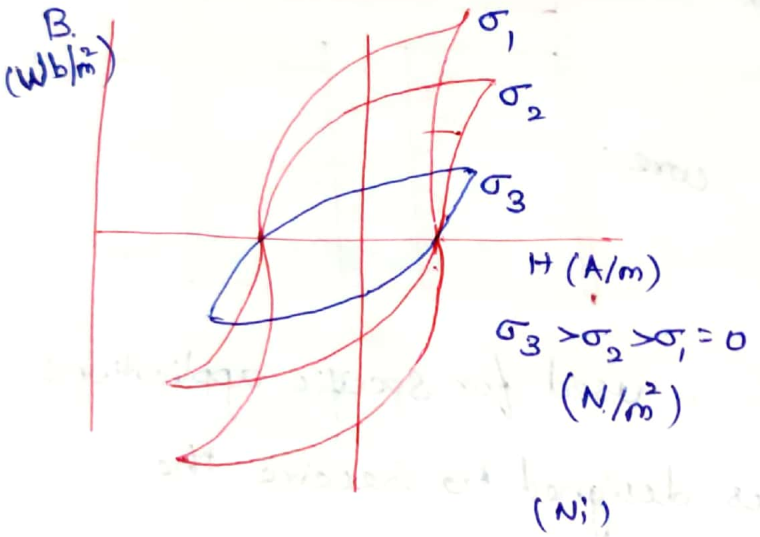
R - coil resistance.

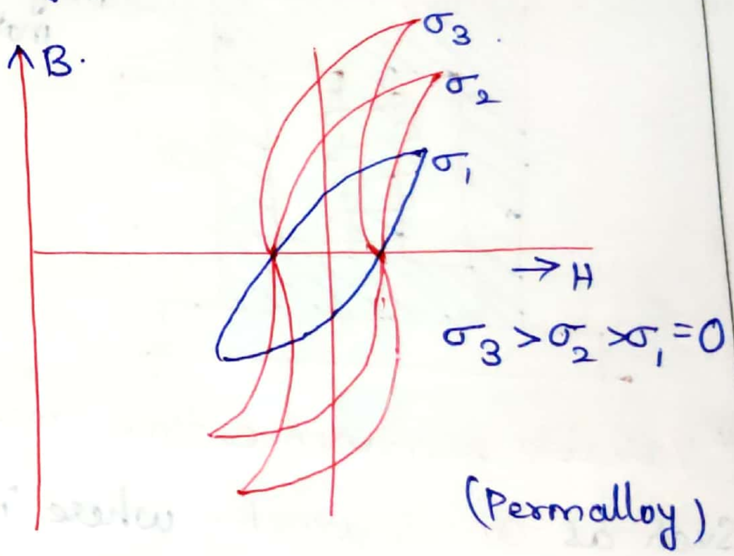
* Characteristics transfer matrix.

$$\begin{bmatrix} f \\ V \end{bmatrix} = \begin{bmatrix} \frac{I_0}{j\omega d} & 0 \\ \frac{-d}{LI_0} & \frac{j\omega d}{I_0} \end{bmatrix} \begin{bmatrix} V \\ i \end{bmatrix}$$

Magnetostrictive Transducer :-

* Not popular - as transducer because of limitations w.r.t materials.
* The output depends on some other variables also other than input quantity.
* Two different types
  - Variable permeability type.
  - Variable remanence type.
* magnetostrictive material - pure Nickel has a slope of hysteresis curve that decreases with increasing tension σ.



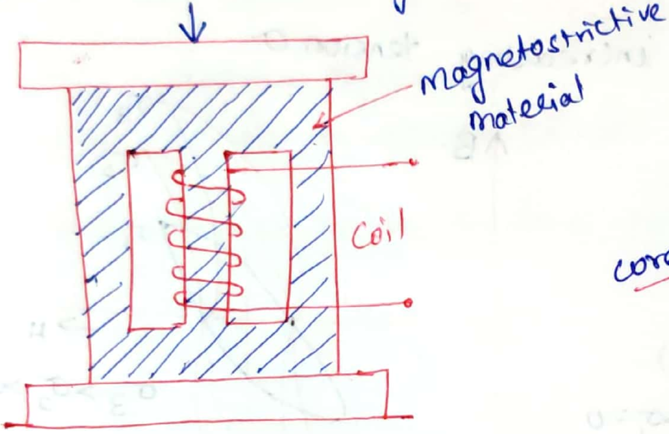


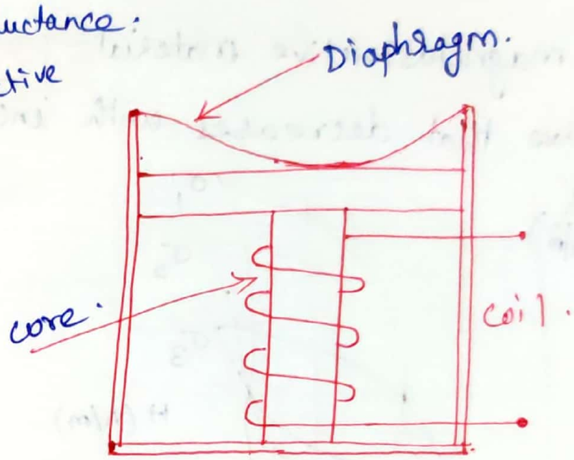
* The change alerts the value of the permability μ, which also decreases with stress & Inductance of a coil wound on it.
* with $\uparrow$ing tension the remanence magnetism B_0 $\downarrow$es.
* Ni is seen to be a materal with negative magnetostriction.

* Ni-Fe alloy known as permalloy such as Ni 68, Ni 45
* ↑ing tension – ↑es B_0 as also permeability.

* The coil inductance changes with change of force → ~~with~~ which changes permeability of core.

* The coil Inductance is measured thro' bridge with current & freq, the coil also changes the Inductance.





* Variable remanence type transducer used for specific applications such as accelerometer where it is designed to receive the stress thro' a metal diaphragm

* The open circuit voltage is propotional to rate of change of remanence magnetism

$$B_0 - B_{0i} = K_1 \sigma$$

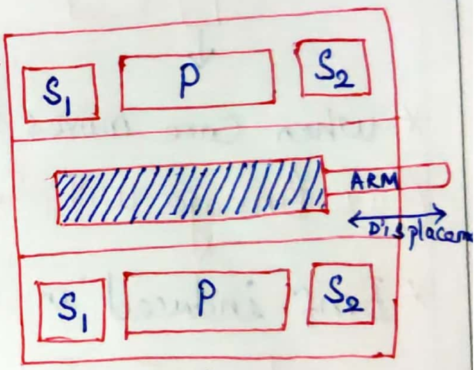
& for n turns of coil the output voltage V is

$$V = n K_2 \frac{dB_0}{dt}$$ $k_i \rightarrow$ constants.

Linear Variable Differential Transformer (LVDT)

* Working principle is same as Transformer (mutual Induction)
* output in secondary coil is in the form of differential Voltage.
* Inductive Transducer - to measure Speed or position of an object
* Converts displacement into Electrical signal. - Electromechanical Inductive Transducer.
* physical quantities Such as Force, weight, Tension, pressure etc are converted to displacement by primary & then LVDT Measures it in terms of Electrical signal.

Construction :-



* LVDT consists of one primary winding (P) & two secondary winding (S_1 & S_2) mounted on cylindrical form
* Secondary windings (S_1 & S_2) has equal no. of turns and is identical on either side of primary winding → so that the net output will be difference of voltage of both secondary voltage.

Working Principle :-

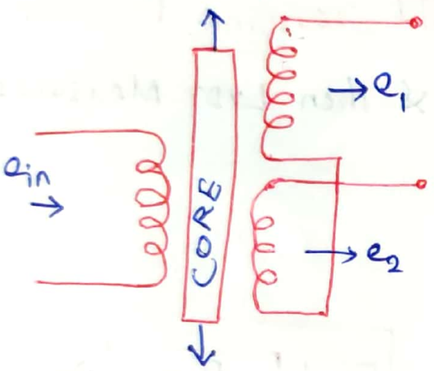
* LVDT is based on mutual Induction principle.
* when AC excitation is applied to primary winding - magnetic field

is produced

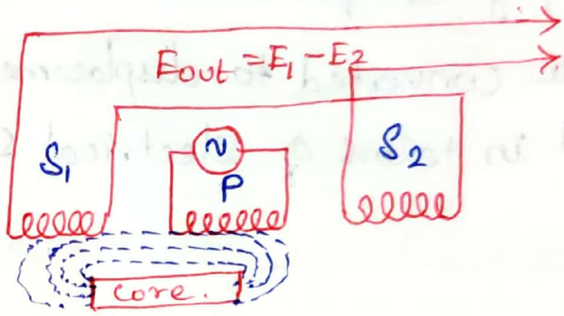
* magnetic field induces mutual current in secondary windings
* E_1 & E_2 are the induced voltages in S_1 & S_2
* Both the secondary windings are connected in series opposition. So the o/p will be the difference of both induced voltages

(E_1 & E_2) $E_0 = E_1 - E_2$.

Case:1 core moves towards Left (S_1)



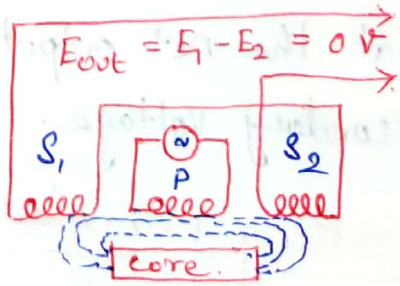
$e_{out} = e_1 - e_1$



* when core moves towards Left S_1 secondary winding, then flux linkage with S_1 is high compared to S_2
* Emf induced in S_1 is more than emf in S_2. $E_1 > E_2$.

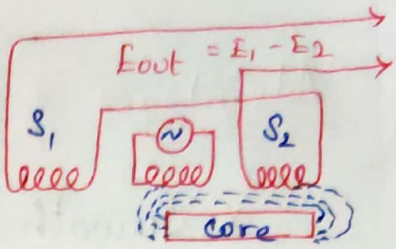
$E_0 = E_1 - E_2$ and the net output will be positive.

Case:2 Core at Null position:-

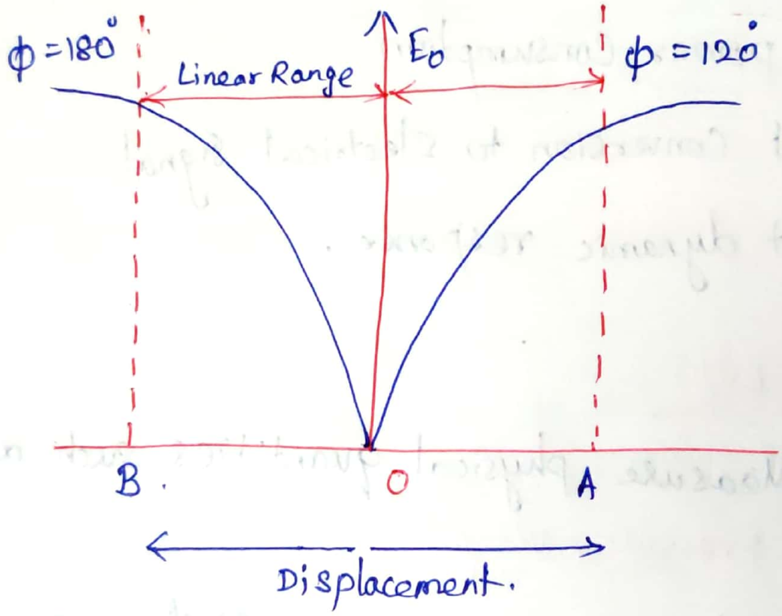


* core at null position → flux linkage with both the secondary windings is same.
* Emf induced in both windings E_1 & E_2 is same.
* output voltage $E_0 = E_1 - E_2 = 0$ → no displacement of core.

Case 3: Core moves towards S_2 (Right)



* Core of LVDT moves towards S_2 secondary winding → flux linkage with S_2 more compared to S_1
* Emf induced S_2 is more than the induced emf in S_1 so $E_2 > E_1$
* Net differential voltage $E_0 = E_1 - E_2$ → negative
* Output voltage in phase opposition – 180° out of phase with primary.



Disadvantages of LVDT :-

* Sensitive to stray magnetic field → extra setup required to protect it from stray magnetic field.
* gets affected by vibrations and temperature variations.

Advantages of LVDT :-

* Smooth & wide range of operation
* High sensitivity.
* Low Hysteresis Losses.
* Low Friction Losses.
* Rugged operation
* Low power Consumption
* Direct conversion to electrical signal
* Fast dynamic response.

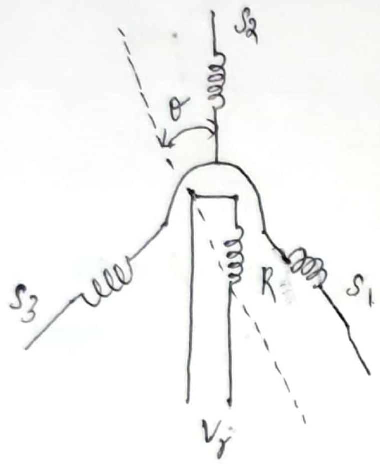
Applications of LVDT :-

* Used to Measure physical quantities such as Force, Tension, pressure, weight.
* Used in industries as a servo mechanism.
* Used in Industrial Automation, Aircraft, Turbine, Satellite, hydraulics.

Synchros

- Electromechanical devices which produce an o/p voltage depending on angular position of rotor and ~~rotor~~ it is different from DC generator.

2 types
(i) Torque type
(ii) control type.

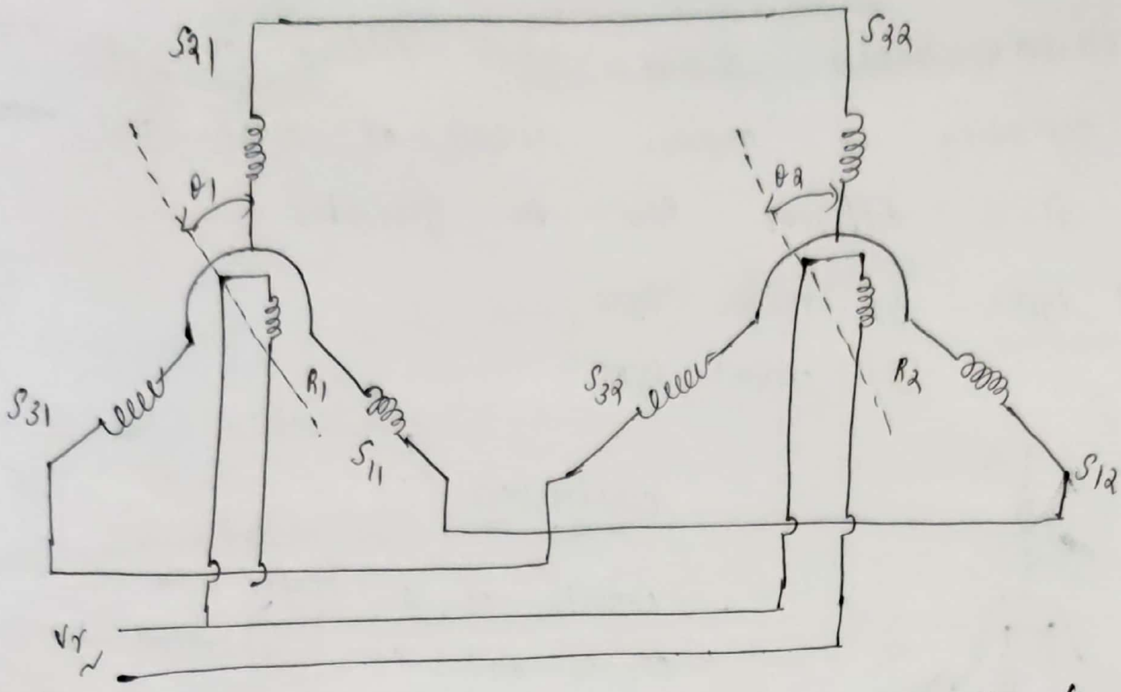


Construction

- consists of a stator with 3 windings S1, S2 and S3 seperated by 120° in space and a rotor R, which is supplied with an ac voltage.

Torque type sensor

- 2 units are coupled.
- A rotation of the rotor R, by an angle θ changes the voltages induced into stator windings S11, S21 and S31 in magnitude and phase.
- These windings are electrically connected to S12, S22 and S32, same voltages with phases as in those of windings of stator 1 produce a field so that R2 if not oriented as R1, would receive a torque and rotation till it attains same rotational position as that of R1.
- Rotated angle produced can be measured using scale.



For a single synchro unit with rotor angle θ for an i/p sinusoidal voltage, $V_r = V_{r0} \sin \omega t$, the voltages induced in windings S1, S2 and S3 are,

$$V_{S1} = K V_{r0} \sin \omega t \cos(\theta + 120^\circ)$$

$$V_{S2} = K V_{r0} \sin \omega t \cos \theta$$

$$V_{S3} = K V_{r0} \sin \omega t \cos(\theta + 240^\circ)$$

K - constant - ratio of rotor to stator turns.

Line voltages are given by,

$$V_{S12} = K\sqrt{3}\, V_{r0} \sin \omega t \sin(\theta + 240^\circ)$$

$$V_{S23} = K\sqrt{3}\, V_{r0} \sin \omega t \sin(\theta + 120^\circ)$$

$$V_{S31} = K\sqrt{3}\, V_{r0} \sin \omega t \sin \theta$$

If $\theta = 0^\circ$, $V_{S2} = K V_{r0} \sin \omega t$ and $V_{S31} = 0$, then this position of rotor is marked as zero position or reference position.

Torque type sensors

Assume that $\theta_1 = \theta_2$, then there is no compensation current because of any unbalanced terminal voltages.

If $\theta_1 \neq \theta_2$, a torque would be produced on the receiver synchro rotor till equality is achieved.

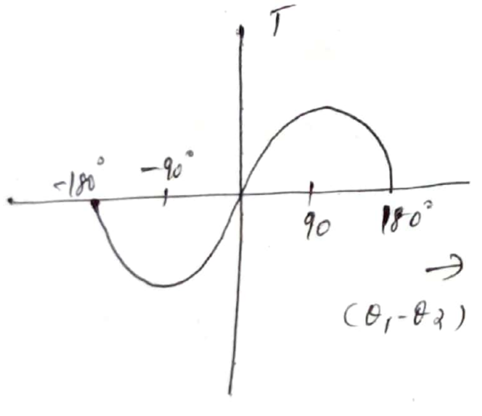
Torque is approx. sinusoidal in form.

$$T \simeq K_t \sin(\theta_1 - \theta_2)$$

Max. torque occurs at $\theta_1 - \theta_2 = 90°$.

For $\theta_2 \rightarrow \theta_1$ ie; when $\theta_1 - \theta_2$ is small, torque curve is approx. linear.

The sensors are designed with resolution of $5 \times 10^{-4} - 10^{-2}$ Nm/deg with an angular error of $\pm 0.5 - \pm 1.5$. Rotational speed of 300 rpm.



- If the torque becomes large, and if error is to be kept small, the receiver synchro rotor is not connected to the line, instead an error voltage is taken out from rotor R_2, amplified and a servo motor is driven to bring R_2 in position.

Applications

(1) Error detection
(2) Adding & subtracting rotary angles
(3) Remote position sensing
(4) Antenna position Detector
(5) Navy equipments.
(6) Underwater detection system
(7) Weapon system.

Piezo electric sensor

Elements – crystals of certain classes are said to exhibit piezo electric effect which essentially means electric polarization produced by mechanical strain in the crystals.

- The effect is reversible ie; a strain may be produced in the crystal by electrically polarizing it using an external source.

- A piezo electric crystal is represented by a set of 3 cartesian coordinates so that the polarization P can be represented in vector form as

$$P = P_{x}x + P_{y}y + P_{z}z.$$

p_{xx}, p_{yy} and p_{zz} – stresses

axial – σ

shear – χ

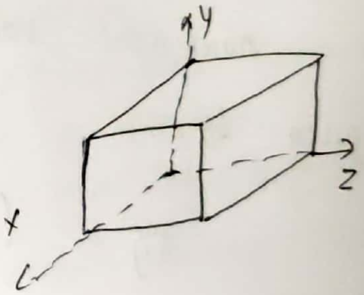
Constants of crystal – d

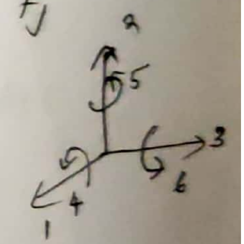
With reference to crystal axes X-Y-Z, we obtain

$$\begin{bmatrix} p_{xx} \\ p_{yy} \\ p_{zz} \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \chi_{yz} \\ \chi_{zx} \\ \chi_{xy} \end{bmatrix}$$

The d-constants are defined as,

$$d_{ij} = \frac{\text{charge generated in direction } i}{\text{force applied in direction } j} = \frac{\phi_i}{f_j}$$





The reverse effect d-coefficients are defined as,

$$d_{ij} = \frac{\text{strain in direction } i}{\text{field applied in direc. } j}$$

$$= \frac{\xi_i}{E_j} \quad \text{expressed as } (m/m)/(v/m)$$

d-coefficient – It is defined as the voltage gradient or field in the crystal per unit pressure imparted to it.

Maintaining direction as before, it can be shown that,

$$g_{ij} = \frac{q_i}{\varepsilon_d f_j} = \frac{d_{ij}}{\varepsilon_d}$$

3rd coefficient, h-coefficient is defined as voltage gradient per unit strain which appears to be reciprocal of d_{ij}

- h coefficient is easily obtained by g coefficient by multiplying it with young's modulus in the appropriate direction.

$$E = \frac{\sigma}{\varepsilon}$$

- crystals are characterised by coupling coefficient which is a measure of efficiency of the crystal as energy converter.

- The numerical value of coupling coefficient is given by,

$$K_{ij} = (d_{ij} \; h_{ij})^{1/2}$$

The value of d_{11} for quartz is 2.3×10^{-12} coulombs/N.

Dielectric const $= 4.06 \times 10^{-11}$ F/m

$$g_{11} = 56 \times 10^{-3} \; (V/m) \; (N/m^2).$$

Piezo electric materials

Materials are divided into 2 groups

(i) occurs naturally such as quartz, Rochelle salt, Tourmaline

ii) those produced synthetically such as lithium sulphate or ammonium dihydrogen phosphate and Barium titanate.

- Material properties that are relevant to piezoelectric sensors are.
  - (i) dielectric constant
  - (ii) d- coefficients (xx)
  - (iii) resistivity
  - iv) young's modulus
  - (v) humidity range
  - (vi) temperature range
  - vii) density

- Rochelle salt is used in microphones because of high sensitivity and permitivity

- Tourmaline has poor sensitivity and is costly.
  Adv - It has longest temp. range
  - shows large volume expander mode capability ie; with high force in all 3 directions, it gives a large d-value in x-x direction.

- Lithium sulphate is good in volume expander mode but ammonium dihydrogen phosphate is extensively used for acceleration and pressure sensing purposes.

- Barium titanate - polycrystalline ceramic has high ϵ_d and with induced polarization, it is very conveniently used in many transducers.

Ultrasonic sensors

- When an electric field is applied to the crystal it changes its shape. This property is utilized in generating acoustic or ultrasound wave.

- For transmitting such wave, good medium and interfacing should be chosen, Barium titanate material is chosen, but requires prior polarization.

- It consists of randomly oriented tiny piezoelectric crystallites which are properly oriented mostly by DC polling field of several thousand volts/cm and material is cooled through Curie temp.

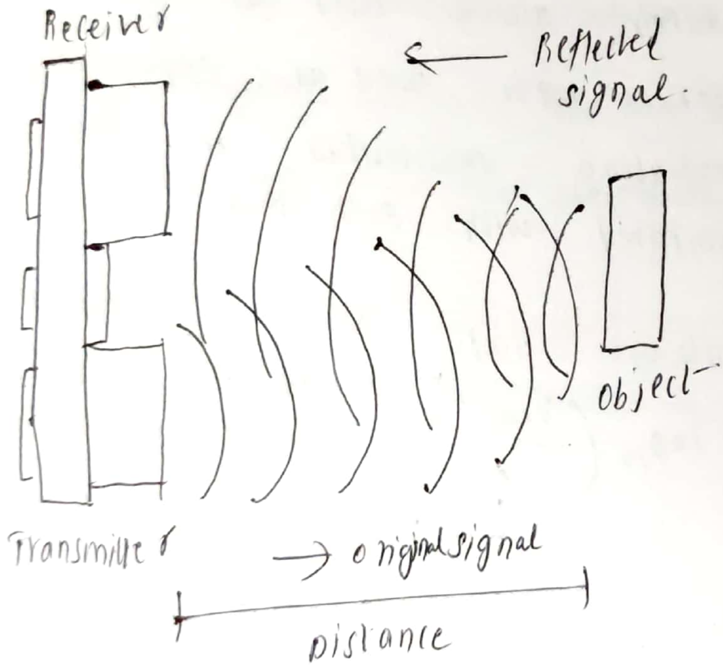
- It consists of randomly oriented tiny piezoelectric crystallites which are properly oriented mostly by DC polling field of several thousand volts/cm.

- A strong piezoelectric effect has been observed in compounds such as $PbZrO_3 - PbTiO_3$ called. PZT materials.

- piezoelectric transducers can generate continuous wave ultrasound which is used in SONAR.

- Ultrasonic piezo crystals operate in the range of 0.5 - 10 MHZ.

- They are directly attached to the transmitting medium or are separated by a small distance which is filled with coupling materials of suitable acoustic properties
- Typical couplants at low temp are water, grease and petrojelly and for high temp. special polymer couplants may be used.
- For continuous wave operation, sensor is energized by a tuned osc while for pulsed application 'relaxation' osc are used to charge a capacitor which is discharged across sensor.



Calculation of sensitivity

sensitivity is defined as the ratio of an o/p quantity to an i/p quantity.

- For an ultrasonic transducer characterised as a 2 port n/w, there are mechanical quantities of force and velocity (F, V) at the acoustic port and quantities of voltage and current (V, I) at electrical port.

- Since an ultrasonic transducer can be used as either transmitter or a receiver, there are a variety of sensitivities that can be defined from these quantities.

- Sensitivity is measured based on reciprocity and pulse-echo methods. One transducer always used as receiving. Two another transducers were used as sequentially transmitters. The radiating sensitivities of these transducers were compared with each other.

- Sensitivity in logarithmic units can be written as,

$$S = 20 \log_{10} \left(\frac{V_{out}}{V_{in}} \right)$$

V_{out} → amplitude of volt. recorded at receiving transducer

V_{in} → volt. applied to transmitting transducer

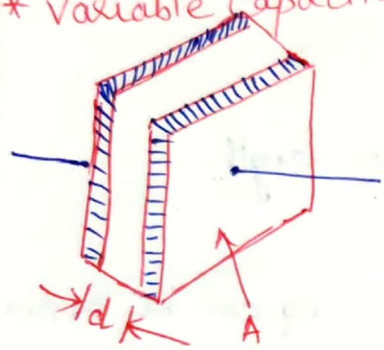
SRMIST, RAMAPURAM

Department of Electronics and Communication Engineering

Course Code: 18ECO133T Subject Name: Sensors and Transducers

Capacitive Sensors :-

* Capacitive Sensors - Two parallel metal plates separated by air called dielectric material
* Typical capacitor - distance between two plates fixed
* variable capacitor - distance between two plates variable.



$$\text{Capacitance}(C) = \frac{\varepsilon A}{d} = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

ε_0 - Permitivity of free space.

ε_r - relative Dielectric constant

A - Area of plates

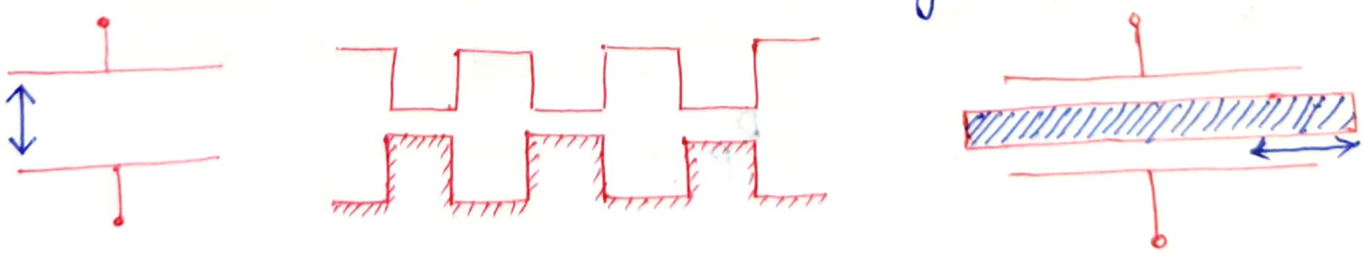
d - Distance b/w plates.

* Three types of Capacitive sensors are (variable capacitance)

(a) * by varying distance b/w two or more parallel electrodes

(b) * by varying area b/w electrodes - Serrated electrodes electrodes with teeth - one mo

(c) * by varying dielectric constant of the material → material has to move b/w pair of electrodes & change in capacitance



(a) (b) (c)

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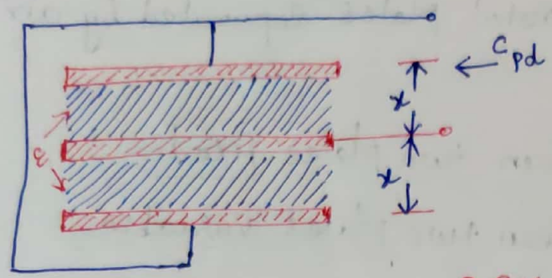
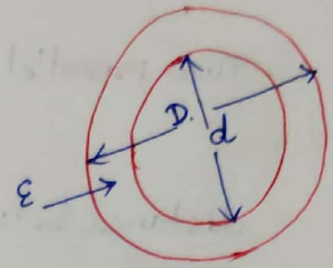
* The parallel plate capacitive sensors is often used in a differential form with three plates





$$C_{pd} = \frac{2\varepsilon \alpha}{x}$$

$$C_c = \frac{2\pi \varepsilon l}{\ln(D/d)}$$ l - cylinder length

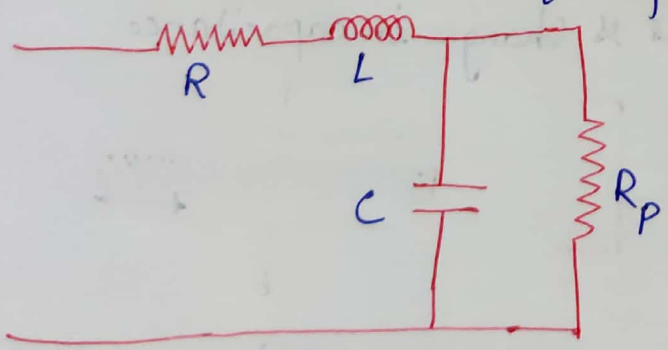
for very thin layer of dielectric material the above eq can be approx.

$$C_{ca} = \frac{\pi \varepsilon l (D+d)}{D-d}$$

If a parallel plate pair has number of layers as dielectric const then

$$C_{pi} = \frac{\alpha}{\sum x_i/\varepsilon_i}$$

* The equivalent circuit of capacitive transducer

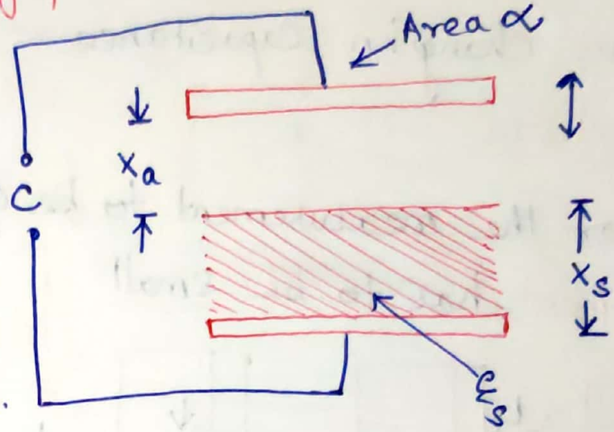


* Parallel plate Capacitive sensor
* Serrated plate Capacitive sensor
* Variable permittivity or Variable Thickness Dielectric capacitive sensor.

Parallel plate capacitive sensor :-

* Consider a pair of parallel plates with a solid dielectric of thickness x_s and an air gap x_0 then the capacitance c is

$$C = \frac{\alpha}{\left(\frac{x_a}{\varepsilon_a}\right)+\left(\frac{x_s}{\varepsilon_s}\right)}$$



* with plate moving a decrease in x_a increases c & vice versa.

$$C \pm \partial c = \frac{\alpha}{\left(\frac{x_a \mp \partial x_a}{\varepsilon_a} + \frac{x_s}{\varepsilon_s}\right)}$$

Consider $\varepsilon_a \approx 1$

$$\mp \frac{\partial c}{c} = \pm \left(\frac{\partial x_a}{x_a + x_s}\right) \left[\frac{1}{\frac{1+\frac{x_s}{x_a \varepsilon_s}}{1+\frac{x_s}{x_a}} \mp \frac{\partial x_a}{x_a + x_s}}\right]$$

* The quantity $(1+x_s/x_a\varepsilon_s)/(1+x_s/x_a)$ – Important factor in determining the value of $\frac{\partial c}{c}$ and represented as $1/\beta$

β - Sensitivity factor - also responsible for nonlinearity

$$\mp \frac{\partial c}{c} = \pm \left(\frac{\partial x_a}{x_a}\right)\left(\frac{\beta}{1+\lambda}\right)\left[1 \pm \left[\frac{\delta x_a}{x_a}\ \frac{\beta}{1+\lambda}\right] + \left[\frac{\delta x_a}{x_a}\ \frac{\beta}{1+\lambda}\right]^2 \pm \cdots\right]$$

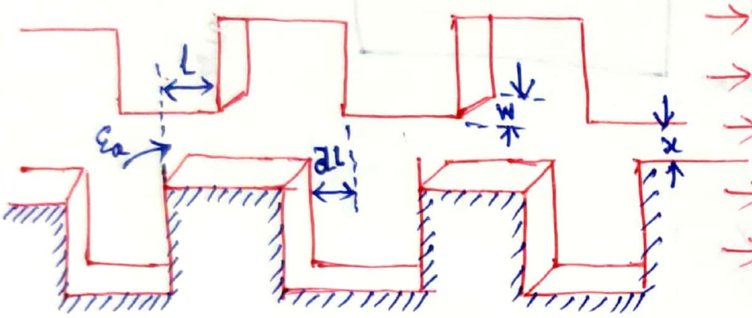
β - function of $x_a \cdot x_s$ and ε_s, the plots of β Vs λ with ε_s as a Parameter → shows that with increasing λ, β increases with ε_s.

* capacitors have fringing effects – Provided with guard ring surrounding the plate of capacitor → with same potential.

Serrated plate Capacitive Sensor :-

* Contains a pair of flat, serrated plates, one is fixed in position, the other with a small relative movement – that shows change in capacitance – used to measure small angular variations.

* for the measurement to be of any significance, the relative movement has to be small.



→ active tooth length – l
→ air gap as – x
→ tooth width – w
→ no. of teeth pair – n
→ air permitivity – ε_a. then.

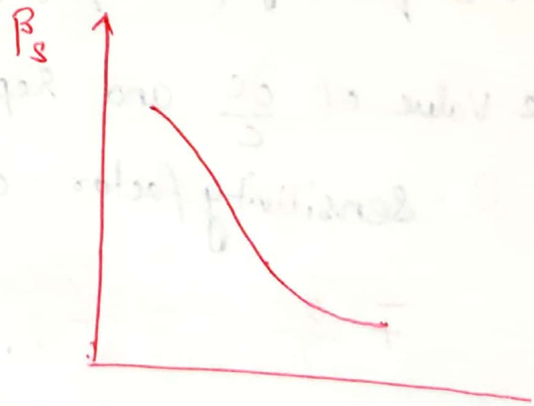
Capacitance $C = \dfrac{\varepsilon_a l w n}{x}$

* small relative movement ∂l of the moving plate $\dfrac{\partial c}{c} = \dfrac{\partial l}{l}$

* Assume no fringing effect the leakage can be allowed. therfor.

$$\frac{\partial c}{c} = \frac{\partial l}{l}\left[\frac{1}{1+\frac{kx}{l}}\right]$$

sensitivity factor

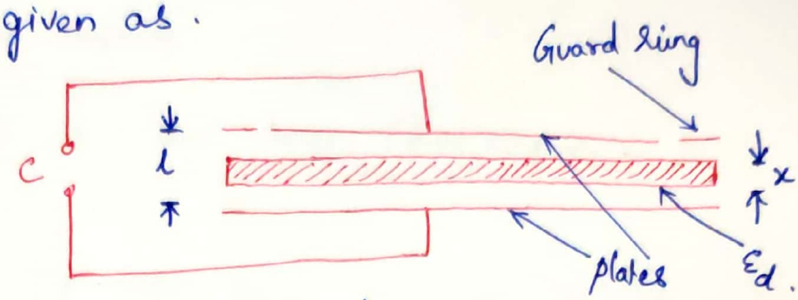


* β_s is actually the ratio of non leakage to total flux → x/l.

Variable Permitivity or Variable Thickness Dielectric Capacitive Sensor.

* with plate effective area α and other dimensions, the Capacitance 'C' is given as.

$$C = \frac{\alpha}{l - x + \frac{x}{\varepsilon_d}}$$



* The normalized change in capacitance is

$$\left(\frac{\partial c}{c}\right)_{\varepsilon_d} = \pm \frac{\partial \varepsilon_d}{\varepsilon_d} \frac{1/[1+\varepsilon_d(l-x)/x]}{1 \pm \frac{1}{1+x/(\varepsilon_d(l-x))} \cdot \frac{\partial \varepsilon_d}{\partial \varepsilon_d}}$$

sensitivity factor.

η_n

* if $\eta_n \frac{\partial \varepsilon_d}{\varepsilon_d}$ is small, then first order approximation.

$$\left[\frac{\partial c}{c}\right]_{\varepsilon_d} = \frac{\partial \varepsilon_d}{\varepsilon_d} \cdot \frac{1}{1+\varepsilon_d(l-x)/x} \left[1 \mp \frac{\partial \varepsilon_d/\varepsilon_d}{1 + x/\varepsilon_d(l-x)}\right]$$

* Instead of variation in ε_d there may be variation in x, so

$$\left(\frac{\partial c}{c}\right)_x = \frac{\partial x}{x} \frac{\frac{\varepsilon_d - 1}{1+\varepsilon_d(l-x)/x}}{1 \mp \frac{\varepsilon_d - 1}{1+\varepsilon_d(l-x)/x} \cdot \frac{dx}{x}}$$

is very $\ll 1$ then

$$\left[\frac{\partial c}{c}\right]_x = \frac{\partial x}{x} \frac{\varepsilon_d - 1}{1+\varepsilon_d(l-x)/x} \left[1 + \frac{\varepsilon_d - 1}{1+\varepsilon_d(l-x)/x} \cdot \frac{dx}{x}\right]$$

* Sensitivity factor & nonlinearity factor are identical.

Microphone

- It is a type of acoustic transducer or sensor
- It is an acoustic - to - electrical transducer or sensor that converts sound in air into an electrical signal.

Microphone freq response

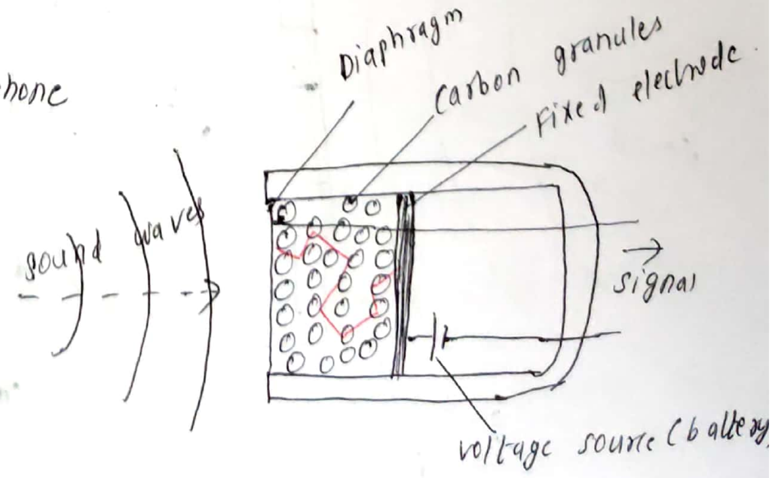
- It has ability to hear tones (high and low) across audible spectrum
- Human ear can hear range of 20 Hz to 20,000 HZ

overview of microphone

Diaphragm – It is a part of microphone which receives the vibration from sound waves.

- Thickness and material of diaphragm are changed depending on sound waves to be received.
- The electrical circuit is used to change these detected vibrations into an electrical signal that images the sound with an o/p voltage or current.

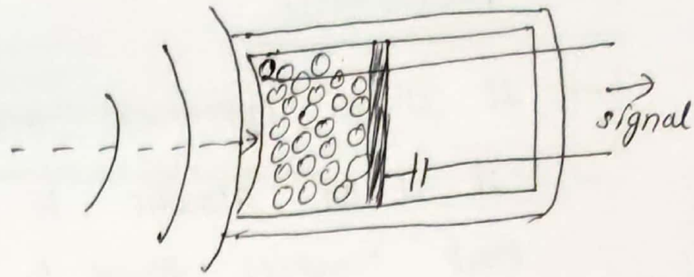
carbon Button microphone



Diaphragm – Thin metal plate

- Diaphragm is connected to a button full of carbon granules.

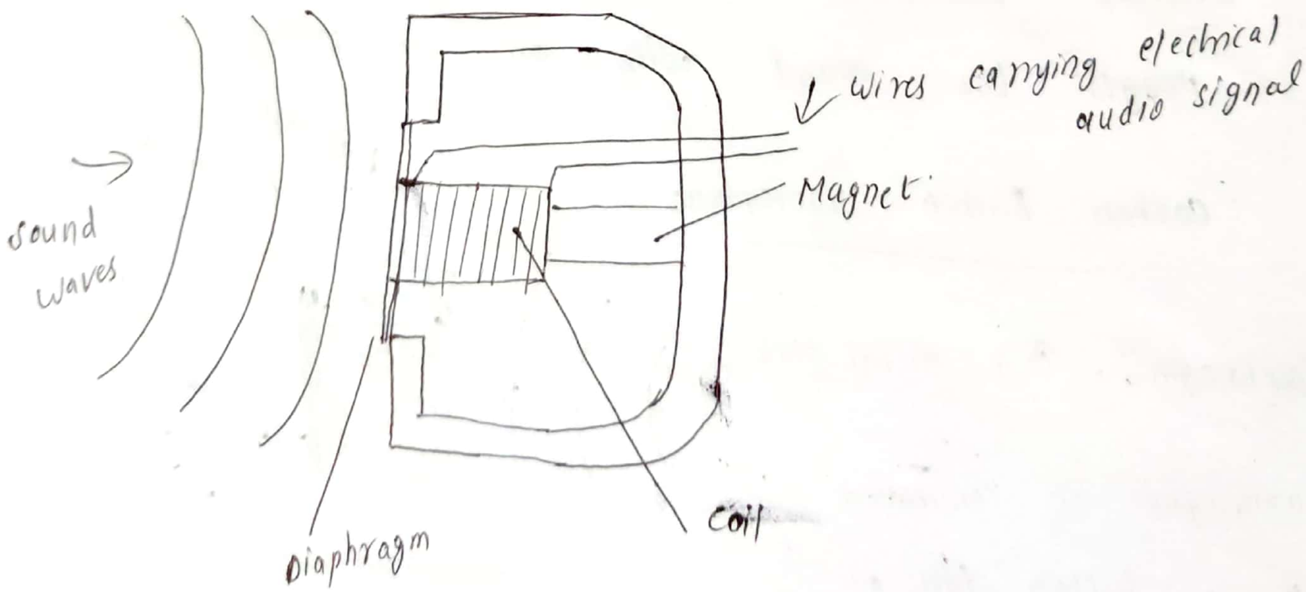
- sound pressure changes the resistance through the button by compressing / decompressing the carbon by pushing the diaphragm



Dynamic microphones

Diaphragm - plastic

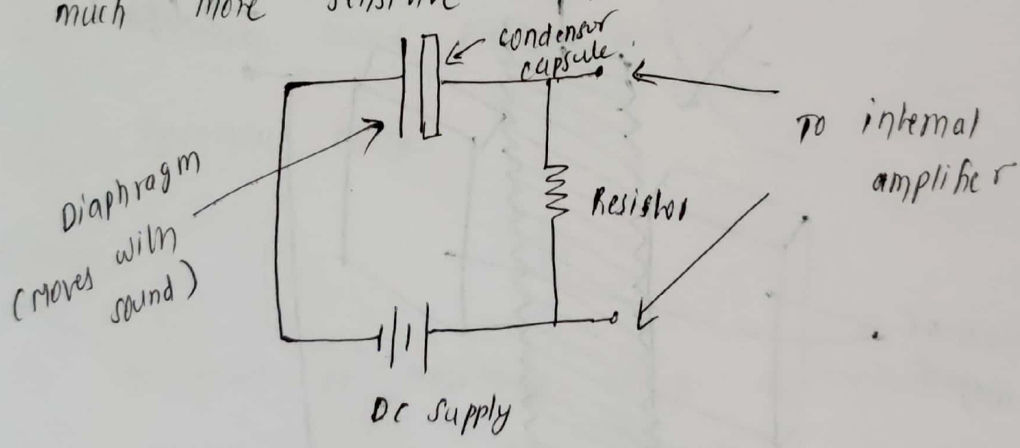
- consists of a diaphragm suspended in front of a magnet to which a coil of wire is attached.
- The coil sits in the gaps of the magnet. vibrations of diaphragm makes the coil move in the gap causing an AC to flow
- Durable design and versatile in use
- No need of power



condensor microphone

Diaphragm - Thin metal strip suspended next to a charged electric plate.

- Here, the diaphragm is one side of a capacitor which moves in reaction to changes in sound field.
- Since 2 plates are charged, motion changes the voltage between the 2 plates and these voltages changes induce electron flow.
- This requires some sort of ext. power source (battery or phantom power)
- Because diaphragm is very light, condenser mic's tend to be have highly detailed response and much more sensitive than dynamic mic



Dynamic	condenser
- Rugged / Durable	Delicate / sensitive
- Does not need power, no self-noise	- Needs power, has self noise
- Less sensitive, lower o/p, needs more amplification	- More sensitive, higher o/p, needs less amplification

- Less prone to overload distortion, can withstand higher SPL's

- Generally cheaper

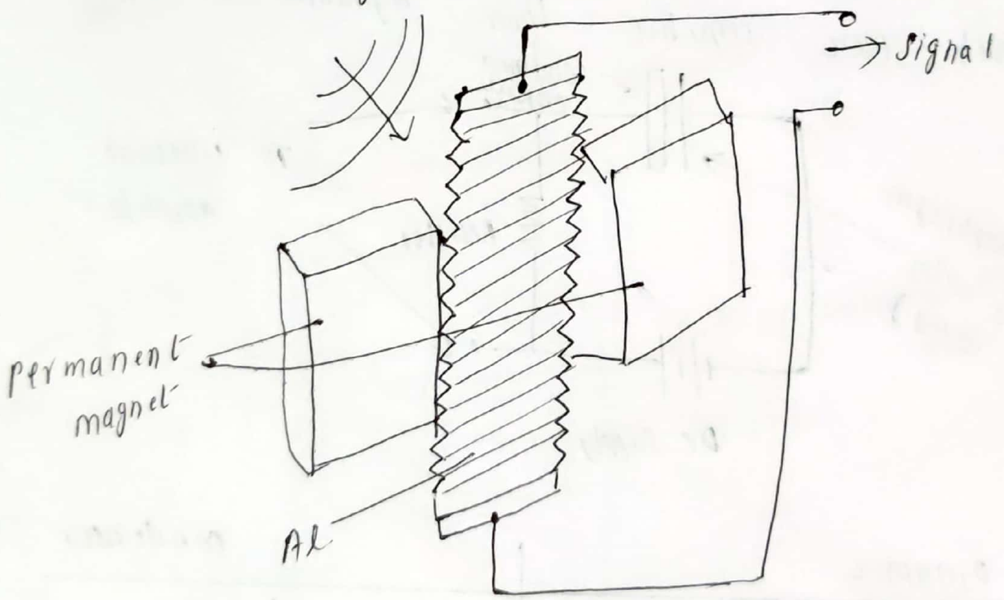
More detailed sound.

Better frequency response

- Generally more expensive.

Ribbon microphone

- Diaphragm - Thin piece of metal (usually Al) foil suspended in a magnetic field.
- vibrations in ribbon produce a small voltage which is then stepped up by a transformer.
- Diaphragm is very easily damaged by wind or loud incoming sounds



Applications

- Telephones
- Hearing aids
- Public address systems for concert halls and public events

- Motion picture production
- Live and recorded audio engineering
- 2-way radios
- Megaphones, radio and television broadcasting
- In computers for recording voice, speech recognition

Microphone responses and measurements

There are 5 properties to consider,

* Freq response
* Transient response
* Self-noise
* Maximum sound pressure level
* Dynamic range

Freq response

- It is the o/p level or sensitivity of a microphone over its operating range from lowest to highest freq.
- A microphone that has a flat freq. response produces equal o/p at all frequencies and is known as a flat response microphone.
  Used in piano or acoustic guitar

- A microphone that has varied freq response produces differing o/p of freq and is known as shaped response microphone. The curve will contain peaks and troughs.

- Shaped response microphones are useful for reducing pickup of unwanted sound and noise outside freq range of an instrument.