INSTRUMENTATION (II/II)

Course Code: ENEX - 252
(Module#3)

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✓ Class Outline

1. Introduction to Transducer
2. Introduction to Sensor
3. Types of Sensor
4. Introduction to actuator

Introduction to Transducer

What is Transducer?

- Signal in electrical form is easy to transmit, process, store or any other purpose of processing.
- So, any physical phenomenon is transformed into equivalent electrical form.

✔ any device or electrical component, that converts energy from one form to another form is transducer.

For Example:

① loudspeaker is a transducer converting low frequency electrical signal into audible sound energy.

② A microphone converts audible sound energy into voltage or current form (sound energy equivalents o sound pressure variation).

Introduction to Transducer

What is Sensor

- A sensor is a special case of transducer that convets any physical phenomenon into equivalent electrical form.
- that means, electrical analogy of a physical quantity such as distance, velocity, acceleration, temperature, pressure etc.

Introduction to Transducer

Classification/Types of Transducer

1. Based on working principle
   a. Resistive, b. inductive and c. capacitive
2. Based on if directly sense of measured quantity.
   a. primary, b. secondary
3. Based on external power dependency.
   a. passive, b. active
4. Based on types of output signal
   a. Analog b. Digital
5. Energy forward and reverse conversion
   a. Transducers b. Inverse Transducers

Introduction to Transducer

Factors to be considered while selecting a transducer

Followings are the characteristics to be considered while selecting sensors.

1. Operating principle
2. sensitivity
3. operating range
4. accuracy
5. errors
6. transient and frequency response
7. loading effect
8. environmental compatibility
9. stability and reliability
10. static characteristics

Introduction to Transducer

Primary and Secndary Transducer

- When the input signal is directly sensed by the transducer and physical phenomenon is converted into the electrical form directly then such a transducer is primary transducer.

  For Example: thermister used to sense the temperature,

- but when the input signal is sensed first by some detector or sensor and then its output being of some form other than input signal is given as input to a transducer for conversion into electrical form, such a transducer is secondary transducer.

  For Example: LVDT while measuring pressure.

Introduction to Transducer

Active and passive

- if any transducer generates its output in the form of electrical voltage without any auxiliary source, the transducer is **active transducer**.

  For Example: thermocouple, piezo-electric crystal

- For the transducer which need external power supply to measure the electrical output parameters such as resistace, inductance or capacitance is **passive transducer**.

  For Example: resistive transducer, inductive transducer, or capacitive transducer.

Introduction to Transducer

Analog and Digital Transducer

- Analog transducer converts input signal into output signal which is a continuous time signal;

  For Example: strain gauge, thermisters, thermocouple etc.

- Digital transducer converts input signal into the output signal of the form pulse or discrete output.
- Sometime analog transducer combined with ADC is also digital transducer.

  For Example: Quartz Crystal used in Quartz watch.

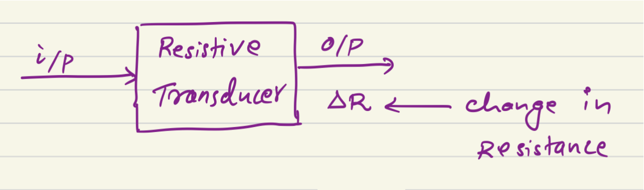
Introduction to sensor

Resistive Transducer

- Input quantity to be measured equivalently change the resistance.

  Examples: potentiometer (POT), strain gauge, resistance thermometer, photo conductive cell.

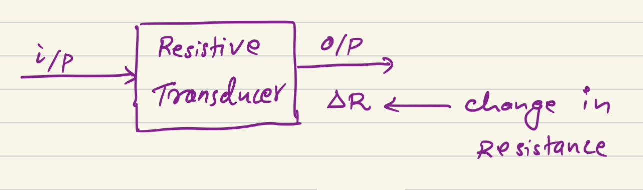
- In all of the case, input is measured as change in resistance equivalently.



Introduction to to sensor

Potentiometer: | Resistive Transducer

- is resistive transducer,
- used for change in displacement
- displacement may be either **linear** or **rotary**.



Linear Potentiometer: | Resistive Transducer

- Considering the electrical equivalent circuit,

  Let applied voltage $= e_i$

  Total resistance of potentiometer $= R_p$

  equivalently total length of potentiometer $= x_t$

  Resistance per unit length $= \frac{R_p}{x_t}$

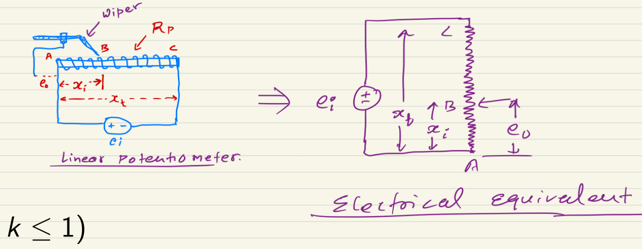
  For displacement AB $= x_i$,

  resistance of the displacement $R_{AB} = \frac{R_p}{x_t} x_i$

$$R_{AB} = \frac{x_i}{x_t} * R_p$$

$$R_{AB} = kR_p.....(i)$$

where $k = \frac{x_i}{x_t}$ $(0 \leq k \leq 1)$



Introduction to sensor

Linear Potentiometer: | Resistive sensor

- therefore, voltage output across the displacement is

$e_o = \left[\frac{R_{AB}}{R_{AB}+R_{BC}}\right] e_i ...(ii)$

from (i) and (ii) $e_o = k * e_i$

therefore, $\frac{e_o}{e_i} = \frac{x_i}{x_t} = k$

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

From above relation,

it can be conclude that input and output

voltage has linear relation.

Introduction to sensor

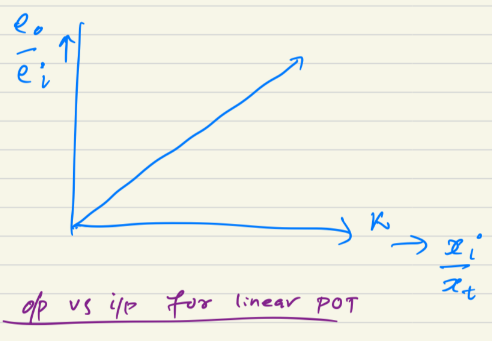
Linear Potentiometer: | Resistive sensor

Sensitivity:

$$s = \frac{\text{O/P magnitude}}{\text{i/p magnitude}}$$

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

which is constant



Introduction to sensor

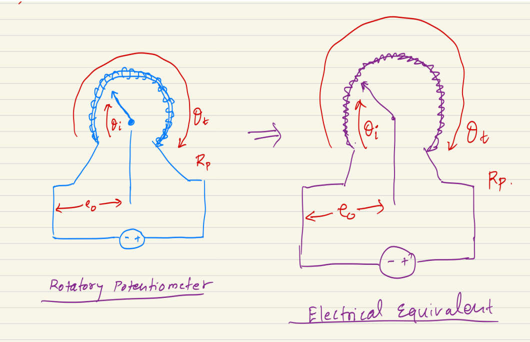
Rotatory Potentiometer: | Resistive sensor

✔ Similar logic can be applied to rotatory potentiometer as linear potentiometer.

$$e_o = ke_i = \frac{\theta_i}{\theta_t} e_i$$

$$\frac{e_o}{e_i} = \frac{\theta_i}{\theta_t} = k$$

$$\frac{e_o}{\theta_i} = \frac{e_i}{\theta_t} = \text{constant}$$

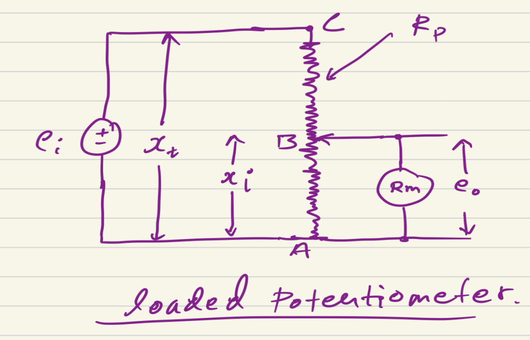


$$\text{Sensitivity(s)} = \frac{e_o}{\theta_i} = \frac{e_i}{\theta_t} = \text{constant}$$

Linear Potentiometer: | Resistive sensor

Loading Effect:

$$e_o = k * e_i = \frac{x_i}{x_t} e_i \; ..... \; (a)$$



Linear Potentiometer: | Resistive sensor

Loading Effect:

If the voltmeter is ideal, that is R_m is infinitely large then voltage across displacement is given by

$$e_o = k * e_i = \frac{x_i}{x_t} e_i \; ..... \; (a)$$

However, practical voltmeter has some larger value of R_m (not infinite)

➜ that is, a resistance R_m across displacement resistance; so, there is decrease in resistance across displacement due to voltmeter resistance R_m.

Linear Potentiometer: | Resistive sensor

Loading Effect:

Equivalently, from the relation $[v = i * R]$, there is decrease in output voltage, i.e less than o/p given by relation (a) above.

This error is loading error, and the effect is loading effect.

The loading effect is due to internal resistance of voltmeter loading the relation between input and output non-linear.

Linear Potentiometer: | Resistive sensor

Loading Effect:

Resistance after connecting R_m (voltmeter)

$$R'_{BA} = kR_p || R_m = \frac{kR_p R_m}{kR_p + R_m}$$

Output voltage reading (in voltmeter)

$$e_o = \frac{R'_{BA}}{R'_{BA} + R_{BC}} * e_i$$

$$e_o = \frac{\frac{kR_p R_m}{kR_p + R_m}}{\frac{kR_p R_m}{kR_p + R_m} + R_{BC}} * e_i \qquad \text{Substituting } R_{BC} = R_p - kR_p$$

$$e_o = \frac{kR_p R_m}{kR_p R_m + kR_p^2 - k^2 R_p^2 + R_m R_p - kR_p R_m} * e_i$$

Linear Potentiometer: | Resistive sensor

Loading Effect:

Dividing right-side by $R_p R_m$

$$e_o = \frac{k}{k\frac{R_p}{R_m} - k^2\frac{R_p}{R_m} + 1} * e_i$$

Let $\frac{R_m}{R_p} = \alpha$

$$e_o = \frac{k}{\frac{k}{\alpha} - \frac{k^2}{\alpha} + 1} e_i = \frac{\alpha k}{k - k^2 + \alpha} e_i$$

➜ From the above relation, it can be observed that there is non-linear relation between input and output due to presence of the term k^2

Introduction to sensor

What is next?

Explore more on:

- ✔ Explore on strain gauge and its mathematical derivation.
- ✔ What is Resistive Thermometer, explore on photo-conductive cell ?
- ✔ what is Inductive Transducer? draw Linear variable differential Transformer (LVDT). what are the different cases while operating?

Linear Potentiometer: | Resistive sensor

Loading Effect in Potentio-meter:

1. Relative error
2. Absolute error.

Linear Potentiometer: | Resistive sensor

Relative error:

$$E_r = \frac{e_o \text{ without error - } e_o \text{ with error}}{e_o \text{ without error}}$$

$$E_r = \frac{k * e_i - \frac{\alpha k * e_i}{\alpha + k(1-k)}}{k * e_i}$$

$$E_r = 1 - \frac{\alpha}{\alpha + k(1-k)}$$

Linear Potentiometer: | Resistive Transducer

Relative error:

Kepping α constant, relative error depends only on k;

to find the value of k where E_r is maximum, differentiate error with respect to k and make derivative equals zero.

$$\frac{dE_r}{dk} = \frac{d}{dk}\left[\frac{k(1-k)}{\alpha + k(1-k)}\right] = 0$$

$$(1-2k)(\alpha + k - k^2 - k + k^2) = 0$$

$$(1-2k)\alpha = 0$$

since $\alpha = \frac{R_p}{R_m}$, $(1-2k) = 0$; so $k = \frac{1}{2}$

So, the error is maximum at k = 0.5

Introduction to sensor

Linear Potentiometer: | Resistive sensor

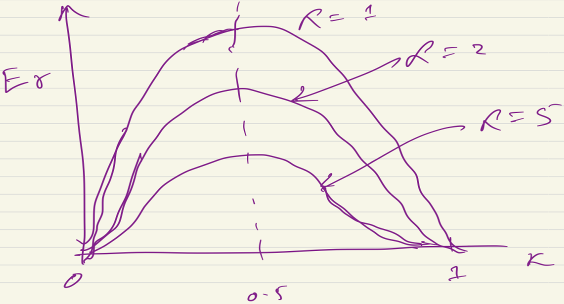
Relative error:

$$E_r = \frac{k(1-k)}{\alpha + k(1-k)}$$

(a) when $\alpha = 1$, $k = 0$; $E_r = 0$

(b) when $\alpha = 1$, $k = 0.5$ $E_r = E_r(max)$

(c) when $\alpha = 1$, $k = 1$ $E_r = 0$



Linear Potentiometer: | Resistive sensor

Absolute error:

$$E_a = \frac{e_o \text{ without error} - e_o \text{ with error}}{\text{input voltage}}$$

$$E_a = \frac{ke_i - \frac{\alpha k}{\alpha + k(1-k)} e_i}{e_i} = k - \frac{\alpha k}{\alpha + k(1-k)}$$

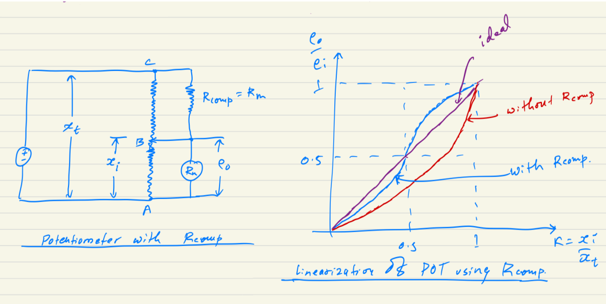
$$E_a = \frac{k^2(1-k)}{\alpha + k(1-k)} = k\left[\frac{k(1-k)}{\alpha + k(1-k)}\right]$$

$$E_a = kE_r$$

Linear Potentiometer: | Resistive sensor

Method to reduce Loading effect:

- use digital meter instead of analog meters (it is because digital meter has high input impedance).
- use buffer amplifier in combination with voltmeter (in series)
- modify construction of POT as shown; $R_{\text{comp}} = R_m$ in parallel with remaining portion of potentiometer.



Linear Potentiometer: | Resistive sensor

Power Rating of Potentio-meter:

- power rating $\sim$ heat dissipation capacity.
- $P = \frac{e_i^2}{R_p}$
- For maximum input voltage $e_{i(max)}$ power dissipation will be maximum.

$$P_{max} = \frac{e_{i(max)}^2}{R_p}$$

$$e_{i(max)} = \sqrt{P_{max} R_p}$$

Linear Potentiometer: | Resistive sensor

Linearity and Sensitivity:

For **Linearity**:

we know,

$$e_o = \frac{\alpha k}{\alpha + k(1-k)} e_i$$

- ✔ For infinitely large value of α, R_m is high (ideal case) compared to R_p

  above equation approximate to $e_o = k * e_i$

- ✔ that is; for very very small R_p, α tends to infinity, E_r or E_a tends to 0; so linear relation between input and output.

Linear Potentiometer: | Resistive sensor

Linearity and Sensitivity:

For **Sensitivity**:

sensitivity is given as $s = \frac{e_o}{e_i} = \frac{e_i}{x_t}$

for increasing sensitivity, e_o should be increasing

but, for increased e_o heat dissipation $p = \frac{e_i^2}{R_p}$

✔ So, the heat dissipation should be minimal as increased e_i gives increased heat dissipation.

Introduction to sensor

Strain Gauge: | Resistive sensor

Thin wafer likedevice, attached to material o measure applied strain ($\frac{\Delta l}{l}$)

- It is transduce that measure mechanical displacement into change in resistance.

Load cell torque meter, diaphram type pressure, temperature sensors, etc employ thin gauge as secondary transducers.

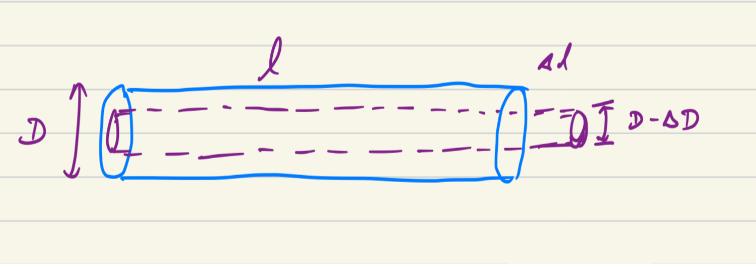
Introduction to sensor

Straing Gauge: | Resistive sensor

Working Principle:

Consider conductor of uniform cross section A, and length l with resistivity ρ $\quad R = \rho \frac{l}{A}$

it can be argued that, if the conductor is stretched or compressed, changes in both length (Δl) and cross section (ΔA) also small change in ρ will cause change in resistance.



Straing Gauge: | Resistive sensor

Working Principle:

On applying normal stress (s) to cross section A,

$$\frac{dR}{ds} = \frac{d}{ds}\left(\rho\frac{l}{A}\right)$$

$$\frac{dR}{ds} = \frac{\rho}{A} * \frac{\partial l}{\partial s} - \frac{\rho l}{A^2} * \frac{\partial A}{\partial s} + \frac{l}{A} * \frac{\partial \rho}{\partial s}$$

dividing $R = \frac{\rho l}{A}$

$$\frac{1}{R} * \frac{dR}{ds} = \frac{A}{\rho l}\left[\frac{\rho}{A} * \frac{\partial l}{\partial s} - \frac{\rho l}{A^2} * \frac{\partial A}{\partial s} + \frac{l}{A} * \frac{\partial \rho}{\partial s}\right]$$

$$\frac{1}{R} * \frac{dR}{ds} = \frac{1}{l} * \frac{\partial l}{\partial s} - \frac{1}{A} * \frac{\partial A}{\partial s} + \frac{1}{\rho} * \frac{\partial \rho}{\partial s}$$

Straing Gauge: | Resistive Transducer

Working Principle:

On applying normal stress (s) to cross section A,

$$\frac{1}{R} * \frac{dR}{ds} = \frac{1}{l} * \frac{\partial l}{\partial s} - \frac{1}{A} * \frac{\partial A}{\partial s} + \frac{1}{\rho} * \frac{\partial \rho}{\partial s}$$

Replacing $A = \frac{\pi D^2}{4}$ and poison ration: $\gamma = \frac{-\frac{\partial D}{D}}{\frac{\partial l}{l}}$

$$\frac{1}{R} * \frac{dR}{ds} = \frac{1}{l} * \frac{\partial l}{\partial s} - \frac{2}{D} * \frac{\partial D}{\partial s} + \frac{1}{\rho} * \frac{\partial \rho}{\partial s}$$

from above poison ration: $\frac{\partial D}{D} = -\gamma \frac{\partial l}{l}$

$$\frac{1}{R} * \frac{dR}{ds} = \frac{1}{l} * \frac{\partial l}{\partial s} + \frac{2\gamma}{l} * \frac{\partial l}{\partial s} + \frac{1}{\rho} * \frac{\partial \rho}{\partial s}$$

Straing Gauge: | Resistive Transducer

Working Principle:

On applying normal stress (s) to cross section A,

$$\frac{1}{R} * \frac{dR}{ds} = \frac{1}{l} * \frac{\partial l}{\partial s} + \frac{2\gamma}{l} * \frac{\partial l}{\partial s} + \frac{1}{\rho} * \frac{\partial \rho}{\partial s}$$

For very small variation:

$$\frac{\Delta R}{R} = \frac{\Delta l}{l} + 2\gamma\frac{\Delta l}{l} + \frac{\Delta \rho}{\rho}$$

$$\frac{\frac{\Delta R}{R}}{\frac{\Delta l}{l}} = 1 + 2\gamma + \frac{\frac{\Delta \rho}{\rho}}{\frac{\Delta l}{l}} \quad \text{where} \frac{\frac{\Delta R}{R}}{\frac{\Delta l}{l}} \text{is gauge factor} (G_f)$$

Guage factor (G_f) is defined as ration of per unit change in resistance to per unit change in length

Straing Gauge: | Resistive Sensor

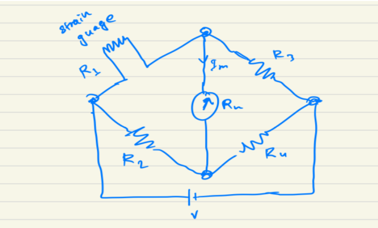
Applications of strain gauge:

wheat stone bridge is employed to measure change in resistance due to strain applied.

For no strain and balanced; So $\frac{R1}{R_2} = \frac{R3}{R4}$ for known R_2, R_3, R_4

when strain is applied in arm R_1, the bridge circuit is imbalance then current flows through galvanometer.

the current flow Im is proportional to application of strain on R_1 which can be calibrated to obtain value of strain.



Introduction to Sensor

What is next?

Explore more on:

- ✔ Capacitive transducer: capacitive displacement, capacitive liquid level transducer.
- ✔ What is thermo-electric transducer?
- ✔ working principle of piezoelectric transducer with equivalent circuit.

Resistance Thermometer: | Resistive Sensor

- It is resistive thermometer
- It is used to measure temperature.

There are two types of resistive thermometer.

1. metal resistance thermometer
2. semiconductor resistance thermometer (thermister).

Resistance Thermometer: | Resistive Sensor

Metal Resistance thermometer

- is dependents on change in resistance of metal wire due to change in temperature.
- in general resistance increases with increase in temperature.
- the change relation is linear for some range of temperature,
- the range is different for different metals and materials.

The general expression for resistance at temperature T(K) is given as:

$$R_T = R_o \left[1 + \alpha T + \beta T^2 + \gamma T^3 + ...\right]$$

R_o is reistance at T = 0 K, and α, β, and γ are temperature coefficients with $\alpha > \beta > \gamma$

➜ For linear relation, $R_T = R_o [1 + \alpha T]$

Introduction to Sensor

Resistance Thermometer: | Resistive Sensor

Metal Resistance thermometer

- Generally, platinum or nickel or copper wire on glass or ceramic are used;
- platinum has closely linear relation in the range -200 $^\circ\mathrm{C}$ to $+$ 850 $^\circ\mathrm{C}$
- nickel has linear range about -80 $^\circ\mathrm{C}$ to $+$300 $^\circ\mathrm{C}$
- copper has range of -200 $^\circ\mathrm{C}$ to $+$250 $^\circ\mathrm{C}$;
- nickel and copper are cheaper but less stable.

Resistance Thermometer: | Resistive Sensor

Semiconductor Resistance thermometer

- thermisters are also known as thermally sensitive resister
- made from oxide or chromium, cobalt, nickel etc.
- the oxides are semiconductor in nature.
- in resistance decreases with increase in temperature.
- General expression for the relation is

$$R_T = R_o e^{\beta\left[\frac{1}{T} - \frac{1}{T_o}\right]}$$

where β is constant depends on material used.

T and T_o are temperature in kelvin.

Resistance Thermometer: | Resistive Sensor

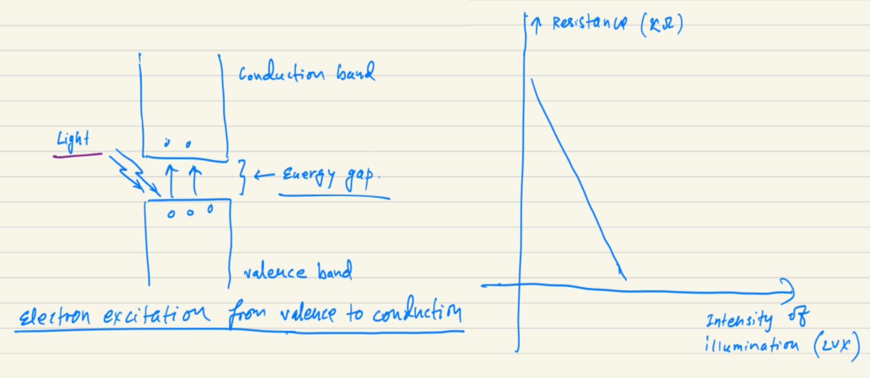
Photoconductive Cell

- also known as Light dependent Resistors (LDR)
- are semiconductor materials.
- they have properties like change in resistance when electromagnetic radiation is incident on them.
- when radiation of sufficiently high frequency is incident on them, electrons are excited from valence band to conduction band.
- this results in increase in number of charge carrier in conduction band (electron);
- equivalently, decrease in resistance.
- as intensity of light increases, number of charge carrier electrons increases in conduction band.

Resistance Thermometer: | Resistive Sensor

Photo-conductive Cell

- Cadmium Sulphide or Lead Sulphide doped materials are used for photo-conductive cell.



Introduction to Sensor

Inductive Sensor

- In this type transducer, input being measured is transformed into change in inductance.
- One of the example is Linear Variable Differential Transformer (LVDT)

Linear Variable Differential Transformer (LVDT)

- used to measure displacement;
- it has one primary coil and two identical secondary coil.
- the coils are wound on the same insulating former.
- there is an iron core which moves inside the former
- the displacement of the core is input to the transducer.

Inductive Sensor

Linear Variable Differential Transformer (LVDT)

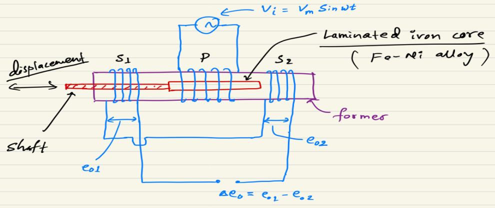
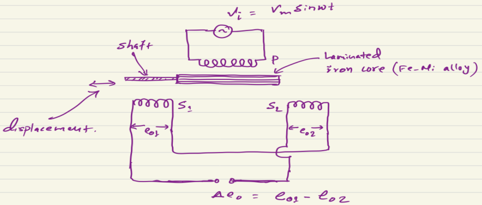


Fig. Linear Variable Differential transformer



Electrical equivalent

Inductive Sensor

Principle: | **Linear Variable Differential Transformer (LVDT)**

- when sinusoidal input $v_i = v_m sinwt$ is applied to primary winding, sinusoidal flux will link with primary as well as secondary windings s_1 and s_2
- there will induce emf at s_1 and s_2.
- lets say e_{o1} emf at s_1 and e_{o2} at s_2
- According to the circuit structure: $\Delta e_o = e_{o1} - e_{02}$

  where Δe_o will be in phase with v_i or 180 out of phase.

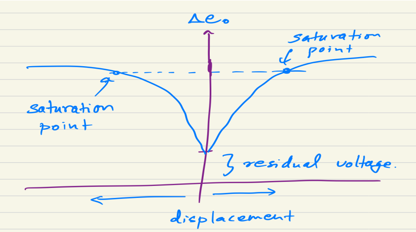


Fig. Displacement Vs output Δe_o

Inductive Sensor

Principle: | **Linear Variable Differential Transformer (LVDT)**

✔ Case-I: Core at the midpoint between s_1 and s_2

- the linking flux to s_1 and s_2 will be same ideally
- so, induced emf e_{o1} and e_{o2} will be equal.
- practically, there will be some output emf (δe_o) which is known as residual voltage.

Inductive Sensor

Principle: | **Linear Variable Differential Transformer (LVDT)**

✔ Case-II: Core moving left-side

- flux linking with s_1 increases whereas that with s_2 decreases.
- therefore, $\Delta e_o = e_{o1} - e_{o2}$ increases.
- there will be linear relation between differential output Δe_o and the displacement up to saturation point
- beyond the saturation point, the relation is non-linear.
- Δe_o is in phase with voltage applied to primary coil.

Inductive Sensor

Principle: | **Linear Variable Differential Transformer (LVDT)**

✔ Case-III: Core moving right-side

- flux linking with s_2 increases whereas that with s_1 decreases.
- therefore, $\Delta e_o = e_{o1} - e_{o2}$ increases.
- again, there will be linear relation between differential output Δe_o and the displacement up to saturation point
- beyond the saturation point, the relation is non-linear.
- Δe_o is out of phase with voltage applied to primary coil.

Capacitive Sensor

- input being measured is transformed into change in capacitance.
    1. capacitive displacement transducer
    2. Capacitive liquid level transducer

Capacitive displacement transducer:

- consists of two parallel plates: one fixed and another movable.
- the displacement to be measured is coupled with movable plate.

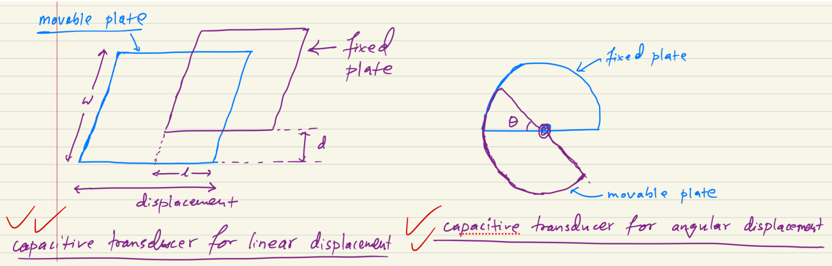
  $c = \epsilon \frac{A}{d}$ or $c = \epsilon_o \epsilon_r \frac{A}{d}$

  where ϵ is permitivity of the medium between plates; $\epsilon_o = 8.854 * 10^{-12} F/m$, A is overlapping area and d is separation distance.

  ✔ from the above equation, changes in capacitance will be observed when there is change in A, d, or ϵ.

Capacitive Sensor

Change in overlapping Area (A)



$c = \epsilon_o \epsilon_r \frac{wl}{d} \quad c \propto l$

sensitivity: $s = \frac{\Delta o/p}{\Delta i/p}$

$s = \frac{\partial c}{\partial l} = \frac{\partial}{\partial l}\left(\epsilon_o \epsilon_r \frac{wl}{d}\right)$

$s = \epsilon_o \epsilon_r \frac{w}{d}$ is constant

$A_{max} = \frac{\pi r^2}{2}$, therefore,

$c_{max} = \epsilon_0 \epsilon_r \frac{\pi r^2}{2d}$

$A_\theta = \frac{\theta r^2}{2}$ therefore,

$c_\theta = \epsilon_0 \epsilon_r \frac{\theta r^2}{2d} \rightarrow c_\theta \propto \theta$

Capacitive Sensor

Change in overlapping Area (A)

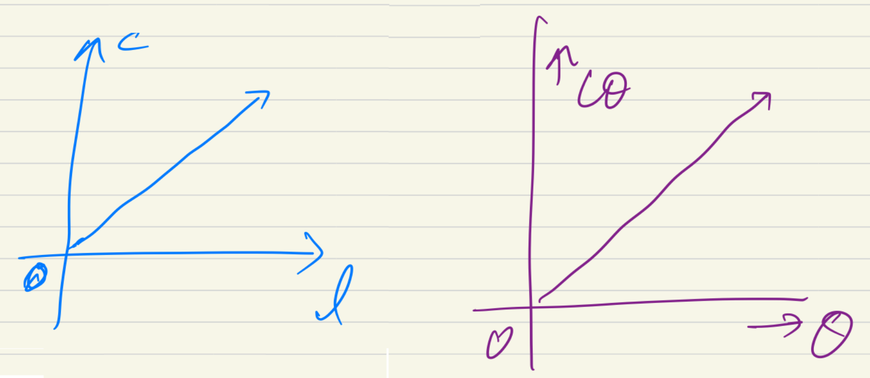


Fig. 1 sensitivity graph for change in C with change in overlapping A

Capacitive Sensor

Change in separation (d)

- consist of two plates: one fixed and another movable
- the displacement to be measured is coupled with movable plate.

$c = \epsilon_o \epsilon_r \frac{A}{d}$

sensitivity: $s = \frac{\Delta o/p}{\Delta i/p}$

$$s = \frac{\partial c}{\partial d}$$

$$s = \frac{\partial}{\partial d}\left(\epsilon_o \epsilon_r \frac{A}{d}\right) = -\epsilon_o \epsilon_r \frac{A}{d^2} = -\frac{c}{d}$$

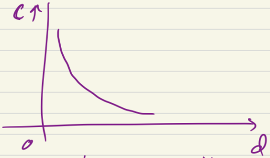
$s \propto \frac{1}{d^2}$

what could be the graph look like ?

Introduction to Sensor

Capacitive Sensor

Change in separation (d)



separation vs Capacitance

✓ From the graph, output and input has non-linear relation.

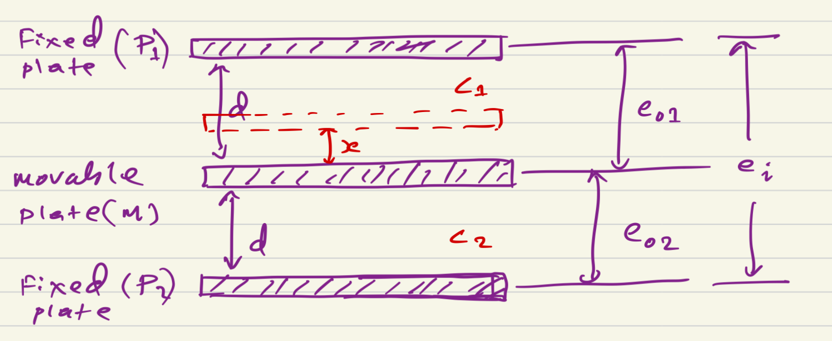
→ to make the linear, we can min separation distance very small, and the displacement that can be measured is very small.

minimize

Capacitive Sensor

Change in separation (d)

- to make the relation linear we can make differential arrangement.



Capacitive Sensor

Change in separation (d)

When plate M at midpoint of P_1 and P_2 plates

$$c_1 = c_2 = \epsilon_o \epsilon_r \frac{A}{d}$$
$$e_{o1} = \frac{c_2}{c_1 + c_2} e_i = \frac{e_i}{2}$$
$$e_{o2} = \frac{c_1}{c_1 + c_2} e_i = \frac{e_i}{2}$$

Therefore, differential output is given as $\Delta e_o = e_{o1} - e_{o2} = 0$

Capacitive Sensor

Change in separation (d)

When plate M move up by a distance x_i

$$c_1 = \epsilon_o \epsilon_r \frac{A}{d-x}$$
$$c_2 = \epsilon_o \epsilon_r \frac{A}{d+x}$$
$$e_{o1} = \frac{c_2}{c_1+c_2} e_i$$
$$e_{o2} = \frac{c_1}{c_1+c_2} e_i$$

Therefore, differential output is given as:

$$\Delta e_o = e_{o1} - e_{o2} = \frac{c_1-c_2}{c_1+c_2} e_i$$

Capacitive Sensor

Change in separation (d)

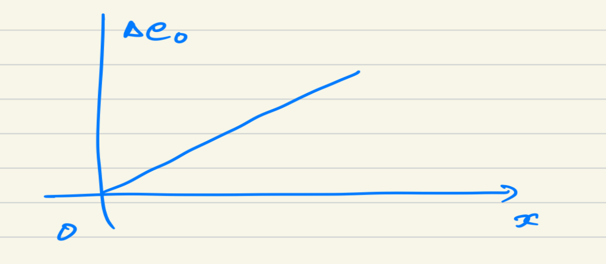
When plate M move up by a distance x_i

$\Delta e_o = e_{o1} - e_{o2} = \frac{c_1 - c_2}{c_1 + c_2} e_i$

Now evaluate $c_1 - c_2 = \epsilon_o \epsilon_r A \left[\frac{1}{d-x} - \frac{1}{d+x}\right] = \epsilon_o \epsilon_r A \left[\frac{2x}{d^2-x^2}\right]$

Again evaluate $c_1 + c_2 = \epsilon_o \epsilon_r A \left[\frac{1}{d-x} + \frac{1}{d+x}\right] = \epsilon_o \epsilon_r A \left[\frac{2d}{d^2-x^2}\right]$

therefore, $\Delta e_o = \frac{x}{d} e_i$ which is linear and $\Delta \propto x$



Capacitive Sensor

Change in separation (d)

When plate M move up by a distance x_i

Sensitivity (s) :

$$s = \frac{\Delta o/p}{\Delta i/p} = \frac{\partial}{\partial x}[\Delta e_o]$$

$$s = \frac{\partial}{\partial x}\left[\frac{x}{d}e_i\right] = \frac{e_i}{d}$$

Here $s = \frac{e_i}{d}$ is constant;

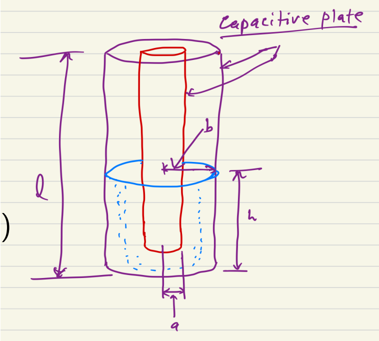
Therefore, the sensitivity of the device is constant.

Capacitive Sensor

Capacitive Liquid Level Transducer

It has two cylindrical plate with radii 'a' and 'b'

Capacitance per unit length is given as: $c_{\text{per unit length}} = \frac{2\pi\epsilon_o\epsilon_r}{\ln\left(\frac{b}{a}\right)} \ldots.(i)$



Capacitive Sensor

Capacitive Liquid Level Transducer

- ✔ c_1 with liquid and c_2 with air between the capacitor plate.
- ✔ being in parallel configuration, $c = c_1 + c_2$

$$c = \frac{2\pi\epsilon_o\epsilon_r h}{\ln\left(\frac{b}{a}\right)} + \frac{2\pi\epsilon_o(l-h)}{\ln\left(\frac{b}{a}\right)}$$

$$c = \frac{2\pi\epsilon_o}{\ln\left(\frac{b}{a}\right)}\left[\epsilon_r h + (l-h)\right]$$

$$c = \frac{2\pi\epsilon_o}{\ln\left(\frac{b}{a}\right)}\left[(\epsilon_r - 1)h + l\right] ...(ii)$$

Capacitive Sensor

Capacitive Liquid Level Transducer

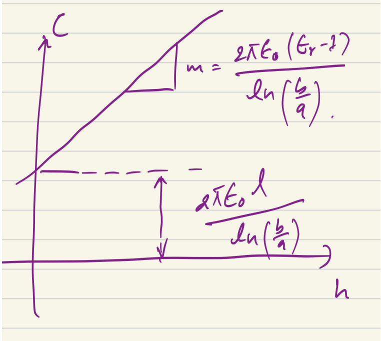
From the relation (ii), it can be argued that with liquid height, capacitance changes with change in liquid height.

From equation (ii)

$$c = \frac{2\pi\epsilon_o\epsilon_r}{\ln\left(\frac{b}{a}\right)} l + \frac{2\pi\epsilon_o}{\ln\left(\frac{b}{a}\right)}(\epsilon_r - 1)h$$

For varying $x = h$, equation is similar to $y = k + mx$

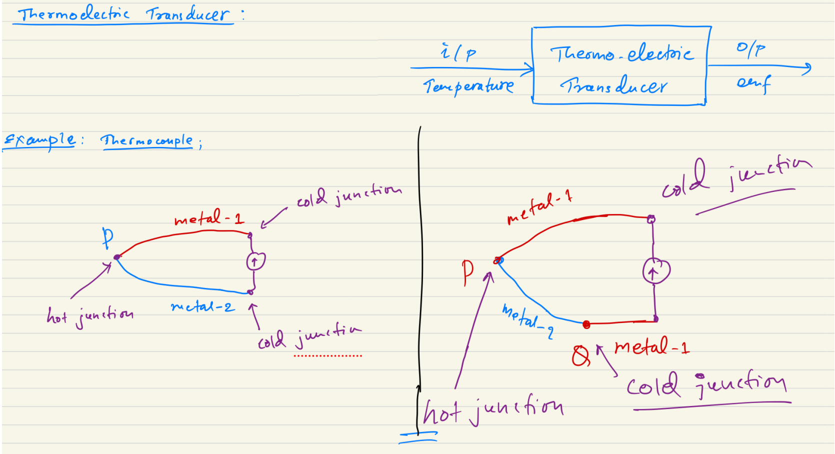
Corresponding parameters $k = ?$, and $m = ?$



Introduction to Sensor

Thermoelectric Sensor

- input is thermal energy (temperature);
- output is electrical energy – emf



Introduction to Sensor

Thermoelectric Sensor

- when two different materials are in contact, there is a potential difference across the junction;
- potential difference depends on:

  (i) metals used and

  (ii) temperature of the junction.
- $v = \alpha(T_{hot} - T_{cold})$ where α is **seeback** effect.
- if the temperature at the junctions are same then there is no net potential difference.

Introduction to Sensor

Thermoelectric Sensor

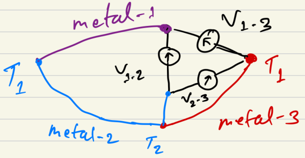
Basic Laws of thermocouple:

(i) emf depends on temperature of the junctions and is independent of temperature of the connecting wires.

(ii) if the third metal M3 is connected either in metal M1 or in metal M2, there is no change in emf developed provided new junctions at the same temperature.

(iii) If the third metal M3 is connected either at hot junction or at cold junction there is change in emf developed;

(iv) Law of intermediate metal:



$\Rightarrow$ then $E_{1-3} = E_{1-2} + E_{2-3}$

Introduction to Sensor

Piezo-electric Sensor

- ✔ mainly used for measurement of displacement
- ✔ used in measurement of force, pressure, or acceleration.

Working Principle:

- In certain crystals, electric field apears across certain surface of the crystal if the dimension of the crystal is changed by mechanical force applied.
- the mechanism is reversible; that is, if varying potential is applied to proper axis, there will be change in dimension.
- this effect is known as **piezoelectric effect**.
- metal plates are used with selected surface (face) for load wire connection.

Piezo-electric Sensor

- Piezoelectric material are insulated, so the electrode plate become the plate of capacitor, so charge generators.
- piezoelectric effect is direction sensitive; that is, voltage produced by tensile force may be of different amplitude and phase to that produced by compressive force.

Three types of piezoelectic materials:

1. **natural:** Quartz, Rochelle salt.
2. **Synthetic:** Lithium Sulphate,
3. **Ceramics:** Barium tartarate.

Piezo-electric Sensor

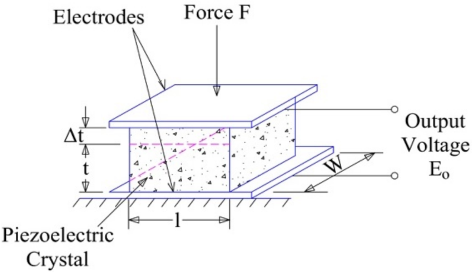
✔ charge generated is directly proportional to the force applied.

- that is, $Q \propto F$ or $Q = dF$ where d is charge sensitivity (C/N)

Capacitance formed:

$$C_p = \epsilon \frac{A}{t}$$

$$C_p = \epsilon_o \epsilon_r \frac{A}{t}$$



where A is area of the crysta surface,

and t is thickness of the crystal;

Piezo-electric Sensor

Voltage generated is given as:

$$v_o = \frac{Q}{c_p} = \frac{dF}{\epsilon_o \epsilon_r \frac{A}{t}}$$

$$v_o = \frac{d}{\epsilon_o \epsilon_r} \left(\frac{F}{A} \right) t$$

$v_o = g.P.t$ where $g = \frac{d}{\epsilon_o \epsilon_r}$ and $P = \frac{F}{A}$

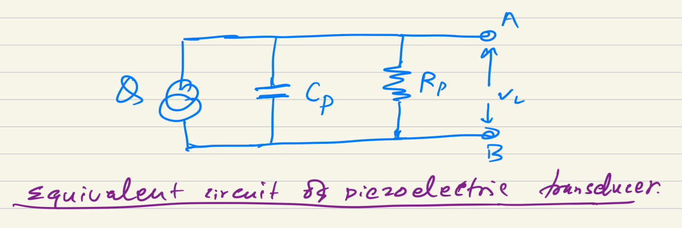
$g = \frac{v_o/t}{P}$ where v_o/t is electrical stress – potential gradient, voltage gradient or electric field intensity.

and P is mechanical stress.

Piezo-electric Sensor

Equivalent Circuit for Piezoelectric Transducer

- As it is charge generator, equivalent circuit is:

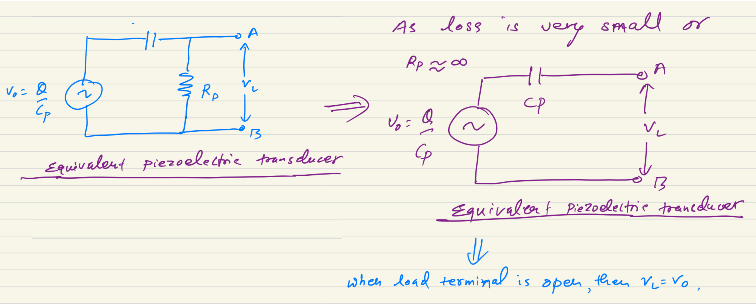


- R_p is leakage resistance which is responsible for dielectric loss
- V_L is load voltage.

Piezo-electric Sensor

Equivalent Circuit for Piezoelectric Transducer

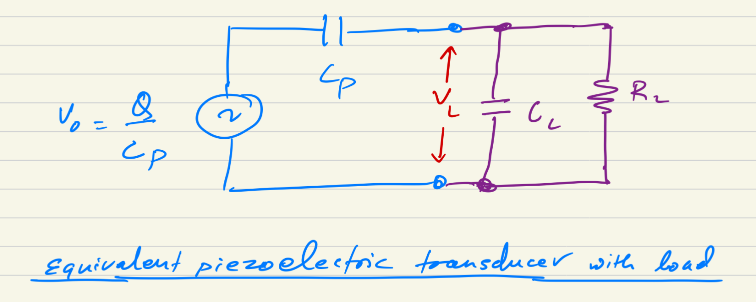
- Transforming charge generator as voltage source,



Piezo-electric Sensor

Equivalent Circuit for Piezoelectric Transducer

- In practice, when connecting load having capacitance c_L and resistance R_L as shown below:



Piezo-electric Sensor

Equivalent Circuit for Piezoelectric Transducer

- From the previous piezoelectric transducer with load,

$$\frac{1}{Z_L} = \frac{1}{R_L} + \frac{1}{X_L} = \frac{1}{R_L} + \frac{1}{\frac{1}{jwc_L}} = \frac{\frac{1}{jwc_L}+R_L}{R_L\frac{1}{jwc_L}}$$

✔ So, **Load Impedance** $Z_L = \frac{R_L}{1+jwc_L R_L}$ and

✔ **Source Impedance**, $Z_p = \frac{1}{jwc_P}$

Now voltage across load $V_L = \frac{Z_L}{Z_L+Z_P} v_o$

$$V_L = \frac{\left(\frac{R_L}{1+jwc_L R_L}\right)}{\left(\frac{R_L}{1+jwc_L R_L}\right)+\frac{1}{jwc_P}} v_o = \frac{jwR_L c_P}{1+jwR_L(c_p+c_L)} v_o$$

➜ Magnitude of voltage is: $|V_L| = \frac{wR_L c_P}{\sqrt{1+[wR_L(c_P+c_L)]^2}} v_o$

Piezo-electric Sensor

Equivalent Circuit for Piezoelectric Transducer

✔ Magnitude of voltage is: $|V_L| = \frac{wR_Lc_P}{\sqrt{1+[wR_L(c_P+c_L)]^2}}v_o$

For very high frequency:

$$|V_L| = \frac{wR_Lc_P}{wR_L(c_P+c_L)}v_o$$

$$|V_L| = \frac{c_P}{c_P+c_L}v_o$$

$$|V_L| = \frac{Q}{c_P+c_L}$$

➜ $|V_L| = \frac{d.F}{c_P+c_L}$ is load voltage for piezoelectric crystal.

Types of Sensor

Different types of sensor?

- based on the nature of the signal they detect or respond to, sensor can be classified as:

① Electrical Sensor

➜ These detect electrical quantities or other physical parameters or convert signals into electrical form of energy.

- Voltage sensor;
- Current sensor;
- Resistance Temperature Detectors (RTD);
- Capacitive/Inductive sensors

Types of Sensor

Different types of sensor?

- based on the nature of the signal they detect or respond to, sensor can be classified as:

② Mechanical Sensors

➜ These sense physical/mechanical changes such as displacement, pressure, or force.

- Strain gauge
- Pressure sensor
- Load cell
- Accelerometer
- Gyroscope

Types of Sensor

Different types of sensor?

- based on the nature of the signal they detect or respond to, sensor can be classified as:

③ Thermal Sensors

➜ These measure temperature or heat flow.

  - Thermocouples
  - Thermistors
  - Infrared temperature sensors
  - Pyrometers

Types of Sensor

Different types of sensor?

- based on the nature of the signal they detect or respond to, sensor can be classified as:

④ Optical Sensors

➜ These detect light or changes in light intensity.

  - Photodiodes
  - Phototransistors
  - LIDAR
  - CCD (Charge-Coupled Device)

Types of Sensor

Different types of sensor?

- based on the nature of the signal they detect or respond to, sensor can be classified as:

⑤ Acoustic Sensors

➜ These detect sound waves, pressure waves, or vibration.

- Microphones
- Ultrasonic sensors
- Piezoelectric sensors
- SONAR

Types of Sensor

Different types of sensor?

- based on the nature of the signal they detect or respond to, sensor can be classified as:

⑥ Chemical Sensors

➜ These detect the presence or concentration of chemical substances.

- pH sensors
- Gas sensors (e.g., CO_2, O_2, and NH_3)
- Ion-selective electrodes
- Electrochemical sensors

Types of Sensor

Different types of sensor?

- based on the nature of the signal they detect or respond to, sensor can be classified as:

⑦ Biological (Biosensors)

➜ These detect biological responses or substances, often using enzymes, antibodies, or cells.

- Glucose biosensors
- DNA biosensors
- Immunosensors
- Wearable health sensors

Types of Sensor

Different types of sensor?

- based on the nature of the signal they detect or respond to, sensor can be classified as:

⑧ Magnetic Sensors

➜ These detect magnetic fields or magnetic properties.

- Hall-effect sensors
- Magnetometers
- Compass modules (e.g., MEMS)

Types of Sensor

Different types of sensor?

- based on the nature of the signal they detect or respond to, sensor can be classified as:

⑨ Radiation Sensors

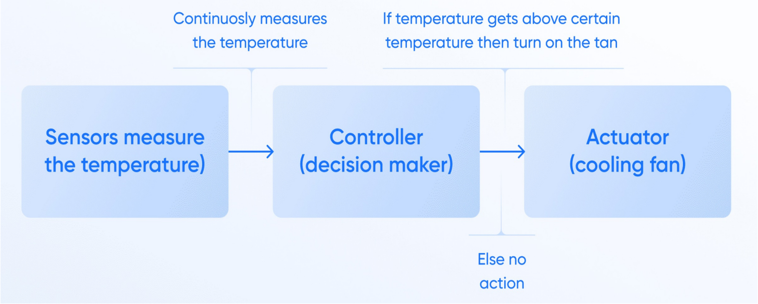
➜ These detect ionizing or non-ionizing radiation.

  - Geiger-Müller tube
  - Scintillation detectors
  - UV sensors

Introduction to actuator

What is Actuator?

- An actuator is a device that converts a control signal (electrical, hydraulic, or pneumatic) into mechanical movement.
- It's the "muscle" of any automated system — it causes movement or maintains position.



Classification: | Actuators

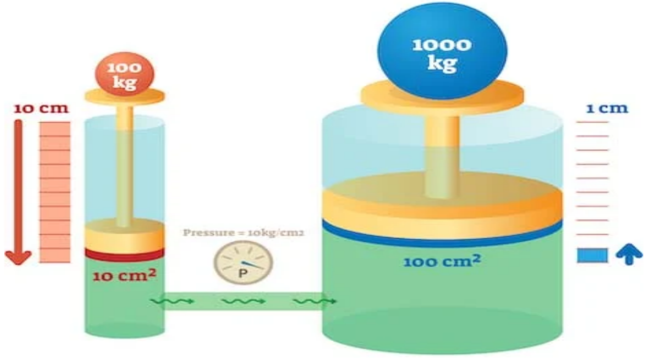
✔ Based on Operating Energy:

1. Hydraulic Actuators
2. Pneumatic Actuators
3. Electric Actuators
4. Mechanical Actuators

Introduction to actuator

Hydraulic Actuator

- Hydraulic actuators are mechanical devices that use pressurized fluid (usually oil) to produce linear or rotary motion.
- They are widely used in heavy machinery like excavators, aircraft control systems, and industrial machines due to their high power density and precision.



Introduction to actuator

Working Principle: | Hydraulic Actuator

- ✔ **Input Signal**: A controller or operator sends a command (e.g., move forward).
- ✔ **Pump Pressurizes Fluid**: The pump pushes hydraulic fluid into the system.
- ✔ **Control Valve Directs Flow**: Valve sends the fluid to one side of the actuator.
- ✔ **Pressure Acts on Piston**:

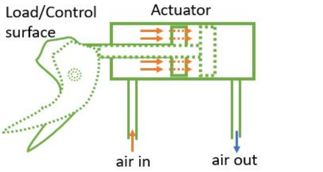
  The high-pressure fluid pushes the piston in the cylinder.

  The piston extends or retracts, creating linear motion.
- ✔ **Output Motion**: The actuator moves the load (e.g., lifting a crane arm).
- ✔ **Fluid Return**: The displaced fluid on the other side of the piston returns to the reservoir.

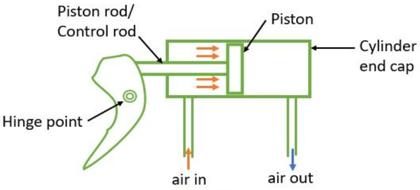
Introduction to actuator

Pneumatic Actuator

- A pneumatic actuator is a mechanical device that converts compressed air pressure into linear or rotary motion.
- It is widely used in automation systems, valve operation, material handling, and robotics due to its simplicity, speed, and clean operation.



Working mechanism of an actuator



Parts of an actuator

Introduction to actuator

Working Principle: | Pneumatic Actuator

- ✔ **Compressed Air Input**:

  Air is compressed using a compressor and stored in a tank.

  When activated, air flows into the actuator via a control valve.

- ✔ **Pressure Force on Piston**:

  The air enters one side of the cylinder.

  The pressure difference pushes the piston in a linear direction.

Working Principle: | pneumatic Actuator

- ✔ **Motion Generation**:

  The piston movement is transmitted to external mechanical systems (e.g., to open/close a valve or move a robotic arm).

  For double-acting cylinders, air is alternately applied to both sides of the piston for bidirectional motion.

- ✔ **Air Exhaust**:

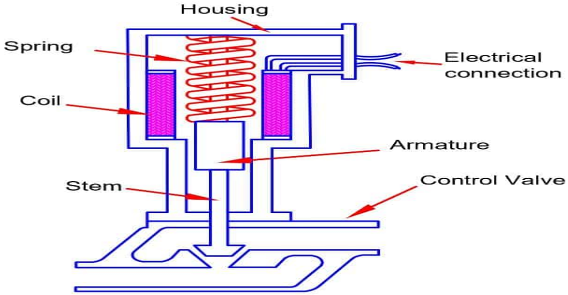
  After moving the piston, the air is vented out through an exhaust port.

  Air is non-toxic and safe to vent in most environments.

Introduction to actuator

Electric Actuator?

- An electric actuator is a device that converts electrical energy (typically from a motor) into mechanical motion—either rotary or linear.
- Electric actuators are widely used in automation systems, robotics, industrial machines, and precision positioning devices.



Introduction to actuator

Working Principle For Rotary Motion: Electric Actuator?

- ✔ **Power Supply**:

  Electrical power is supplied to the motor (DC/AC/stepper/servo).

- ✔ **Motor Rotation:**

  The electric motor generates rotary motion (torque and speed) based on the voltage and control signals.

- ✔ **Gearbox:**

  A gearbox is often used to reduce speed and increase torque for better control and power.

- ✔ **Output Shaft:**

  The rotary motion is transmitted through the shaft to drive a load (e.g., turning a valve or rotating a robotic arm).

Introduction to actuator

Mechanical Actuator

- A mechanical actuator is a device that converts one form of mechanical motion into another (e.g., rotary to linear or vice versa) to perform a desired action.
- Unlike hydraulic, pneumatic, or electric actuators that rely on external energy sources (fluid, air, electricity), mechanical actuators often utilize manual force, gravity, or mechanical energy stored in components like springs, cams, gears, or levers.

Introduction to actuator

Working Principle: | Mechanical Actuator

1. **Lead Screw (Screw Jack) Example**:

   Input: Rotational motion (manual or motor-driven)

   Mechanism: Screw threads convert rotational motion into linear.

   Output: Linear displacement of the screw or nut.

   Working: When the screw is rotated, the thread guides the nut along the screw axis, moving it linearly. This is commonly used in vices, car jacks, and CNC machines.

2. **Rack and Pinion Example:**

   Input: Rotary motion (turning the pinion gear)

   Mechanism: Gear teeth convert rotary motion to linear motion of the rack.

   Output: Linear displacement

   Used in: Car steering systems, sliding gates.

Introduction to actuator

Other types of Actuator

- Explore on magnetic and thermal actuators.
- what are the actuators in IOT applications ? explore ad explain.

As you go
Assignment

Assignment Module#3 is available at MS-Team.

Submission Deadline: 9th June 2025 (*Before 3:00 PM*)