ME407 . MECHATRONICS

MODULE - V

- System Modeling - Mathematical models and basic building blocks of general mechanical, electrical, fluid and thermal systems.
- Mechatronics in Robotics - Electrical drives: DC, AC, brushless, servo and stepper motors, Harmonic drives
- Force and tactile sensors. Range finders: ultrasonic and light based range finders.

SYSTEM MODELING

⇒ The mathematical models are equations which describe the relation between the input and output of a system.

⇒ These models can be used to enable forecasts to be made of system's behaviour under specific conditions

⇒ Systems can be made up from a range of building blocks from a number of basic building blocks.

MECHANICAL SYSTEM BUILDING BLOCKS

⇒ The basic building blocks used to represent mechanical systems are;

↳ Springs
↳ Dashpots
↳ Masses

SPRINGS

⇒ The springs represent the stiffness of a system

⇒ In case of a linear spring;

$$F = kx$$

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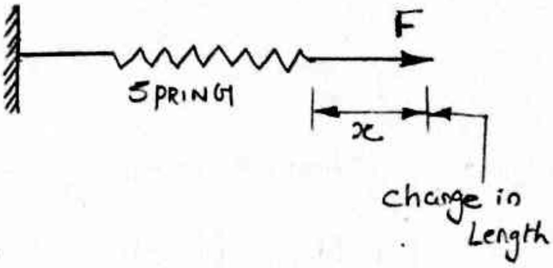
Where;

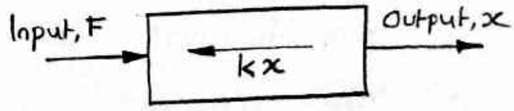
$F \rightarrow$ Applied force

$k \rightarrow$ A constant

$x \rightarrow$ Extension or Compression.



⇒ The spring when stretched stores energy, the energy being released when the spring goes back to its original length.



Energy stored $E = \frac{1}{2} k x^2$

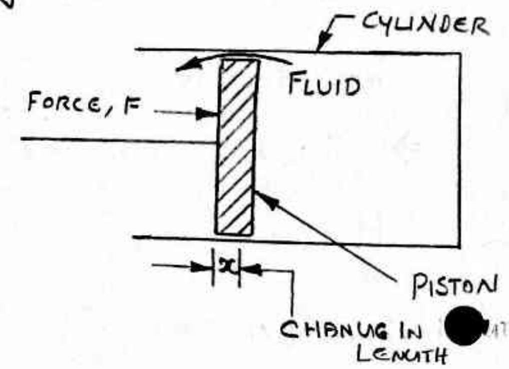
$$= \frac{1}{2} \frac{F^2}{k}$$

DASHPOTS

⇒ Dashpots represent the forces opposing motion, ie, frictional or damping effects.

⇒ The faster the object is pushed, greater becomes the opposing forces.

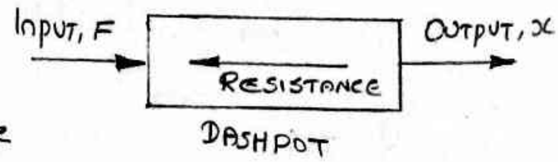
⇒ In ideal case, the damping force is proportional to the velocity of the piston.



$$F = c.V$$

where;

$c \rightarrow$ a constant



⇒ Since velocity is the rate of change of distance moved x,

$$F = c.\frac{dx}{dt}$$

⇒ In a dashpot there is no energy stored. It dissipates energy rather storing it.

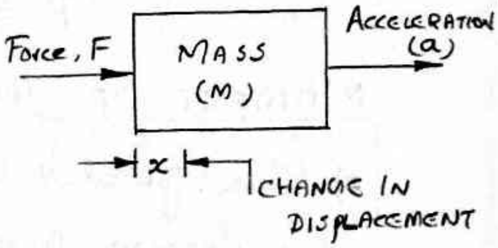
Power dissipated, $P = c V^2$

MASSES

⇒ Masses represents the inertia or resistance to acceleration

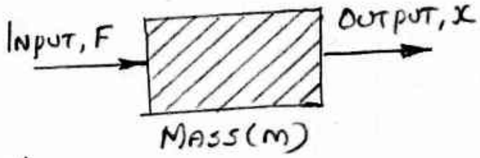
⇒ It exhibits the property that the bigger the mass, the greater the force required to a specific acceleration.

⇒ As per Newton's law;



$$F = ma$$

$$= m \times \frac{dv}{dt} = m \times \frac{d}{dt}\left(\frac{dx}{dt}\right)$$



$$F = m \times \frac{d^2x}{dt^2}$$

⇒ Kinetic energy in the mass when it is moving with a velocity v, and released when it stops moving;

$$E = \frac{1}{2} m v^2$$

ROTATIONAL SYSTEMS

TORSIONAL SPRING

⇒ In a torsional spring the angle rotated (θ) is proportional to the torque (T)

$$T = k\theta$$

⇒ Energy stored in torsional spring when twisted through an angle θ,

$$E = \frac{1}{2} k\theta^2 = \frac{1}{2} \frac{T^2}{k}$$

ROTARY DAMPER

⇒ In the rotary damper, a disc is rotated in a fluid and the resistive torque (T) is proportional to the angular velocity (ω);

$$T = c\omega = c\frac{d\theta}{dt}$$

⇒ Power dissipated by the rotary damper when rotating with an angular velocity ω;

$$P = c\,\omega^2$$

MOMENT OF INERTIA(I)

⇒ The greater the moment of inertia (I), the greater the torque needed to produce an angular acceleration α;

$$T = I\cdot\alpha$$

$$= I\frac{d\omega}{dt} = I\frac{d}{dt}\left(\frac{d\theta}{dt}\right)$$

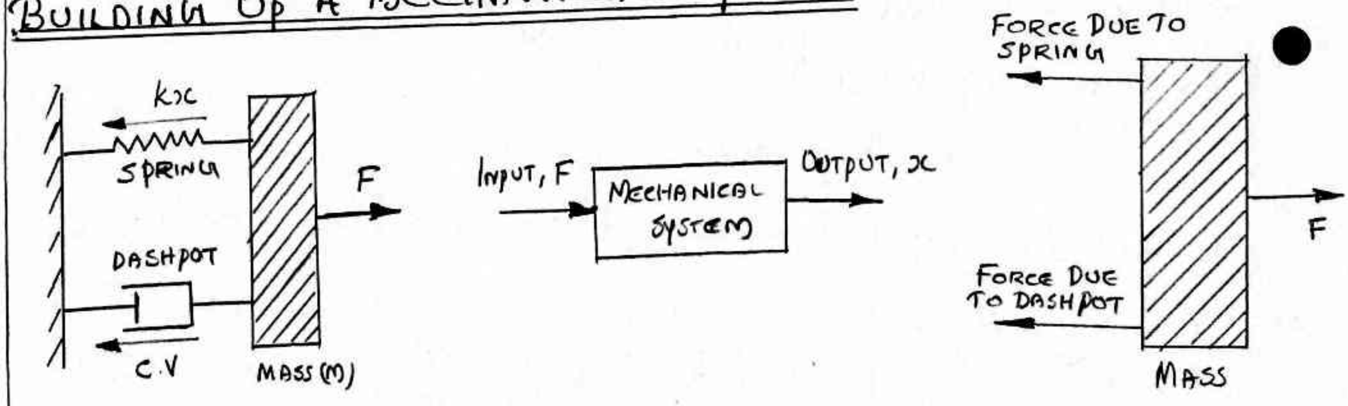
$$= I\frac{d^2\theta}{dt^2}$$

[Angular acceleration is the rate of change of angular velocity and angular velocity is the rate of change of angular displacement]

⇒ Energy stored by a mass rotating with an angular velocity ω;

$$= \frac{1}{2} I\omega^2$$

BUILDING UP A MECHANICAL SYSTEM



(a) COMPONENTS (b) SCHEMATIC (c) FREE BODY DIAGRAM

MECHANICAL SYSTEM

⇒ A mechanical system can be considered to consist of a mass, spring and a dash pot as shown in figure.

⇒ Net force applied to the mass (m) to cause the mass to accelerate;

$$= F - kx - c.v$$

where;

$v \rightarrow$ The velocity with which the piston in the dashpot and hence m is moving.

$x \rightarrow$ The change in length of the spring

$k \rightarrow$ stiffness of the spring

$$F - kx - cv = ma$$

$$F - kx - c\frac{dx}{dt} = m\frac{d^2x}{dt^2}$$

$$m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx = F$$

⇒ It is a second order equation.

ELECTRICAL SYSTEM BUILDING BLOCKS

⇒ The building blocks in an electrical systems are;

↳ Resistors
↳ Inductors
↳ Capacitors

RESISTORS

⇒ The potential difference across a resistor at any instant depends on the current I through it.

$$V = IR$$

where;

$R \rightarrow$ Resistance

⇒ Power dissipated by a resistor

$$P = V \times I = \frac{V^2}{R}$$

INDUCTORS

⇒ The potential difference V across an inductor at any instant depends on the rate of change of current $\left(\frac{dI}{dt}\right)$ through it;

$$V = L.\frac{dI}{dt}$$

where;

L → Inductance

⇒ The direction of the potential difference is in the opposite direction to the potential difference used to drive the current through the inductor, hence the term back emf.

$$I = \frac{1}{L}\int v\,dt$$

⇒ Energy stored by an inductor $= \frac{1}{2} L I^2$

CAPACITORS

⇒ The potential difference across a capacitor depends on the charge 'Q' on the capacitor plates at the instant concerned.

$$V = \frac{Q}{C}$$

where;

C → capacitance

⇒ The current i to or from the capacitor is the rate at which charge moves to or from the capacitor plates. ie;

$$i = \frac{dq}{dt}$$

∴ Total charge on the plate;

$$Q = \int i\,dt$$

$$V = \frac{1}{C}\int i\,dt$$

⇒ Energy stored by capacitor $= \frac{1}{2}CV^2$

BUILDING UP A MODEL FOR AN ELECTRICAL SYSTEM

⇒ Kirchhoff's Laws can be used for combining various building blocks.

KIRCHHOFF'S CURRENT LAW

⇒ The sum of currents entering a junction is equal to the sum of the currents leaving the junction.

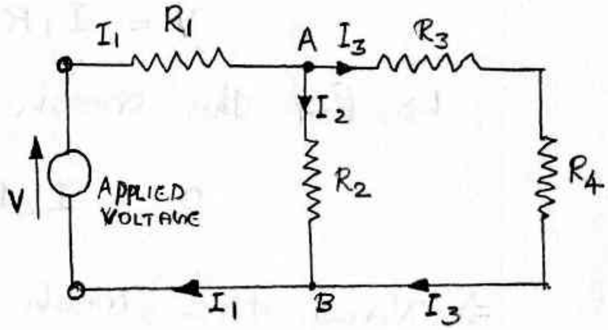
KIRCHHOFF'S VOLTAGE LAW

⇒ The sum of emf's (rise of potential) around any closed loop of a circuit equals the sum of the potential drops in that loop.

NODE ANALYSIS

⇒ It is a convenient method for using Kirchhoff's Current Law.

⇒ Consider the node point A,



NODE ANALYSIS

⇒ According to Kirchhoff's Current Law;

$$I_1 = I_2 + I_3 \quad \text{—— (1)}$$

$$V_1 = V - V_A$$

$$I_1 R_1 = V - V_A$$

$$I_1 = \frac{V - V_A}{R_1}$$

$$I_2 R_2 = V_A$$

$$I_2 = \frac{V_A}{R_2}$$

$$I_3 (R_3 + R_4) = V_A$$

$$I_3 = \frac{V_A}{R_3 + R_4}$$

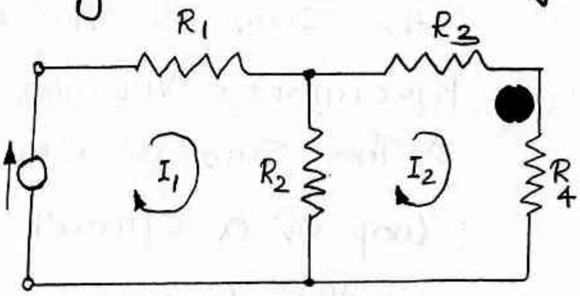
⇒ Substituting in equation 1, we get,

$$\frac{V - V_A}{R_1} = \frac{V_A}{R_2} + \frac{V_A}{R_3 + R_4}$$

MESH ANALYSIS

⇒ It is a convenient method of using Kirchhoff' Voltage Law.

⇒ Let us assume that the currents are circulating in each mesh as shown in figure



MESH ANALYSIS

⇒ According to Kirchhoff' Voltage law

↳ For the mesh with current I_1 and source emf V;

$$V = I_1 R_1 + (I_1 - I_2) R_2$$

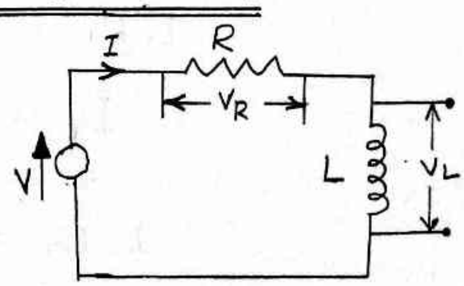
↳ For the mesh with current I_2 and no source emf:

$$0 = I_2 R_3 + I_2 R_4 + (I_2 - I_1) R_2$$

⇒ Now the mesh currents I_1 and I_2 can be found out from the above equations.

RESISTOR - INDUCTOR SYSTEM / (R-L) SYSTEM

⇒ Applying KVL to the circuit loop;



$$V = V_R + V_L$$

where;

$$V_R = IR$$

$$V = IR + V_L$$

Since; $I = \frac{1}{L}\int V_L\, dt$

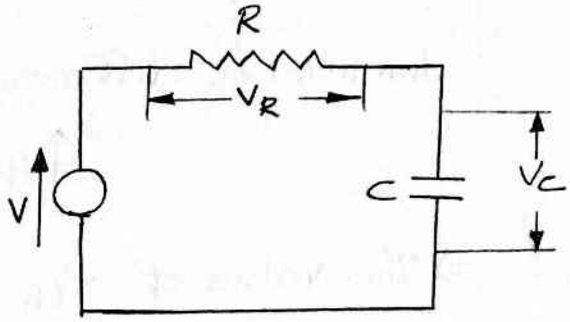
Then; the relationship between input and output is;

$$V = \frac{R}{L}\int V_L\, dt + V_L$$

RESISTOR - CAPACITOR SYSTEM

⇒ Applying KVR to the circuit loop;

$$V = V_R + V_C$$



RESISTOR-CAPACITOR SYSTEM

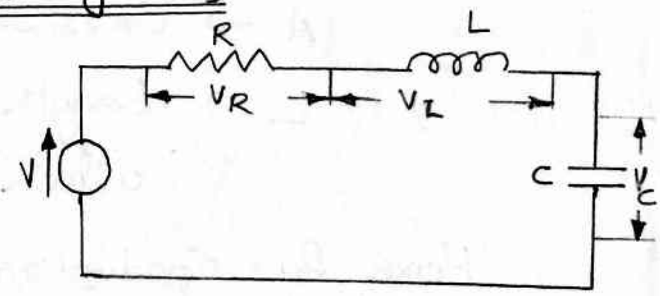
Now; $V_R = IR$

$$I = C.\frac{dV_C}{dt}$$

$$\therefore\ V = RC\frac{dV_C}{dt} + V_C$$

RESISTOR - INDUCTOR - CAPACITOR SYSTEM

⇒ Applying KVL to the circuit loop;



$$V = V_R + V_L + V_C$$

or

$$V = IR + L\frac{dI}{dt} + V_C$$

But; $I = C.\frac{dV_C}{dt}$

$$\frac{dI}{dt} = C\frac{d(dV_C/dt)}{dt} = C\frac{d^2V_C}{dt^2}$$

Hence;

$$V = RC\frac{dV_C}{dt} + LC\frac{d^2V_C}{dt^2} + V_C$$

THERMAL SYSTEM BUILDING BLOCKS

⇒ For thermal systems; there are only two building blocks
↳ Resistance (R_{th})
↳ Capacitance (C_{th})

THERMAL RESISTANCE (R_{th})

⇒ If q_{th} is the rate of flow of heat and $(T_2 - T_1)$ the temperature difference, then

$$q_{th} = \frac{T_2 - T_1}{R_{th}}$$

⇒ The value of R_{th} depends on mode of heat transfer.

⇒ For unidirectional Conduction;

$$q_{th} = kA\frac{(T_2 - T_1)}{L}$$

where;

k → thermal Conductivity
A → Cross sectional area of the material
L → Length of the material between the points at which temperatures are T_1 and T_2

Hence for Conduction;

$$1/R_{th} = \frac{kA}{L}$$

$$R_{th} = \frac{L}{kA}$$

⇒ When the mode of heat transfer is Convection;

$$q_{th} = Ah(T_2 - T_1)$$

where;

h → The heat transfer Coefficient

Thus, with this mode of heat transfer

$$R_{th} = \frac{1}{Ah}$$

Thermal Capacitance (C_{th})

⇒ Thermal capacitance is a measure of the store of internal energy in a system

⇒ If the rate of heat flow into the system is q_{th1} and rate of heat flow out is q_{th2}, then,

$$q_{th1} - q_{th2} = mc\frac{dT}{dt}$$

where;

$m \rightarrow$ Mass

$c \rightarrow$ Specific heat capacity

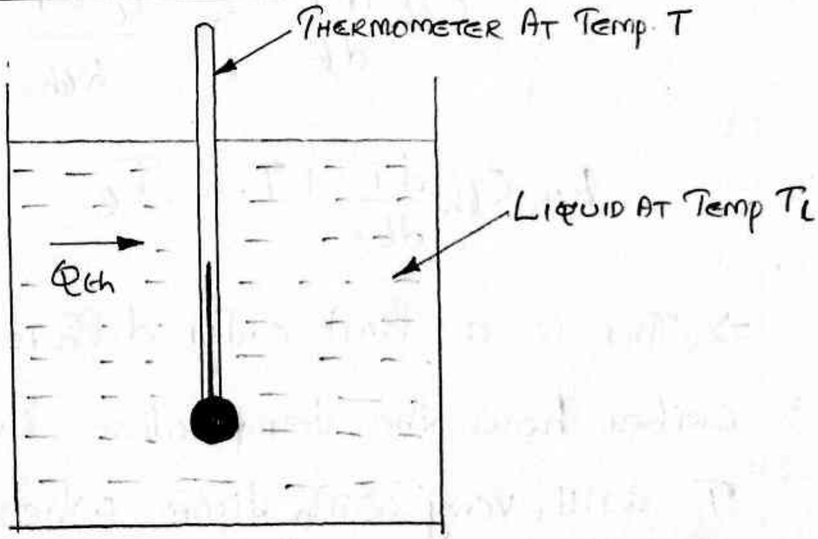
$\frac{dT}{dt} \rightarrow$ Rate of change of temperature.

$$q_{th_1} - q_{th_2} = C_{th}\frac{dT}{dt}$$

where;

$$C_{th} \text{ (thermal Capacitance)} = mc$$

Building Up A Model For A Thermal System



A Thermal System

⇒ Consider a thermometer at temperature T inserted into a liquid at temperature T_L

$$q_{th} = \frac{T_L - T}{R_{th}} \quad \text{——— (1)}$$

where;

q_{th} → Net rate of heat flow from liquid to the thermometer

R_{th} → Thermal resistance.

⇒ Thermal Capacitance (C_{th}) of the thermometer is;

$$q_{th_1} - q_{th_2} = C_{th}\frac{dT}{dt}$$

⇒ Here, there is only a net heat flow from the liquid to the thermometer.

$$\therefore\ q_{th_1} = q_{th} \ ; \ q_{th_2} = 0$$

$$\hookrightarrow \quad q_{th} = C_{th}\frac{dT}{dt}$$

Substituting in eqn (1)

$$C_{th}\frac{dT}{dt} = \frac{T_L - T}{R_{th}}$$

$$R_{th}C_{th}\frac{dT}{dt} + T = T_L.$$

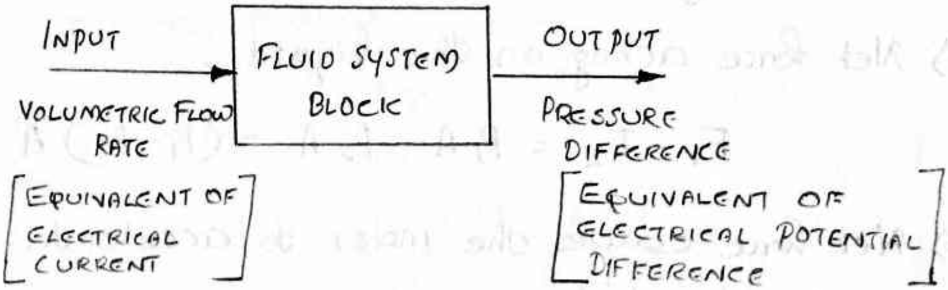
⇒ This is a first order differential equation and describes how the temperature indicated by the thermometer T will vary with time when it is inserted into a hot liquid.

FLUID SYSTEM BUILDING BLOCKS

=> Fluid system can be considered to fall into two categories

↳ Hydraulic system :- Here the fluid is a liquid and is considered to be incompressible

↳ Pneumatic System :- Here the fluid is a gas which can be compressed and consequently shows a change of density.



FLUID SYSTEM

HYDRAULIC SYSTEMS

HYDRAULIC RESISTANCE (R_h)

=> It is the resistance to the flow.

=> It occurs as a result of the liquid flowing through a valve or a change in pipe diameter.

$$P_1 - P_2 = R_h \times Q_1$$

where;

$P_1 - P_2$ → Difference of pressure

R_h → Hydraulic resistance

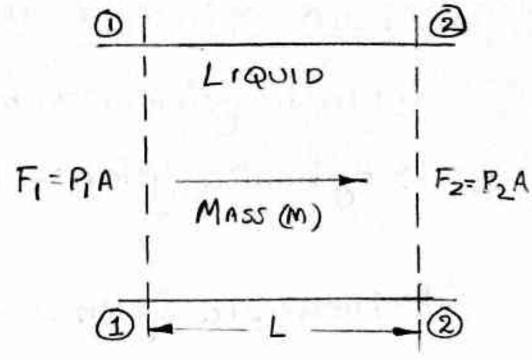
Q_1 → Volume rate of flow of liquid

=> Energy dissipated $P = \frac{1}{R_h}(P_1 - P_2)^2$

HYDRAULIC INERTANCE (I_h)

=> It is equivalent to inductance in electrical systems or a spring in mechanical systems.

⇒ Consider a liquid block of mass 'm',



HYDRAULIC INERTANCE

P_1 → Intensity of pressure at section-1

F_1 → Force acting at section-1

P_2 → Intensity of pressure at section-2

F_2 → Force acting at section-2

A → Cross sectional area

L → Length of the block

⇒ Net force acting on the liquid ;

$$F_1 - F_2 = P_1 A - P_2 A = (P_1 - P_2) A$$

⇒ Net force causes the mass to accelerate with an acceleration 'a' ;

$$(P_1 - P_2) A = ma$$

$$(P_1 - P_2) A = m \frac{dv}{dt}$$

Also, Mass of liquid $m = AL\rho$

$$\therefore (P_1 - P_2) A = AL\rho \frac{dv}{dt}$$

$$(P_1 - P_2) A = L\rho \frac{dQ_1}{dt}$$

$$(P_1 - P_2) = I_h \frac{dQ_1}{dt}$$

Volume rate of flow

$$q = Av$$

$$v = \frac{q}{A}$$

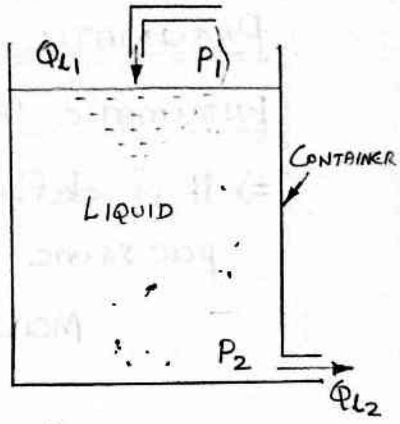
⇒ Hydraulic inertance $I_h = \frac{L\rho}{A}$

⇒ Energy stored by inertance, $E = \frac{1}{2} I_h Q_1^2$

HYDRAULIC CAPACITANCE (C_h)

⇒ This term is used to describe the energy stored in a liquid when it is stored in the form of potential energy.

=> Consider a Container filled with a liquid,



HYDRAULIC CAPACITANCE

A → Cross sectional area of Container

H → Height of liquid in Container

Q_{l_1}, Q_{l_2} → The rates of liquid flow at the entrance and exit of Container

V → Volume of liquid in Container

p → Pressure difference between the input and output.

$$Q_{l_1} - Q_{l_2} = \frac{dV}{dt}$$

$$= \frac{d(AH)}{dt} = A\frac{dH}{dt}$$

Also;

$$p = \rho g H \quad ; H = \frac{p}{\rho g}$$

=> If the liquid is assumed incompressible then ρ does not change with pressure. Then;

$$Q_{l_1} - Q_{l_2} = \frac{A}{\rho g} \cdot \frac{dp}{dt}$$

$$= C_h \cdot \frac{dP}{dt}$$

where;

C_h → Hydraulic Capacitance $= \frac{A}{\rho g}$

=> By integrating;

$$p = \frac{1}{C_h} \int (Q_{l_1} - Q_{l_2})\, dt$$

=> Energy stored by Capacitance

$$E = \frac{1}{2} C_h (P_1 - P_2)^2$$

Pneumatic System

Pneumatic Resistance (R_{pn})

⇒ It is defined in terms of the mass flow rate and pressure difference.

$$\text{Mass flow rate } \dot{m} = \frac{dm}{dt}$$

$$\text{Pressure difference} = P_1 - P_2$$

$$P_1 - P_2 = R_{pn} \cdot \frac{dm}{dt} = R_{pn} \cdot \dot{m}$$

⇒ Power dissipated ;

$$P = \frac{1}{R_{pn}} (P_1 - P_2)^2$$

Pneumatic Inertance (I_{pn})

⇒ The pneumatic inertance is due to the pressure drop necessary to accelerate a block of gas.

⇒ According to Newton's second law;

$$(P_1 - P_2) A = ma$$

$$= m \cdot \frac{dv}{dt} = \frac{d(mv)}{dt}$$

where;

$P_1 - P_2$ → Pressure difference

A → Area of cross section

a → acceleration of gas

⇒ Also;

$$mv = \rho A L \times v = \rho A L \frac{Q_{pn}}{A} = \rho L Q_{pn}$$

where;

L → Length of the block being accelerated

v → Velocity of the gas

Q_{pn} → Volume rate of gas flow.

Thus,

$$(P_1 - P_2) A = L \frac{d(\rho Q_{pn})}{dt} \quad \Big| \quad \dot{m} = \rho Q_{pn}$$

$$P_1 - P_2 = \frac{L}{A} \frac{d\dot{m}}{dt}$$

$$= I_{pn} \frac{d\dot{m}}{dt}$$

where;

$I_{pn} \rightarrow$ Pneumatic inertance $= \frac{L}{A}$

PNEUMATIC CAPACITANCE (C_{pn})

⇒ The pneumatic capacitance is due to the compressibility of the gas and is comparable to the way in which the compression of the spring stores energy.

Let;

$V \rightarrow$ volume of the gas entering the container

$\frac{dm_1}{dt} \rightarrow$ Mass rate of flow entering the container

$\frac{dm_2}{dt} \rightarrow$ Mass rate of flow leaving the container

$\rho \rightarrow$ density of gas in the container

⇒ p and V can vary with time since the gas is compressible

Rate of change of mass in container

$$= \rho \frac{dV}{dt} + V \frac{d\rho}{dt}$$

$\because \frac{dV}{dt} = \frac{dV}{dp} \times \frac{dp}{dt}$ and for ideal gas $pV = mRT$

$$P = \frac{m}{V} RT$$

$$= \rho RT$$

$$\rho = \frac{P}{RT} \Rightarrow \frac{d\rho}{dt} = \frac{1}{RT}\left[\frac{dp}{dt}\right]$$

Now, Rate of change of mass in Container;

$$\frac{dm_1}{dt} - \frac{dm_2}{dt} = \rho \frac{dV}{dp} \times \frac{dp}{dt} + \frac{V}{RT}\frac{dp}{dt}$$

$$= \left[\rho \frac{dV}{dp} + \frac{V}{RT}\right]\frac{dp}{dt}$$

$R \rightarrow$ Gas Constant

$T \rightarrow$ Absolute temp.

$$= \left(C_{pn_1} + C_{pn_2}\right)\frac{dp}{dt}$$

Where;

$C_{pn_1} \rightarrow$ Pneumatic Capacitance due to change of volume of the Container

$C_{pn_2} \rightarrow$ Pneumatic capacitance due to the Compressibility of the gas.

$$\dot{m}_1 - \dot{m}_2 = \left(C_{pn_1} + C_{pn_2}\right)\frac{dp}{dt}$$

$$dp = \left(\frac{1}{C_{pn_1} + C_{pn_2}}\right)(\dot{m}_1 - \dot{m}_2)dt$$

$$P_1 - P_2 = \frac{1}{C_{pn_1} + C_{pn_2}}\int(\dot{m}_1 - \dot{m}_2)\,dt$$

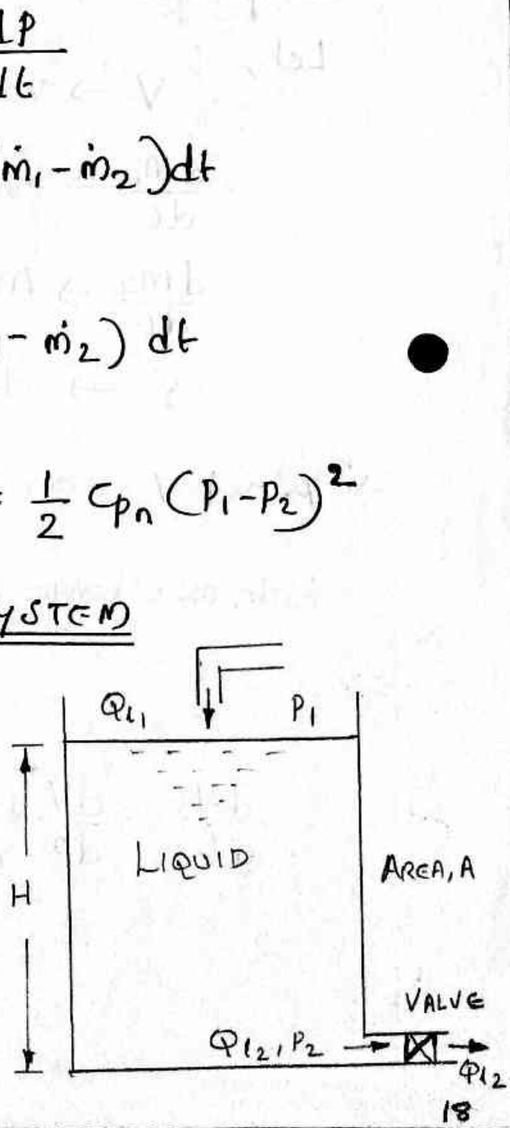
$\Rightarrow$ Energy stored by Capacitance; $E = \frac{1}{2} C_{pn}(P_1 - P_2)^2$

BUILDING UP A MODEL FOR A FLUID SYSTEM

HYDRAULIC SYSTEM

$\Rightarrow$ The system can be considered to consist of;

- ↳ A capacitor - Liquid in the Container
- ↳ A resistor - the valve
- ↳ Inertance neglected since flow rate changes very slowly



⇒ For the capacitor;

$$Q_{l_1} - Q_{l_2} = C_h \frac{dp}{dt} \quad \ldots\ldots (1)$$

⇒ For the resistor;

$$P_1 - P_2 = R_h Q_{l_2} \quad \ldots\ldots (2)$$

$$\because P_1 - P_2 = P = \rho g H$$

$$(2) \Rightarrow \quad Q_{l_2} = \frac{\rho g H}{R_h}$$

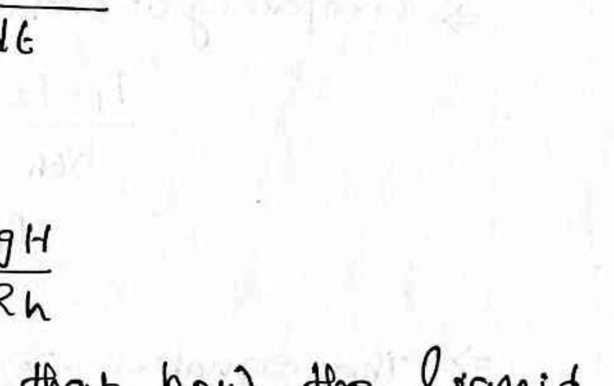
$$(1) \Rightarrow \quad Q_{l_1} - \frac{\rho g H}{R_h} = C_h \frac{d(\rho g H)}{dt}$$

⇒ But; $C_h = \frac{A}{\rho g}$

$$\therefore Q_{l_1} = A \cdot \frac{dH}{dt} + \frac{\rho g H}{R_h}$$

⇒ The above equation conveys that how the liquid height in the container depends on the rate of input of liquid into the container.

PNEUMATIC SYSTEM



⇒ The system can be considered to consists of

↳ A capacitor - The bellow itself

↳ A resistor - A constriction which restricts the rate of flow of gas into the bellows.

↳ Inertance neglected - since the flow rate changes very slowly

⇒ The rate of mass flow ($\dot{m}$) into the bellows is given by;

$$P_1 - P_2 = R_{pn}\,\dot{m} \quad \text{——— (1)}$$

where;

P_1 → Pressure prior to the constriction

P_2 → Pressure after constriction

R_{pn} → Resistance provided by constriction

⇒ The capacitance of the bellows is given by,

$$\dot{m}_1 - \dot{m}_2 = \left(C_{pn_1} + C_{pn_2}\right)\frac{dP_2}{dt} \quad \text{——— (2)}$$

⇒ Comparing (1) and (2)

$$\frac{P_1 - P_2}{R} = \left(C_{pn_1} + C_{pn_2}\right)\frac{dP_2}{dt}$$

$$P_1 = R_{pn}\left(C_{pn_1} + C_{pn_2}\right)\frac{dP_2}{dt} + P_2 \quad \text{——— (3)}$$

⇒ the equation convey that how the pressure in the bellow P_2 varies with time when there is an input of pressure P_1

⇒ Since bellows are just a form of spring;

Force causing expansion or contraction of bellows;

$$F = kx$$

Also, $$P_2 = \frac{F}{A} = \frac{kx}{A}$$

⇒ Equation (3) becomes;

$$P_1 = R_{pn}\left(C_{pn_1} + C_{pn_2}\right)\frac{k}{A}\frac{dx}{dt} + \frac{k}{A}x$$

⇒ Pneumatic Capacitance;

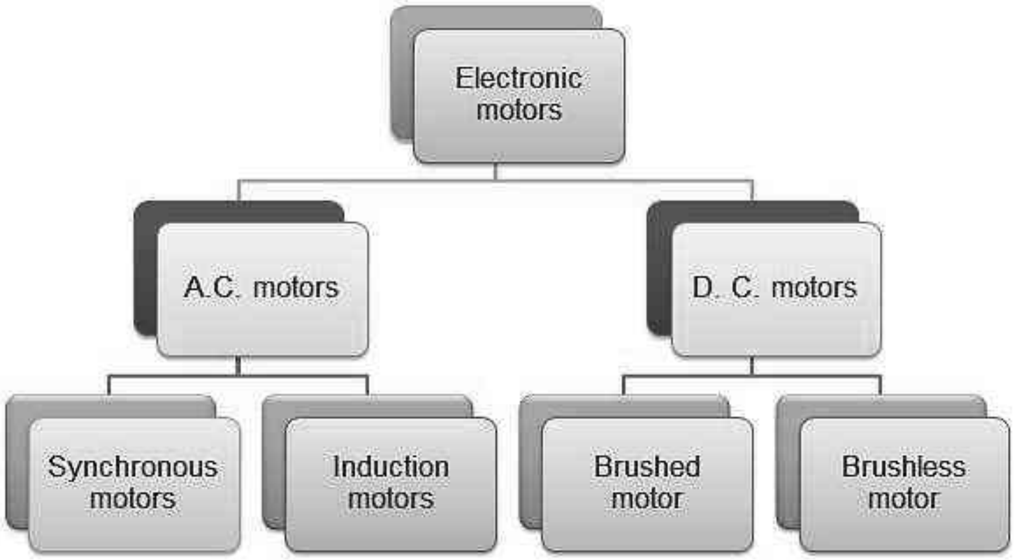
$$C_{pn_1} = \rho\frac{dV}{dP_2} = \rho A\frac{dx}{d(kx/A)} = \frac{\rho A^2}{k} \qquad \Bigg|\ \because V = Ax,\ \ P_2 A = kx$$

$$C_{pn_2} = \frac{V}{RT} = \frac{Ax}{RT}$$

MECHATRONICS IN ROBOTICS

ELECTRICAL DRIVES

- Electric drives are mostly used in position and speed control systems. The motors can be classified into two groups namely DC motors and AC motors.



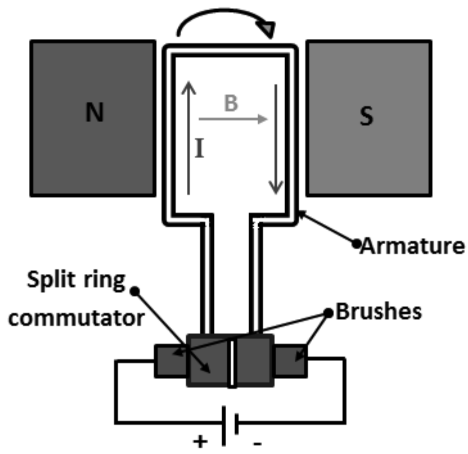
Classification of Motors

DC MOTORS

- A DC motor is a device that converts direct current (electrical energy) into rotation of an element (mechanical energy).
- These motors can further be classified into
    - Brushed DC motor
    - Brushless DC motors

BRUSH TYPE DC MOTOR

- A typical brushed motor consists of an armature coil, slip rings divided into two parts, a pair of brushes and horse shoes electromagnet.
- A simple DC motor has two field poles namely a north pole and a south pole. The magnetic lines of force extend across the opening between the poles from north to south.
- The coil is wound around a soft iron core and is placed in between the magnet poles. These electromagnets receive electricity from an outside power source. The coil ends are connected to split rings.
- The carbon brushes are in contact with the split rings. The brushes are connected to a DC source. Here the split rings rotate with the coil while the brushes remain stationary.
- The working is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by Fleming's left-hand rule.



Brushed DC Motor

- The magnitude of the force is given by

$$F=BIL\sin\theta$$

Where,

B - magnetic field density in weber/m2
I - the current in amperes and
L - the length of the conductor in meter
θ - the angle between the direction of the current in the conductor and the electric field

- If the current and filed are perpendicular then $\theta=90°$. The equation becomes,

$$F=BIL$$

- A direct current in a set of windings creates a magnetic field. This field produces a force which turns the armature. This force is called torque.
- This torque will cause the armature to turn until its magnetic field is aligned with the external field. Once aligned the direction of the current in the windings on the armature reverses, thereby reversing the polarity of the rotor's electromagnetic field.
- A torque is once again exerted on the rotor, and it continues spinning. The change in direction of current is facilitated by the split ring commutator.
- The main purpose of the commutator is to overturn the direction of the electric current in the armature. It also aids in the transmission of current between the armature and the power source.
- The brushes remain stationary, but they are in contact with the armature at the commutator, which rotates with the armature such that at every 180° of rotation, the current in the armature is reversed.

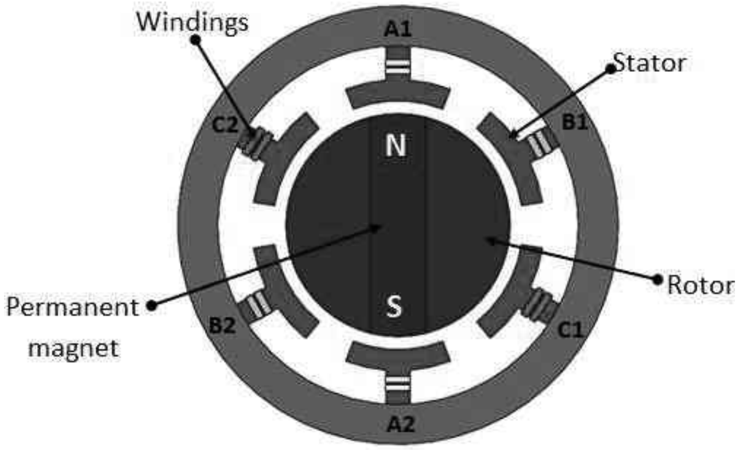
Advantages of brushed DC motor:

- The design of the brushed DC motor is quite simple
- Controlling the speed of a Brush DC Motor is easy
- Very cost effective

Disadvantages of brushed DC motor:

- High maintenance
- Performance decreases with dust particles
- Less reliable in control at lower speeds
- The brushes wear off with usage

BRUSHLESS DC MOTOR



Brushless DC Motor

- A brushless DC motor has a rotor with permanent magnets and a stator with windings. The rotor can be of ceramic permanent magnet type.
- The brushes and commutator are eliminated and the windings are connected to the control electronics. The control electronics replace the commutator and brushes and energize the stator sequentially. Here the conductor is fixed and the magnet moves.
- The current supplied to the stator is based on the position of rotor. It is switched in sequence using transistors. The position of the rotor is sensed by Hall effect sensors. Thus a continuous rotation is obtained.

Advantages of brushless DC motor:

- More precise due to computer control
- More efficient
- No sparking due to absence of brushes
- Less electrical noise
- No brushes to wear out
- Electromagnets are situated on the stator hence easy to cool
- Motor can operate at speeds above 10,000 rpm under loaded and unloaded conditions
- Responsiveness and quick acceleration due to low rotor inertia

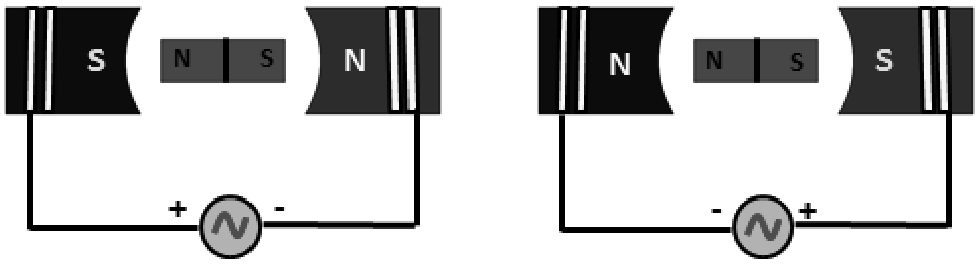
Disadvantages of brushless DC motor:

- Higher initial cost
- Complex due to presence of computer controller
- Brushless DC motor also requires additional system wiring in order to power the electronic commutation circuitry

AC MOTORS

- AC motors convert AC current into the rotation of a mechanical element (mechanical energy). As in the case of DC motor, a current is passed through the coil, generating a torque on the coil.
- Typical components include a stator and a rotor. The armature of rotor is a magnet unlike DC motors and the stator is formed by electromagnets similar to DC motors.

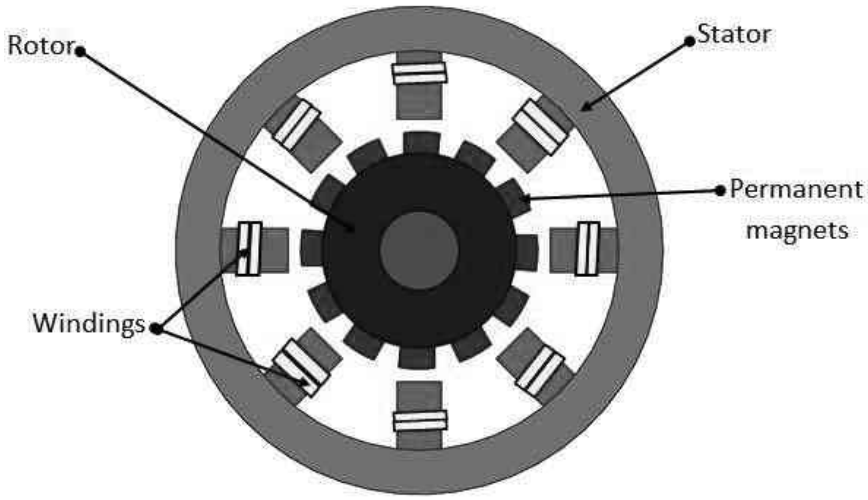
- The main limitation of AC motors over DC motors is that speed is more difficult to control in AC motors.
- To overcome this limitation, AC motors are equipped with variable frequency drives but the improved speed control comes together with a reduced power quality.



AC Motor Working Principle

- Consider the rotor to be a permanent magnet. Current flowing through conductors energizes the magnets and develops N and S poles.
- The strength of electromagnets depends on current. First half cycle current flows in one direction and in the second half cycle it flows in opposite direction. As AC voltage changes the poles alternate.
- AC motors can be classified into
    - Synchronous motors
    - Induction motors.

<u>SYNCHRONOUS MOTORS</u>



AC Synchronous Motor

- A synchronous motor is an AC motor which runs at constant speed fixed by frequency of the system.
- It requires direct current (DC) for excitation and has low starting torque, and hence is suited for applications that start with a low load.
- It has two basic electrical parts namely stator and rotor.
- The stator consists of a group of individual wounded electro-magnets arranged in such a way that they form a hollow cylinder. The stator produces a rotating magnetic field that is proportional to the frequency supplied.

- The rotor is the rotating electrical component. It also consists of a group of permanent magnets arranged around a cylinder, with the poles facing toward the stator poles. The rotor is mounted on the motor shaft.
- The main difference between the synchronous motor and the induction motor is that the rotor of the synchronous motor travels at the same speed as the rotating magnet.
- The stator is given a three phase supply and as the polarity of the stator progressively change the magnetic field rotates, the rotor will follow and rotate with the magnetic field of the stator.
- If a synchronous motor loses lock with the line frequency it will stall. It cannot start by itself, hence has to be started by an auxiliary motor.
- Synchronous speed of an AC motor is determined by the following formula:

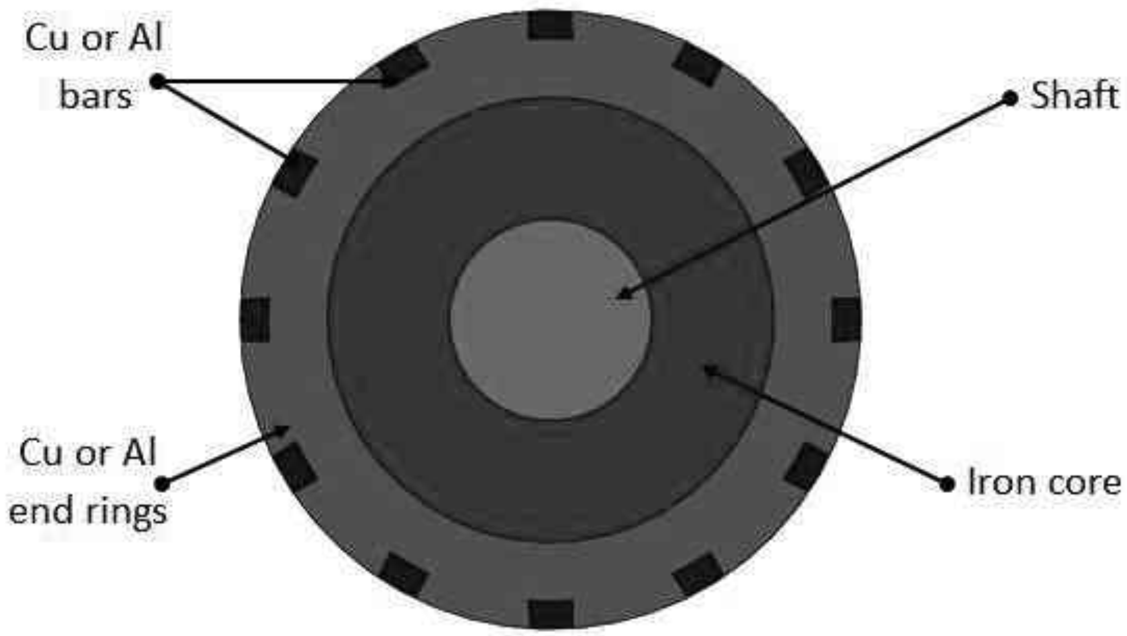
$$N_s = \frac{120 * f}{P}$$

Where,

Ns	-	Revolutions per minute
P	-	Number of pole pairs
f	-	Applied frequency

INDUCTION MOTOR

- Induction motors are quite commonly used in industrial automation. In the synchronous motor the stator poles are wound with coils and rotor is permanent magnet and is supplied with current to create fixed polarity poles.
- In case of induction motor, the stator is similar to synchronous motor with windings but the rotors' construction is different.



Induction Motor Rotor

- Rotor of an induction motor can be of two types:
    - ***A squirrel-cage rotor*** consists of thick conducting bars embedded in parallel slots. The bars can be of copper or aluminum. These bars are fitted at both ends by means end rings.
    - **A wound rotor** has a three-phase, double-layer, distributed winding. The rotor is wound for as many numbers of poles as the stator. The three phases are wired internally and the other ends are connected to slip-rings mounted on a shaft with brushes resting on them.
- Induction motors can be classified into two types:
    - ***Single-phase induction motor*:** It has one stator winding and a squirrel cage rotor. It operates with a single-phase power supply and requires a device to start the motor.
    - ***Three-phase induction motor*:** The rotating magnetic field is produced by the balanced three-phase power supply. These motors can have squirrel cage or wound rotors and are self-starting.
- In an induction motor there is no external power supply to rotor. It works on the principle of induction.
- When a conductor is moved through an existing magnetic field the relative motion of the two causes an electric current to flow in the conductor.
- In an induction motor the current flow in the rotor is not caused by any direct connection of the conductors to a voltage source, but rather by the influence of the rotor conductors cutting across the lines of flux produced by the stator magnetic fields.
- The induced current which is produced in the rotor results in a magnetic field around the rotor. The magnetic field around each rotor conductor will cause the rotor conductor to act like the permanent magnet.
- As the magnetic field of the stator rotates, due to the effect of the three-phase AC power supply, the induced magnetic field of the rotor will be attracted and will follow the rotation.
- However, to produce torque, an induction motor must suffer from slip. Slip is the result of the induced field in the rotor windings lagging behind the rotating magnetic field in the stator windings.
- The slip is given by,

$$S = [(\text{Synchronous speed} - \text{Actual speed})/\text{Synchronous speed}]*100\%$$

Advantages of AC induction motors:

- It has a simple design, low initial cost, rugged construction almost unbreakable
- The operation is simple with less maintenance (as there are no brushes)
- The efficiency of these motors is very high, as there are no frictional losses, with reasonably good power factor
- The control gear for the starting purpose of these motors is minimum and thus simple and reliable operation

Disadvantages of AC induction motors:

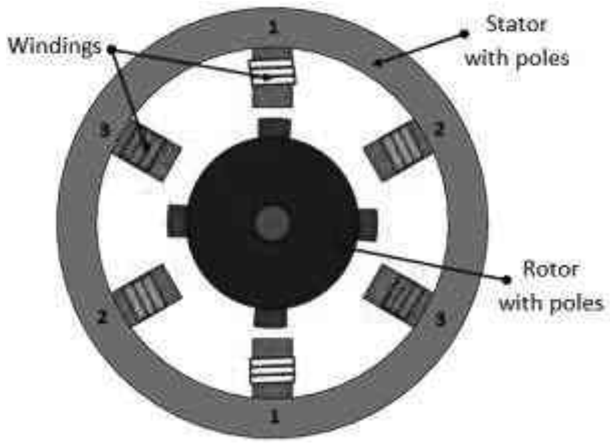
- The speed control of these motors is at the expense of their efficiency
- As the load on the motor increases, the speed decreases
- The starting torque is inferior when compared to DC motors

STEPPER MOTOR

- A stepper motor is a pulse-driven motor that changes the angular position of the rotor in steps. Due to this nature of a stepper motor, it is widely used in low cost, open loop position control systems.
- Types of stepper motors:
    - Permanent Magnet Motor
    - ariable Reluctance Motor

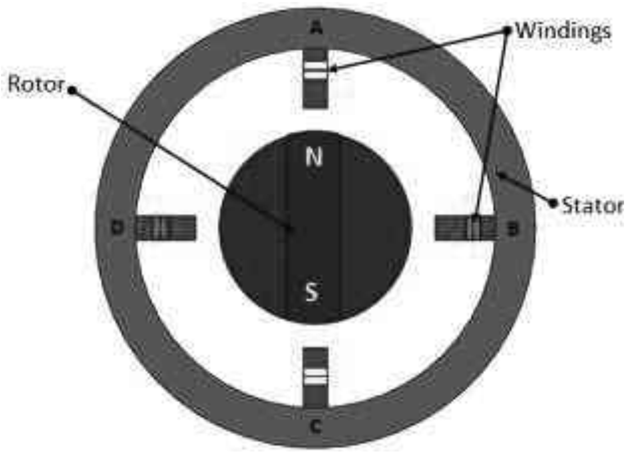
VARIABLE RELUCTANCE MOTOR

- The cylindrical rotor is made of soft steel and has four poles. It has four rotor teeth, 90^0 apart and six stator poles, 60^0 apart.
- Electromagnetic field is produced by activating the stator coils in sequence. It attracts the metal rotor. When the windings are energized in a reoccurring sequence of 2, 3, 1, and so on, the motor will rotate in a 30^0 step angle.
- In the non-energized condition, there is no magnetic flux in the air gap, as the stator is an electromagnet and the rotor is a piece of soft iron; hence, there is no detent torque. This type of stepper motor is called a variable reluctance stepper.



Variable Reluctance Stepper Motor

PERMANENT MAGNET STEPPER MOTOR

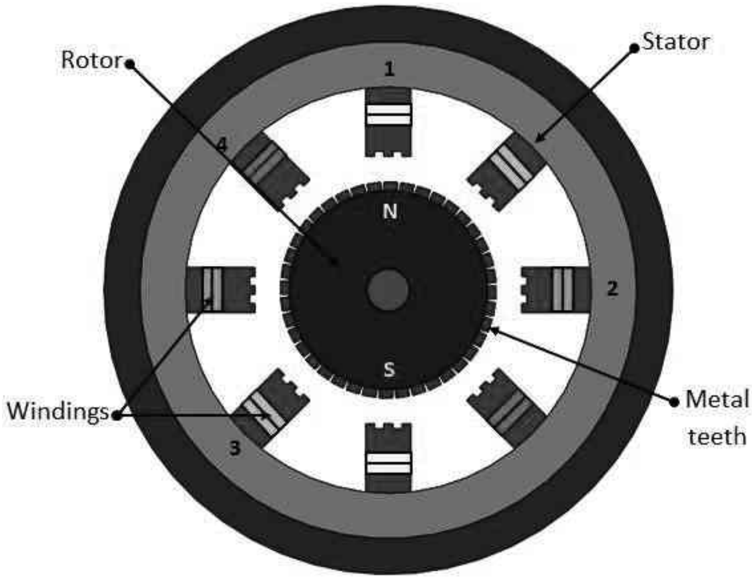


Permanent Magnet Stepper Motor

- In this type of motor, the rotor is a permanent magnet. Unlike the other stepping motors, the PM motor rotor has no teeth and is designed to be magnetized at a right angle to its axis.
- Figure shows a simple, 90^0 PM motor with four phases (A-D). Applying current to each phase in sequence will cause the rotor to rotate by adjusting to the changing magnetic fields.
- Although it operates at fairly low speed, the PM motor has a relatively high torque characteristic. These are low cost motors with typical step angle ranging between 7.5^0 to 15^0.

HYBRID STEPPER MOTOR

- Hybrid stepping motors combine a permanent magnet and a rotor with metal teeth to provide features of the variable reluctance and permanent magnet motors together.
- The number of rotor pole pairs is equal to the number of teeth on one of the rotor's parts. The hybrid motor stator has teeth creating more poles than the main poles windings.



Hybrid Stepper Motor

- Rotation of a hybrid stepping motor is produced in the similar fashion as a permanent magnet stepping motor, by energizing individual windings in a positive or negative direction.
- When a winding is energized, north and south poles are created, depending on the polarity of the current flowing. These generated poles attract the permanent poles of the rotor and also the finer metal teeth present on rotor.
- The rotor moves one step to align the offset magnetized rotor teeth to the corresponding energized windings.
- Hybrid motors are more expensive than motors with permanent magnets, but they use smaller steps, have greater torque and maximum speed.
- Step angle of a stepper motor is given by,

$$\textbf{Step angle} = 360^\circ/\textbf{Number of poles}$$

Advantages of stepper motors:

- Low cost
- Ruggedness
- Simplicity of construction

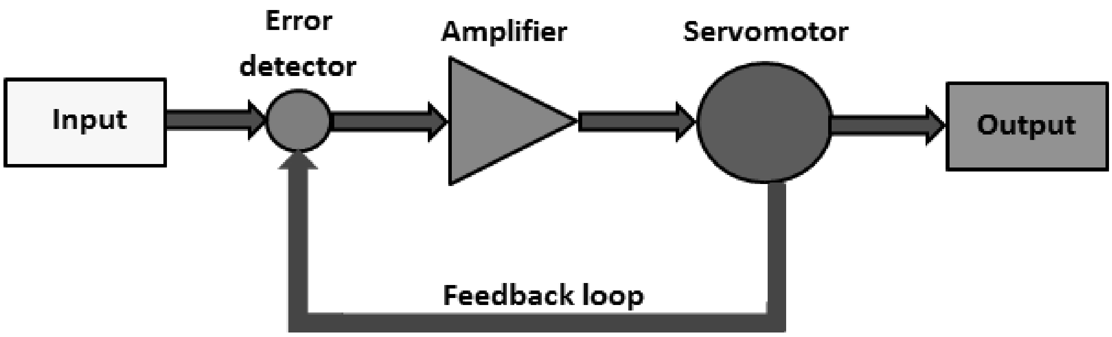
- Low maintenance
- Less likely to stall or slip
- Will work in any environment
- Excellent start-stop and reversing responses

Disadvantages of stepper motors:

- Low torque capacity compared to DC motors
- Limited speed
- During overloading, the synchronization will be broken. Vibration and noise occur when running at high speed.

SERVOMOTOR

- Servomotors are special electromechanical devices that produce precise degrees of rotation. A servo motor is a DC or AC or brushless DC motor combined with a position sensing device.
- Servomotors are also called control motors as they are involved in controlling a mechanical system. The servomotors are used in a closed-loop servo system.
- A reference input is sent to the servo amplifier, which controls the speed of the servomotor. A feedback device is mounted on the machine, which is either an encoder or resolver. This device changes mechanical motion into electrical signals and is used as a feedback.
- This feedback is sent to the error detector, which compares the actual operation with that of the reference input. If there is an error, that error is fed directly to the amplifier, which will be used to make necessary corrections in control action. In many servo systems, both velocity and position are monitored.
- Servomotors provide accurate speed, torque, and have ability of direction control.



Servo System Block Diagram

DC SERVOMOTORS

- DC operated servomotors are usually respond to error signal abruptly and accelerate the load quickly.
- A DC servo motor is actually an assembly of four separate components, namely:
    - DC motor
    - Gear assembly
    - Position-sensing device
    - Control circuit

AC SERVOMOTORS

- In this type of motor, the magnetic force is generated by a permanent magnet and current which further produce the torque. It has no brushes so there is little noise/vibration.
- This motor provides high precision control with the help of high resolution encoder. The stator is composed of a core and a winding.
- The rotor part comprises of shaft, rotor core and a permanent magnet.
- Digital encoder can be of optical or magnetic type. It gives digital signals, which are in proportion of rotation of the shaft.

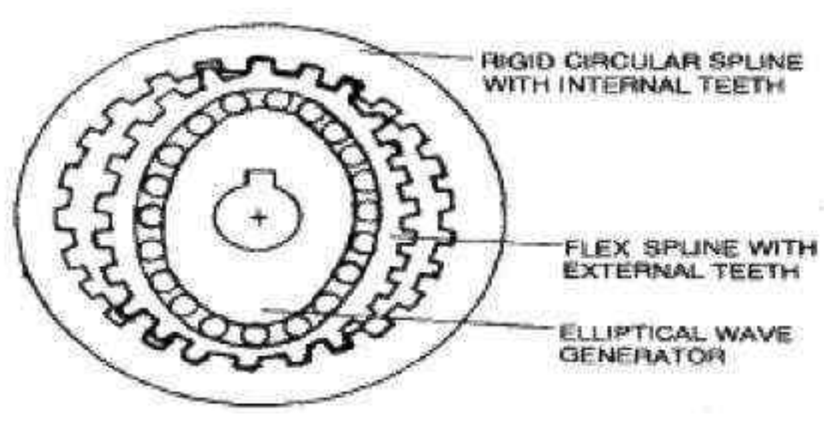
Advantages of servo motors:

- Provides high intermittent torque, high torque to inertia ratio, and high speeds
- Work well for velocity control
- Available in all sizes
- Quiet in operation
- Smoother rotation at lower speeds

Disadvantages of servo motors:

- More expensive than stepper motors
- Require tuning of control loop parameters
- Not suitable for hazardous environments or in vacuum
- Excessive current can result in partial demagnetization of DC type servo motor

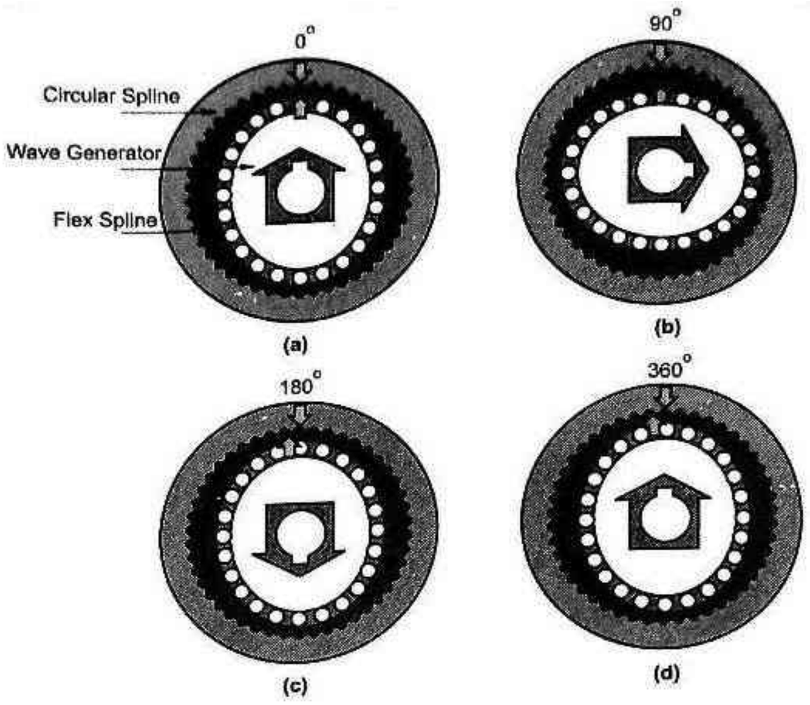
HARMONIC DRIVE



Harmonic Drive

- For speed reduction, standard gear transmission gives sliding friction and backlash. Moreover, it takes more space. Harmonic drive due to its natural preloading eliminates backlash and greatly reduces tooth wear. Harmonic drives are suitable for robot drives due to their smooth and efficient action.
- A harmonic drive consists of a toothed mechanism and it is composed of three main elements.
    - A rigid circular spline
    - An elliptical wave generator
    - A flexible spline (flexspline)

- The flexspline is the main component of a harmonic drive, which can generate a repeated vibration by the wave generator. Due to this reason, the flexspline should have flexibility and good vibration characteristics.
- Harmonic drive is commonly implemented in robotics today and used in aerospace as well for gear reduction, but may also be used to increase rotational speed, or for differential gearing.



Harmonic Drive Working Principle

- The flexspline is slightly smaller in diameter than the circular spline and usually it has two fewer teeth than the circular spline.
- The elliptical shape of the wave generator causes the teeth of the flexspline to engage with the circular spline at two opposite regions across the major axis of the ellipse.
- As the wave generator rotates the teeth of the flexspline engage with the circular spline at major axis.
- For every 180^0 clockwise movement of the wave generator, the flexspline rotates anticlockwise by one tooth in relation to the circular spline.
- For each complete clockwise rotation of the wave generator results in the flexspline moving anticlockwise by two teeth from its original position, relative to the circular spline. Generally this motion is taken out as output.

Advantages of Harmonic Drive:

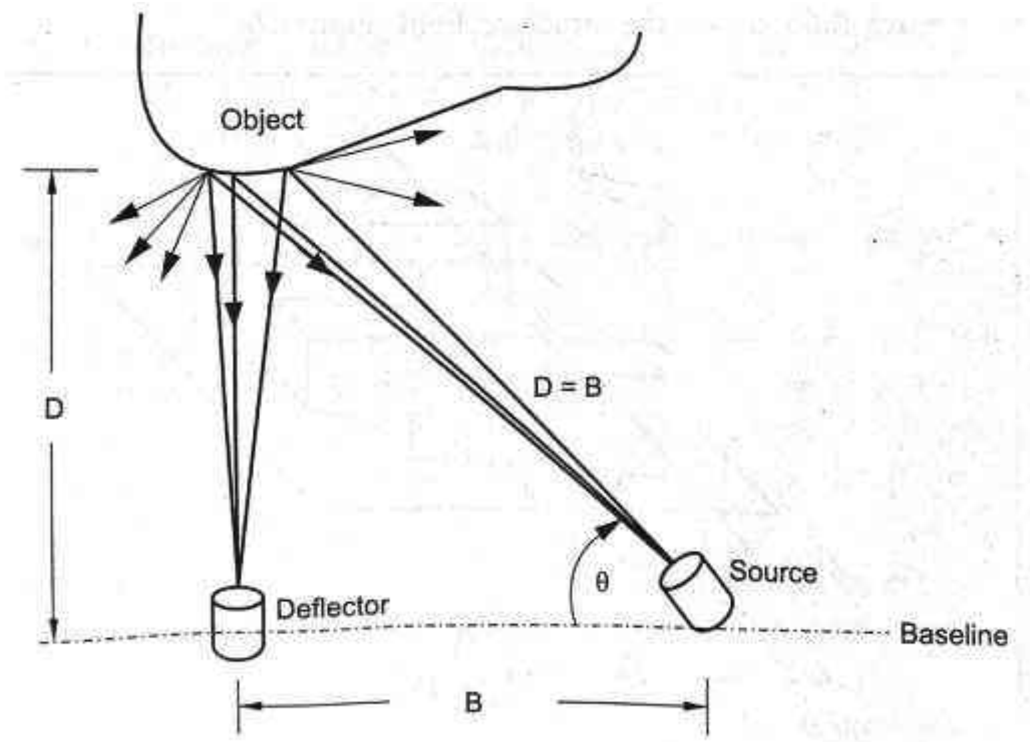
- No backlash
- High compactness
- Light weight
- Higher gear ratio
- Reconfigurable ratios within a standard housing
- Good resolution and excellent repeatability when repositioning inertial loads
- High torque capability

SENSORS IN ROBOTICS

RANGE FINDERS OR RANGE SENSORS

- The distance between the object and the robot hand is measured using the range sensors Within it is range of operation. The calculation of the distance is by visual processing.
- Range sensors find use in robot navigation and avoidance of the obstacles in the path. The location and the general shape characteristics of the part in the work envelope of the robot is done by special applications for the range sensors.
- There are several approaches like,
    - Triangulation method
    - Structured lighting approach
    - Time-of flight range finders etc.
- In these cases, the source of illumination can be light source, laser beam or based on ultrasonic.

TRIANGULATON (LIGHT BASED RANGE FINDERS)



Triangulation Method

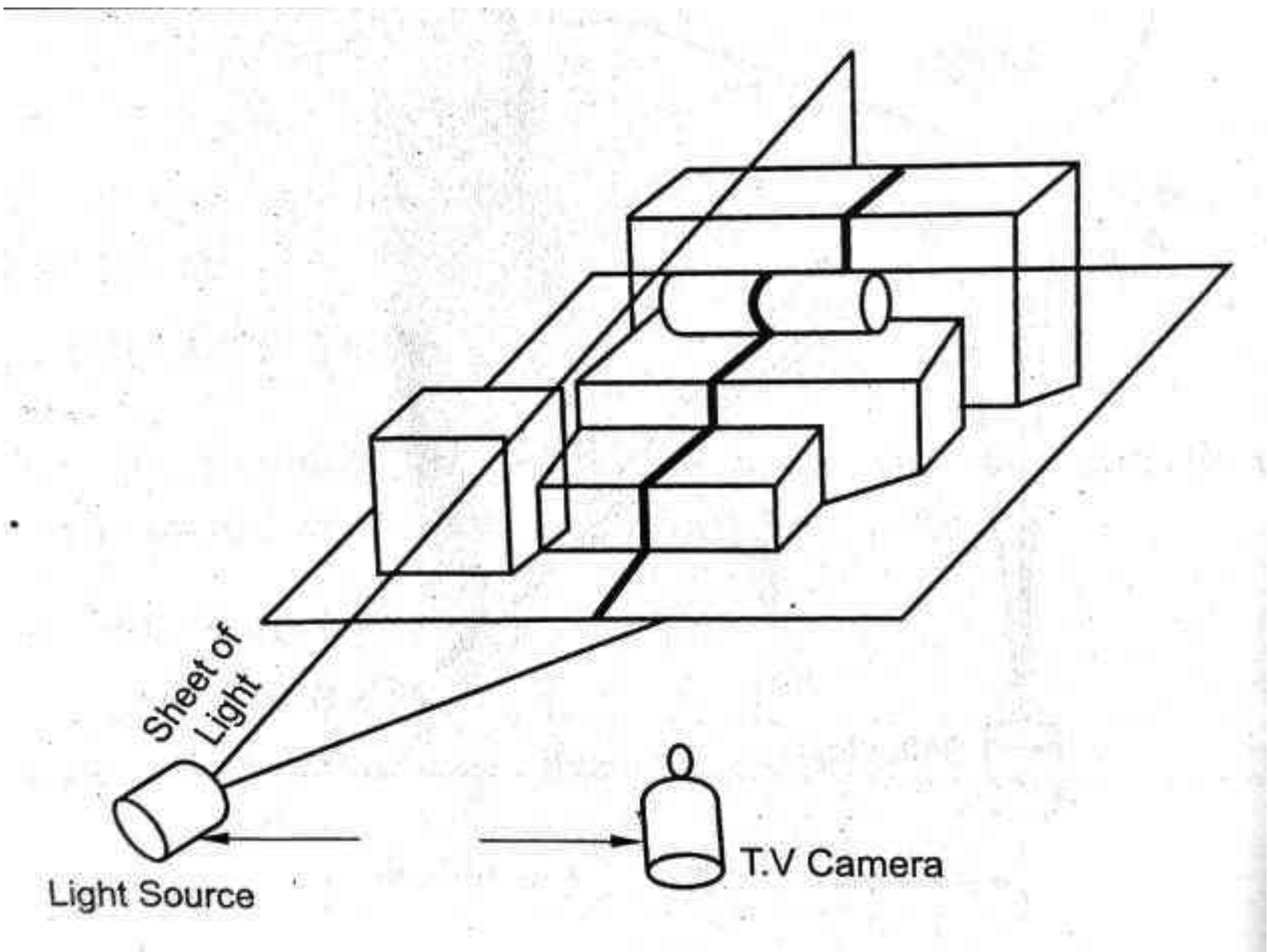
- This is the simplest of the techniques, which is easily demonstrated in the Figure.
- The object is swept over by a narrow beam of sharp light. The sensor focussed on a small spot of the object surface detects the reflected beam of light.
- If 'Θ' is the angle made by the illuminating source and b is the distance between source and the sensor, the distance d of the sensor on the robot is given as;

$$d = b \cdot \tan \theta$$

The distance 'd' can be easily transformed into 3D-co-ordinates

STRUCTURED LIGHTING APPROACH

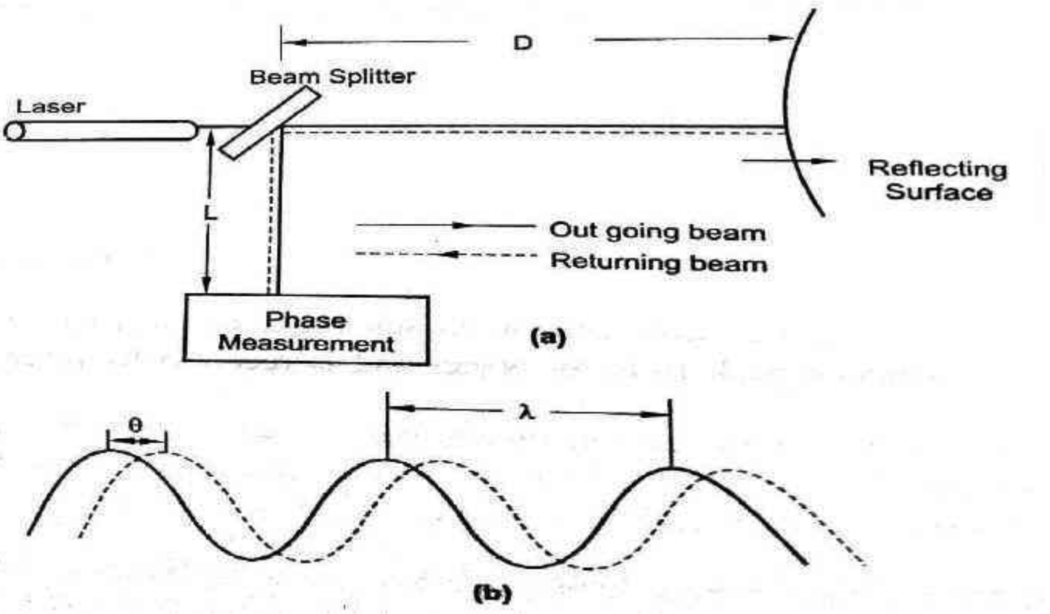
- This approach consists of projecting a light pattern the distortion of the pattern to calculate the range. A pattern in use today is a sheet of light generated narrow slit.
- As illustrated in figure, the intersection of the sheet with objects in the work space yields a light stripe which is viewed through a television camera displaced a distance B from the light source.
- The stripe pattern is easily analysed by a computer to obtain range information. For example, an inflection indicates a change of surface, and a break corresponds to a gap between surfaces.



Structured Lighting Approach

- Specific range values are computed by first calibrating the system. One of the simplest arrangements is shown in figure.
- In this, arrangement, the light source and camera are placed at the same height, and the sheet of light is perpendicular to the line joining the origin of the light sheet and the center of the camera lens. We call the vertical plane containing this line the reference plane.
- Clearly, the reference plane is perpendicular to the sheet of light, and any vertical flat surface that intersects the sheet Will produce a vertical stripe of light in which every point will have the same perpendicular distance to the reference plane.
- The objective of the arrangement shown in figure is to position the camera so that every such vertical stripe also appears vertical in the image plane. In this way, every point, the same column in the image will be known to have the same distance to the reference plane.

LASER RANGE FINDER (TIME OF FLIGHT RANGE FINDER)



Time of Flight Range Finder

- It consists of sending a signal from a transmitter that comes back from an object and is received by a receiver. The distance between the object and the sensor is half the distance travelled by the signal, which can be calculated by measuring the time of flight of the signal by knowing its speed of travel.
- Time of flight range finder uses laser to determine the range and to measure the time it takes for an emitted pulse of light to return coaxially (along the same path) from the reflecting surface.
- The distance of the surface is given by simple relationship

$$D = LT/2$$

Where,

T - pulse transmit time

L - speed of light

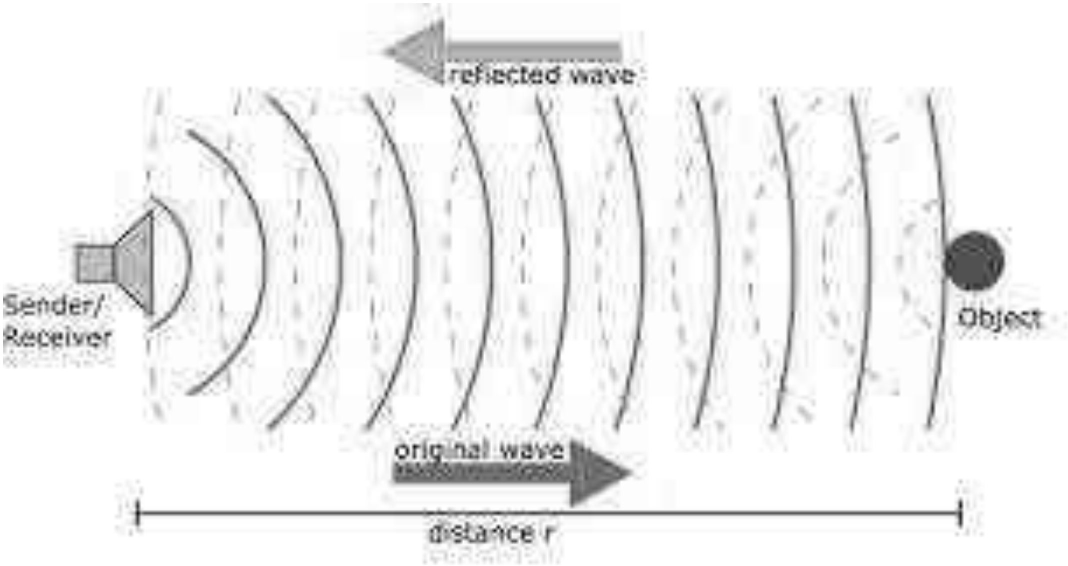
- A pulser – lased system produces a two dimensional array with values proportional to distance. The 2D scan is accomplished by deflecting the laser light via a rotating mirror.
- The working range of this device is on the order of 1 to 4m, with an accuracy of +/- 0.25cm.
- An alternative is a pulse light with continuous beam laser and measure the delay (phase shift) between the outgoing and returning beam.
- A beam of laser light of wave length λ is split into two beams;
    - One called reference beam travels the distance L
    - Other travels to the distance D
- Total distance travelled by the reflected beam is $D' = L+2D$

Advantages:

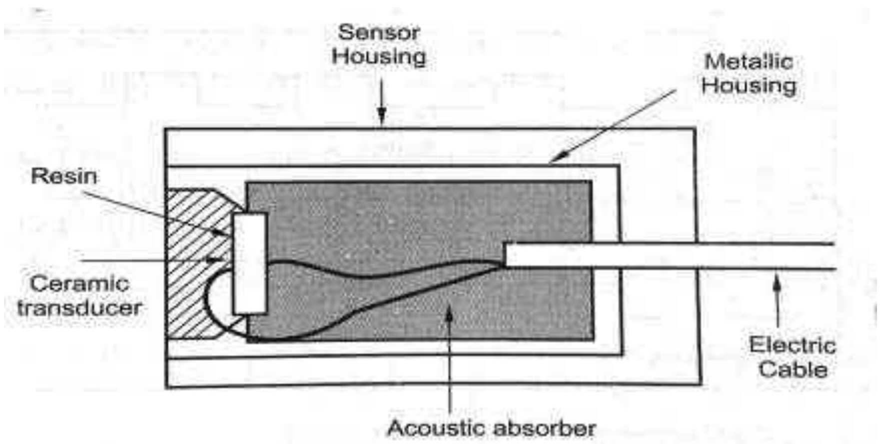
- Time measurement will be very fast and accurate
- For small distance measurement, the wave length of signal must be very small.

ULTRASONIC RANGE FINDER

- Ultrasonic distance-measuring devices use a wide band frequency from a transducer, sending out narrow beams of sound waves which bounce off an object.
- The return signal is picked up by a handheld receiver. Ultrasonic transducers are transducers that convert ultrasound waves to electrical signals or vice versa.



Ultrasonic Range Finder Principle



Ultrasonic Transducer

- Ultrasonic Range Finder transducers can both sense and transmit. These devices work on a principle similar to that of transducers used in radar and sonar systems, which evaluate attributes of a target by interpreting the echoes from radio or sound waves, respectively.
- **Active ultrasonic sensors** generate high-frequency sound waves and evaluate the echo which is received back by the sensor, measuring the time interval between sending the signal and receiving the echo to determine the distance to an object.
- **Passive ultrasonic sensors** are basically microphones that detect ultrasonic noise that is present under certain conditions, convert it to an electrical signal, and report it to a computer.
- Accuracy may affected by,
  - Position of the receiver
  - Outside sound waves/noise

- Noise generated by wind

Applications:

- Surveying,
- Navigation,
- Correcting aim of a projectile weapon for distance

FORCE SENSORS

- A force sensor is the one in which the weight is applied to the scale pan that causes a displacement. The displacement is then measure of the force.
- Types of force sensors are;
    - Strain gauge
    - Piezoelectric switches
    - Microswitches

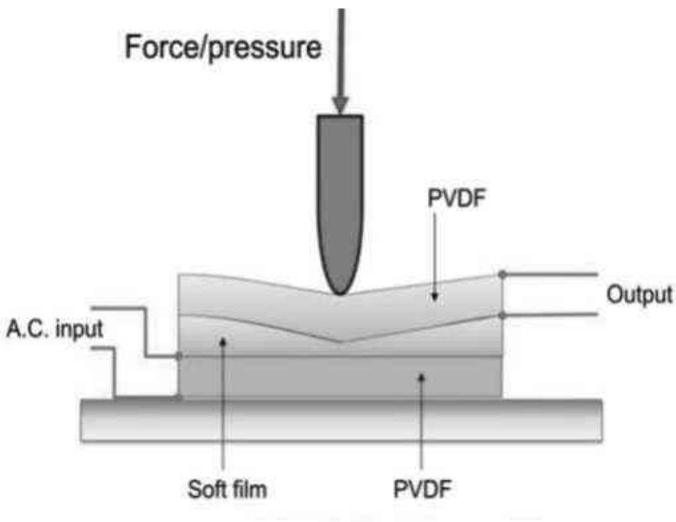
MICROSWITCHES

- Microswitches are extremely simple and common in all robotics. They are used to cut off the electrical current through a conductor, and they can be used for safety purpose, for determining contact for sending signals based on displacements, and other uses.

Advantages:

- Robust
- Simple in design
- Inexpensive
- Simple in operation

TACTILE SENSORS



Tactile Sensors

- In general, tactile sensors are used to sense the contact of fingertips of a robot with an object. They are also used in manufacturing of ‘touch display’ screens of visual display units (VDUs) of CNC machine tools.
- Figure shows the construction of piezo-electric polyvinylidene fluoride (PVDF) based tactile sensor. It has two PVDF layers separated by a soft film which transmits the vibrations.
- An alternating current is applied to lower PVDF layer which generates vibrations due to reverse piezoelectric effect.
- These vibrations are transmitted to the upper PVDF layer via soft film. These vibrations cause alternating voltage across the upper PVDF layer.
- When some pressure is applied on the upper PVDF layer the vibrations gets affected and the output voltage changes. This triggers a switch or an action in robots or touch displays.

TYPES OF TACTILE SENSORS IN ROBOTICS

Force/Torque Sensors

- Force/ torque sensors are used in combination with a tactile array to give the information for force control.
- This type of sensors can sense load anywhere like the distal link of a manipulator and in constrains as a skin sensor.
- The skin sensor generally provides more accurate force measurement at higher bandwidths.
- If the manipulator link is defined generally, and the signal point contact is assumed, then the force/ torque sensor can give the information about the contact location of force and moments- it is called as an intrinsic tactile sensing.

Dynamic Sensors

- Dynamic sensors are smaller accelerometers at the finger strips or at the skin of the robotic finger.
- They general function like pacinian corpuscles in humans and have equally large respective field; thus one or two skins accelerometer are sufficient for entire finger.
- These sensors effectively detect the making and breaking of contact, the vibrations linked with the sliding over textured surfaces.
- If the fingertip is sliding at the speed of a few cm/s overall small bumps or pits in a surface, the temporary changes in the skin became important.
- A piezoelectric polymer such as PVDF produces charge in response to damage can be applied to produce a current, which is directly proportional to the range of change.

Thermal Sensors

- Thermal sensors are important to the human ability to identify the materials of the objects made, but some are used in the robotics as well.
- The thermal sensing involves detecting thermal gradients in the skin, which are correspondent to both the temperature and the thermal conductivity of an object.
- Robotic thermal sensors are involved in the Peltier junctions in combination with the Thermistors.