3. Robot Drives, Actuators and Control

3.1. FUNCTIONS OF DRIVE SYSTEMS

The main motive power of robots is in the drives. Various transmitting elements are employed to drive the mechanical links to a desired position and orientation in the envelope of the robot-manipulator. At present, direct drives to the arms of robots are preferred though power is transmitted or applied to various joints of the robot through gears, belts, cable chains and many other means. There are four basic methods of drives:

- Hydraulic
- Pneumatic
- Electrical (d.c. and a.c. motors)
- Electrical stepper motors

The drive systems are chosen based on the power consumption, positional accuracy, repeatability, speed of operation, stability, reliability, cost and many other related factors. The drive methods are selected also on the basis of using open loop or closed loop controls.

Depending on the drive methods, various actuators are used, namely hydraulic cylinders that handle oil under pressure and use electrohydraulic valve, pneumatic cylinders using air as the fluid medium with solenoid controlled valve and usually d.c. electric motors with electrical amplifiers and controllers and electrical stepper motors with suitable circuitry (ramping circuit) to control the pulses.

In this chapter, different types of drives and actuators with their advantages and disadvantages are discussed.

3.2. GENERAL TYPES OF FLUIDS

Fluids may be gases or liquids. Liquids are considered to be incompressible (higher bulk modulus) as their volume does not change with the change in pressure. Gases on the other hand are readily compressible. The volume of the gas decreases or increases due to the increase or decrease of pressure.

The commonly used hydraulic fluids are petroleum-based fluid with some additives to satisfy the requirements of desired viscosity index, resistance to oxidation, good lubrication properties, chemical stability, low density and foam resistance. Sometimes fire resistant fluids are used with high flash points in some hazardous operating conditions. Additives are used with hydraulic fluids to prevent wear and tear. The above categories of fluids are the liquids used in hydraulic systems.

In pneumatic systems, an important fluid is air. Air is inexpensive. There is no possibility of fire hazard. Used air is thrown out into the atmosphere as exhaust. Clean air can be readily obtained using a filter. Fine oil can be injected into the clean air by a lubricator. On the other hand, air is sluggish and to a little extent corrosive because of the presence of oxygen and water.

3.2.1.1. Basic Fluid Properties

In hydraulics, pressure is transmitted following Pascal's law which states that pressure applied to fluid in a container is transmitted undiminished in all directions. The fluid pressure is defined as the transmitted force acting over a unit area.

$$P = \frac{F}{A}$$

where P = Pressure (pascals or bar)

F = Force (newton, N)

A = Area (square metre, m^2)

and 1 bar = 10^5 N/m^2

1 Pa = 1 N/m^2

Bulk modulus is an index for incompressibility of the hydraulic fluid (say, an oil).

Bulk modulus, β, can be defined as

$$\beta = V\left(\frac{\delta p}{\delta v}\right)$$

where β = bulk modulus

V = original volume of oil

δp and δv are the changes in pressure and volume, respectively.

A hydraulic fluid should not have high viscosity or sluggishness associated with its movement. A hydraulic fluid should also not have low viscosity. The absolute fluid viscosity can be defined as

$$\mu = \frac{\tau}{v/d}$$

where μ = absolute viscosity (dyne s/cm^2 or Poise)

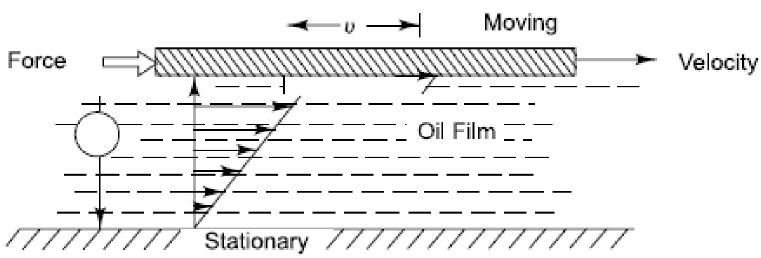
τ = shear stress in the fluid due to the sliding of the adjacent layers

of oil film as shown in Fig. 3.1 (dyne/cm^2)

v/d = slope of the velocity profile [(cm/s)/cm]

and 1 N = 10^5 dynes. 1 m = 100 cm. 1 N. s/m^2 = 10 poise.

Figure 3.1 Velocity profile of fluid



In hydraulic systems, the kinematic viscosity is used and is defined as,

$$\gamma = \frac{\mu}{\rho}$$

where γ = kinematic viscosity (cm^2/s or stoke) [1 stoke = 10^{-4} m^2/s]

μ = absolute viscosity (dyne s/cm^2)

ρ = mass density of the fluid (g/cm^3)

In general, the viscosity index in a given scale is a relative measure of the viscosity of an oil with respect to the temperature change. A high viscosity index is good for a hydraulic fluid.

It is common experience that air entrapped and dissolved in a hydraulic fluid causes bubbles. These bubbles are carried and may sometimes cause damage to the pump components by cavitation effect. The dissolved air destroys a very important property of incompressibility of the fluid and may cause inaccuracy and instability of the hydraulic actuators. Proper care should be taken to prevent leakage in the suction line and keep the delivery line dipped into the reservoir. Sometimes foam resistance is increased by addition of some additives in the reservoir.

Lubricating property of a hydraulic fluid is important as otherwise the fluid may cause wear due to frictional force. Coefficient of friction is the index for measuring the lubricating property of the oil.

$$\text{Coefficient of friction} = \frac{\text{Frictional force}}{\text{Normal force}}$$

3.2.1.2. Mechanics of Hydraulic Systems

Consider the equations:

1. $v = \dfrac{d}{t}$

   v = velocity (m/s)

   d = distance (m)

   t = time (s)

2. $F = ma$

   F = force (N)

   m = mass (kg)

   a = acceleration (m/s^2)

3.2.1.3. Corollary

i. Work or Energy: $W = Fd$

   W = work (J)

   F = force (N)

   d = distance (m)

ii. Power: $P = \dfrac{Fd}{t} = Fv$

iii. F = force (N)

   v = velocity (m/s)

P = power (W)

In case of hydraulic motor, power can be related to the rotational speed of motor.

i. Flow rate

The average velocity can be found from

$$v_{avg} = \frac{Q}{A}$$

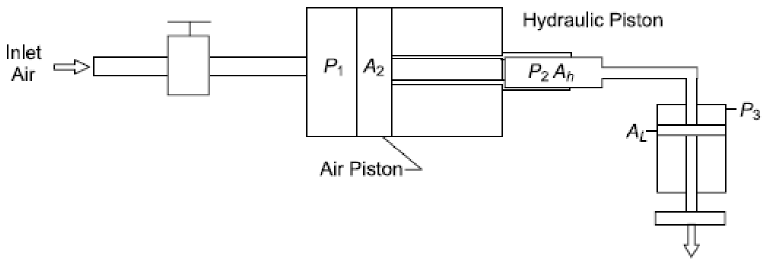
where v = velocity (m/s)

Q = flow rate (m^3/s)

A = cross-sectional area (m^2)

Air supply is available in the shop floor. The air pressure can be utilized to boost the pressure up to many times through the hydraulic system. Figure 3.2 indicates air used as hydraulic pressure booster.

Figure 3.2 Air to hydraulic pressure booster



$$P_1 A_a = P_2 A_h$$

or

$$P_2 = \frac{P_1 A_a}{A_h} \text{ as } A_a >> A_h$$

Now $P_3 = P_2$

$$\text{Load} = P_3 A_L = P_2 A_L.$$

P_1 = Air pressure in (first cylinder)

P_2 = Pressure on hydraulic piston (second cylinder)

P_3 = Pressure on the third cylinder

A_a = Area of air piston

A_h = Area of hydraulic piston

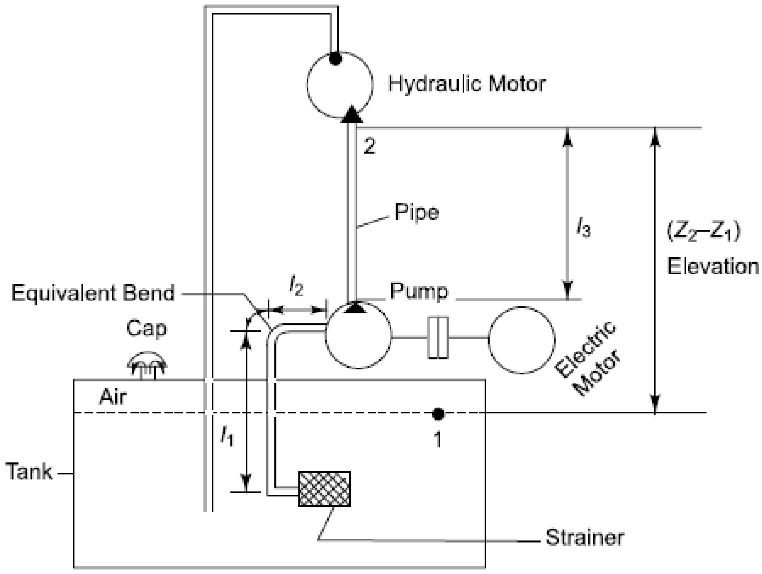
A_L = Area of piston for transmitting load

Thus, higher load (forces) can be generated by the inlet low air pressure.

3.2.1.4. Bernoulli's Equation

Bernoulli's equation is derived from the law of conservation of energy, which states that the total energy in a system remains constant as energy can neither be created nor destroyed. In a hydraulic system, work is done by a pump delivering fluid either in a hydraulic actuator or in a hydraulic motor. However, there may be fluid loss during its flow through the pipe. Bernoulli's equation for a basic hydraulic system shown in Fig. 3.3 can be expressed on the assumption that the total energy at station 1 is equal to the total energy at station 2. Total energy at station 1 + energy added by a pump – energy loss due to friction – energy delivered by a motor = Total energy at station 2.

Figure 3.3 *Simple hydraulic system*



Total energy at station 2 can be expressed in terms of potential energy due to elevation plus the potential energy gained due to pressure plus the kinetic energy of the fluid due to the velocity.

- The potential energy, (PE) is expressed as elevation head (*Z*)
- The potential energy due to pressure is expressed as pressure head (P/γ)
- The kinetic energy, (KE) due to velocity is expressed as velocity head ($v^2/2g$).

$$\text{At station 2, total energy} = Z_2 + \frac{P_2}{\gamma} + \frac{v_2^2}{2g}$$

At station 1, total energy = $\left(Z_1 + \frac{P_1}{\gamma} + \frac{v_1^2}{2g}\right) + h_{\text{pump}}$

$$- h_{\text{loss}} - h_{\text{motor}}$$

$$= \left(Z_1 + \frac{P_1}{\gamma} + \frac{v_1^2}{2g}\right) + h_{\text{pump}}$$

$$-f\left\{\frac{l_1 + l_e + l_2 + l_3}{D}\right\}\frac{v^2}{2g} - h_{\text{motor}}$$

where h_{pump} = energy added per unit quantity of fluid added by pump energy (pump head)

h_{ioss} = frictional head losses of the fluid passing from station 1 to station 2

h_{motor} = energy per unit quantity of fluid delivered by a motor (motor head).

The head losses in pipes, bends or valves can be determined from the equivalent length. The head losses in pipes assuming laminar flow can be determined from the Hagen–Poiseuille equation and expressed as

$$h_{\text{loss in pipe}} = f\left(\frac{L}{D}\right)\left(\frac{v^2}{2g}\right) = \frac{64}{N_{\text{Reynold}}}\left(\frac{L}{D}\right)\left(\frac{v^2}{2g}\right)$$

(3.1)

where $f = \dfrac{64}{N_{\text{Reynold}}}$ = Friction factor (dimensionless)

N = Reynold's number = $vD\left(\dfrac{\rho}{\mu}\right)$

L = Length of pipe, m

v = Average fluid velocity, m/s

g = Acceleration due to gravity, m/s^2

D = Diameter of pipe, m

Head losses in valves and fittings can be found from

$$h_{\text{losses}} = \frac{kv^2}{2g}$$

(3.2)

where k = a factor depending on the type of valve or fittings. From Eqs (3.1) and (3.2)

$$\frac{kv^2}{2g} = f\left(\frac{L}{D}\right)\left(\frac{v^2}{2g}\right)$$

or

$$L_e = \frac{KD}{f}$$

where L_e = equivalent length of valve or fitting, m.

3.3. PUMP CLASSIFICATION

A pump transforms mechanical energy into hydraulic energy. When a prime mover coupled with the piston pump causes a mechanical action in the pump, a partial vacuum is created at the inlet of the pump. Due to the vacuum, the atmospheric pressure forces the fluid out of the oil tank to enter the pump through the inlet check valve. The fluid enters the pump when the piston moves towards the left as shown in Figs 3.4 and 3.5. When the piston moves towards the right, the outlet check valve opens and the discharge of the quantity of the fluid during the outward stroke towards the right occurs through the outlet pipe. The volume of the fluid displaced by the piston is the displacement volume of the piston. Thus a pump produces flow.

Figure 3.4 Hydraulic cylinder

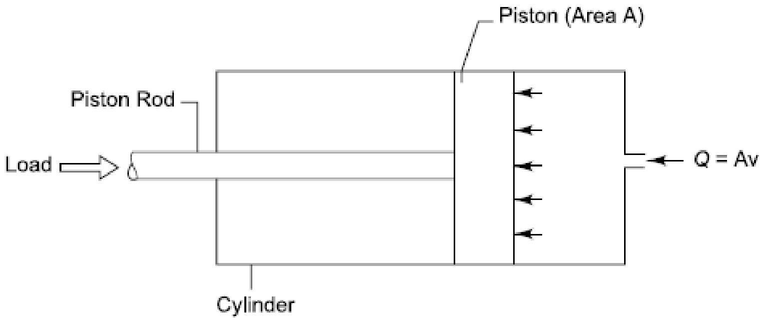
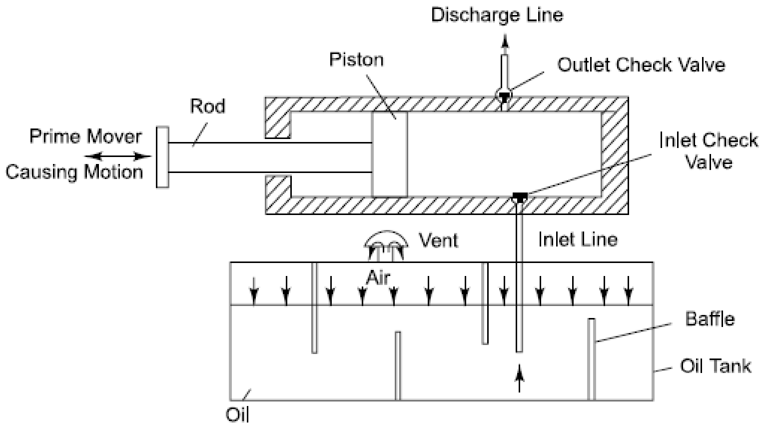


Figure 3.5 Piston pump producing flow



There are two basic classifications of hydraulic pumps:

1. Hydrodynamic or non-positive displacement pumps
2. Hydrostatic or positive displacement pumps

3.3.1. Non-Positive Displacement Pumps

There are two types of pumps in this category. They are (i) the centrifugal (impeller) pump and (ii) the axial (propeller) pump. There is a sufficient clearance between the rotating and the stationary elements. The flow rate of the pump depends on the speed at which the propeller or impeller is driven and the restriction of the outlet or resistance of the external system. With an increase in the restriction of the outlet of the pump, there is a reduction in the rate of discharge flow and some of the fluid leaks backward past the rotating element through the clearance space, following the path of least resistance. When the outlet is completely restricted or closed, the flow stops and the volumetric efficiency falls to zero. If the outlet of the pump is again opened, the pump will have maximum flow. Figures 3.6(a) and (b) indicate the axial type non-positive displacement pump and centrifugal type non-positive displacement pump respectively.

Figure 3.6 Non-positive displacement pumps (a) Axial type (b) Centrifugal type

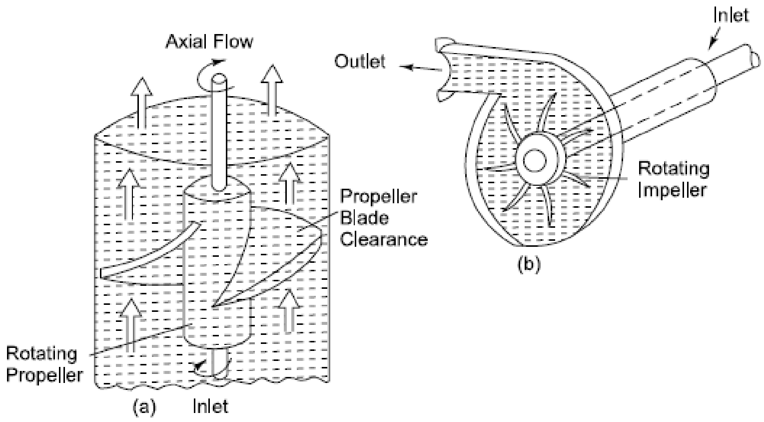
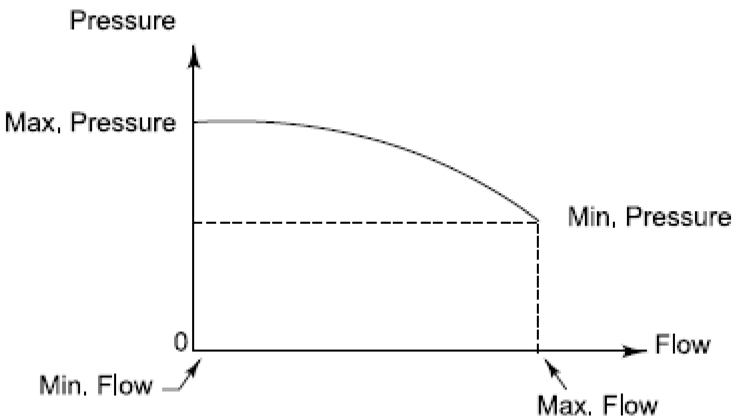


Figure 3.7 indicates a typical pressure-flow diagram of non-positive displacement pump. There is no flow when the outlet valve is completely closed and pressure becomes maximum. However, the pressure is reduced as soon as the valve opens and flow takes place. The non-positive displacement pump creates pressure due to the rotary motion of the propeller or impeller and flow only takes place at the expense of the pressure.

Figure 3.7 Pressure vs. flow curve



3.3.2. Hydrostatic or Positive Displacement Pumps

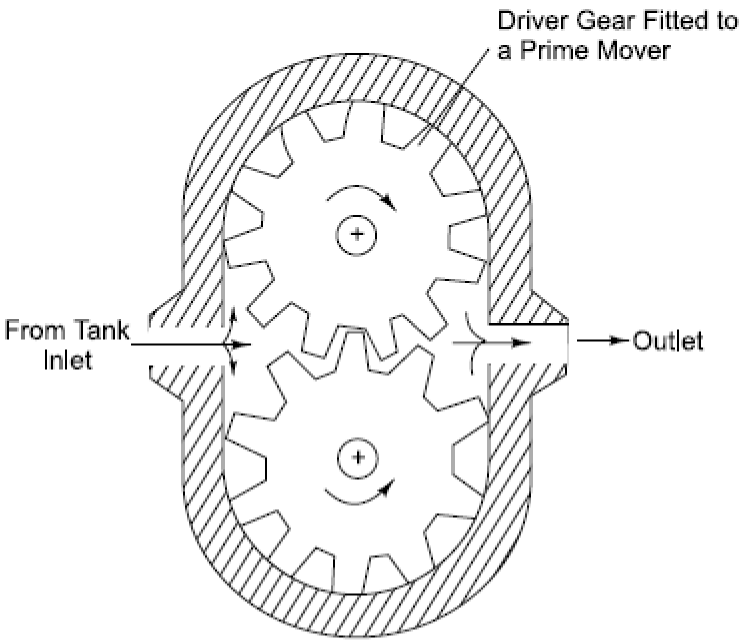
A positive displacement pump delivers a fixed quantity of fluid per revolution of the pump shaft and the output flow is constant at the rated speed of the pump. However, if the outlet valve is closed, pressure may rapidly build up. If the resistance to flow increases due to the load, pressure may be increased and the pump is therefore protected by allowing the fluid to flow back to the tank through a pressure relief valve. The volume of the output flow increases with an increase in the speed of the pump shaft.

Positive displacement pumps may be classified into gear pumps, vane pumps and piston pumps.

3.3.2.1. Gear Pumps

A gear pump is a positive displacement pump in which the driver gear in mesh with the driven gear rotates and carries the fluid from the tank to the outlet pipe as shown in Fig. 3.8. The suction side is towards the portion where the gear teeth come out of mesh. As the gears turn, the size of the chamber at the inlet becomes larger; the volume increases, causing a drop in the pressure below the atmospheric pressure and a vacuum is created. Atmospheric pressure in the tank forces the fluid into the void. The discharge side of the pump is towards the portion where the gear teeth run into mesh. At the outlet, the volume decreases between meshing teeth. As the pump casing has a positive internal seal against leakage, oil is pushed into the outlet pipe from the oil chamber formed between the gear teeth, the pump casing and side wear plate. Gear pumps are sometimes equipped with side wear plates to help seal the gears to avoid oil leakage. A small amount of fluid from the discharge Q is directed towards the outside of the wear plate to create enough pressure on the wear plates on both sides of the gear pump to seal the gears.

Figure 3.8 A gear pump



The volumetric displacement (vol) is given by,

$$\text{vol} = \frac{\pi}{4}\left(d_o^2 - d_i^2\right) \times l$$

The ideal flow rate, Q is obtained as,

$$Q_{\text{ideal}} = (\text{vol}) \times N$$

The volumetric efficiency is found from,

$$\eta_{\text{vol}} = \frac{Q_{\text{actual}}}{Q_{\text{ideal}}} \times 100\%$$

The actual flow rate, Q_{actual} is less than Q_{ideal} due to the loss of fluid, through the clearance space between gear-teeth and pump casing. Here,

d_o = outside diameter of gear teeth, m

d_i = inside diameter of gear teeth, m

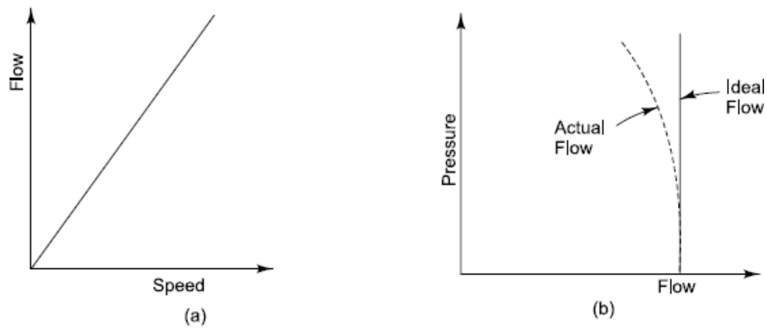
l = width of gear teeth, m

vol = displacement volume of pump, m^3/rev

N = rpm of pump

Pump flow varies directly with speed and the flow versus speed curve is shown in Fig. 3.9(a). Figure 3.9(b) indicates the actual flow curve due to internal leakage under high discharge pressure. The volumetric efficiency becomes lower.

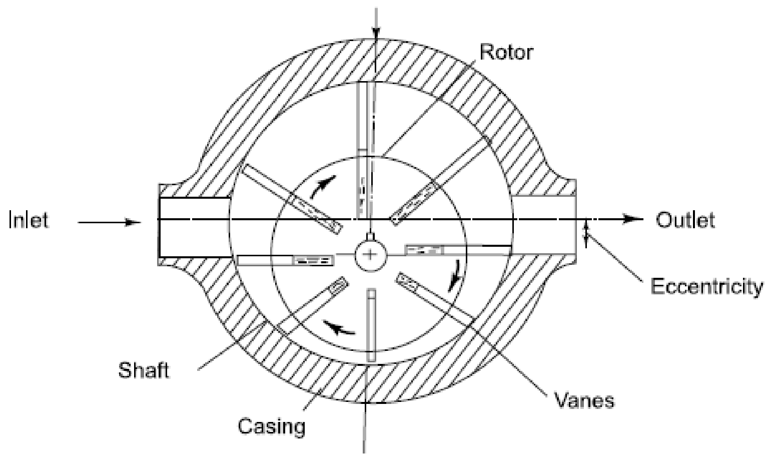
Figure 3.9 *Positive displacement pump characteristics (a) flow vs. speed curve(b) flow vs. pressure curve at constant pump speed*



3.3.2.2. Vane Pumps

Figure 3.10 illustrates a vane pump which contains main elements like the pump housing, the vanes and the rotor. The rotor has radial slots in which the vanes are fitted. The rotor gets its drive and rotates inside the housing while the vanes slide in and out of the slots. The rotor is not centrally located in the cam ring, but there is an eccentricity between the centre line of the rotor and the centre line of the housing. As the rotor attempts to turn, the volume of the space between the rotor and the housing increases and a vacuum is created due to reduction of pressure.

Figure 3.10 *Vane pump*



Oil is taken into the pump's suction chamber during one-half revolution while in the other half of the revolution, the volume decreases due to the sliding of the vanes inside the rotor. Thus due to the reduction of the size of the chamber, the fluid is pumped out through the discharge outlet. Flow takes place due to the eccentricity. If the eccentricity is made zero, there will be no flow of fluid.

The eccentricity (ε) can be estimated as

$$\varepsilon = \frac{d_{\text{cam}} - d_{\text{rotor}}}{2}$$

The displacement volume, (vol) is given by

$$\begin{aligned} \text{vol} &= \pi/4(d_{cam}^2 - d_{rotor}^2)\times l \\ &= \pi/4[(d_{cam} - d_{rotor})(d_{cam} - d_{rotor})]\times l \\ &= \pi/4[(d_{cam} + d_{rotor})(2\varepsilon)]\, l \\ &= \pi/2[d_{cam} + d_{rotor}]\,\varepsilon\cdot l \end{aligned}$$

∴ Volumetric displacement ∞ eccentricity

where d_{cam} = diameter of cam ring, m

d_{rotor} = diameter of rotor, m

l = width of rotor, m

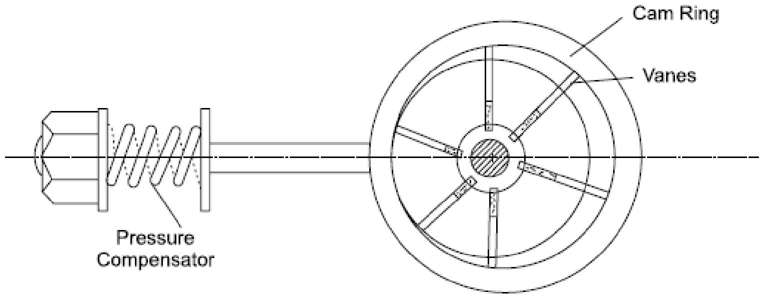
N = rotor rpm

vol = volumetric displacement of pump, m^3

ε = eccentricity

A variable displacement vane pump can be built by using a pressure compensator or a handwheel to move the cam ring to change the eccentricity as shown in Fig. 3.11. Such a pump is self-adjusting and has the mechanism to prevent excessive pressure build-up. The pump's output varies with the demand of the fluid or load.

Figure 3.11 Variable displacement vane pump



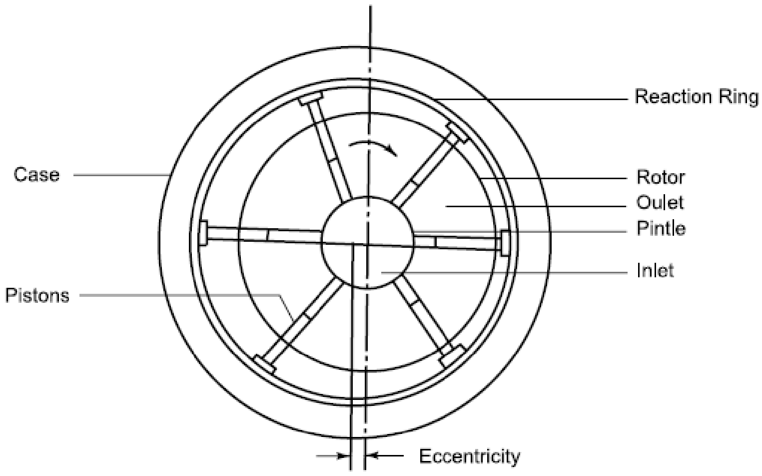
When the eccentricity is maximum, the flow is maximum and when the eccentricity is zero, the output of the pump is zero. However, such pumps are hydraulically unbalanced. Balanced vane pumps are also available with diametrically opposite two-inlet ports and two-outlet ports.

3.3.2.3. Piston Pumps

There are two different types of piston pumps: radial piston pumps and axial piston pumps. Axial piston pumps can be either of bent axis configuration or swash plate design.

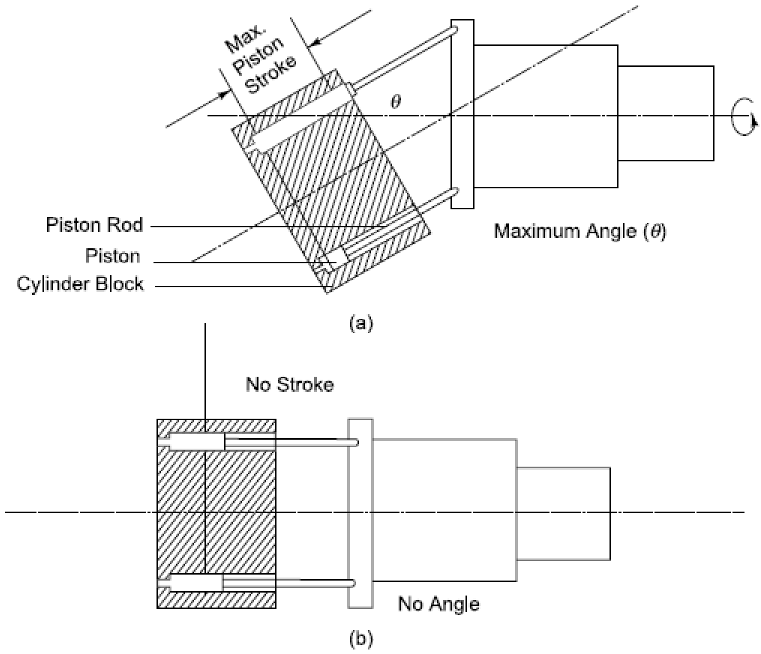
Radial Piston Pumps Like a vane pump, the radially located pistons as shown in Fig. 3.12 move in and out due to the rotational movement of the rotor. As the piston moves out, oil is drawn into the piston and during the inward movement of the piston, the discharge takes place.

Figure 3.12 Radial piston pump



Axial Piston Pumps Figures 3.13(a) and (b) indicate a schematic diagram of bent axis configuration of axial piston pump.

Figure 3.13 Bent axis axial piston pump (a) maximum flow at an angle, θ; (b) no flow at angle, θ = 0°



The drive shaft of the pump is connected to the cylinder block through a universal joint. The cylinder block rotates along with the driving shaft. The cylinder block has a valve plate attached to one end and the valve plate has two openings—one for an inlet and another for an outlet for the fluid. The pistons located in a circle move in the cylinder block and the axis of the cylinder block is set at an angle of offset rotating to the axis of the drive. This is why the pumps are called bent axis axial piston pumps. The piston rods are connected to the drive shaft flange through ball and socket joints. As the input drive shaft rotates, pistons reciprocate and the fluid is delivered through the outlet pipe. The offset angle θ can vary from 0° to any angle to vary the displacement of the pump. When $\theta = 0°$, there is no flow and when θ is maximum, the flow is maximum as the stroke is enhanced. For reduced angle, the flow is reduced.

The displacement volumes (vol) can be found from

$$\begin{aligned} \text{vol} &= nAL \\ &= nA\,(D \tan\,\theta) \end{aligned}$$

∴ the flow rate Q is determined from

$$Q = naD \tan\theta \times N$$

where n = number of pistons

A = area of pistons

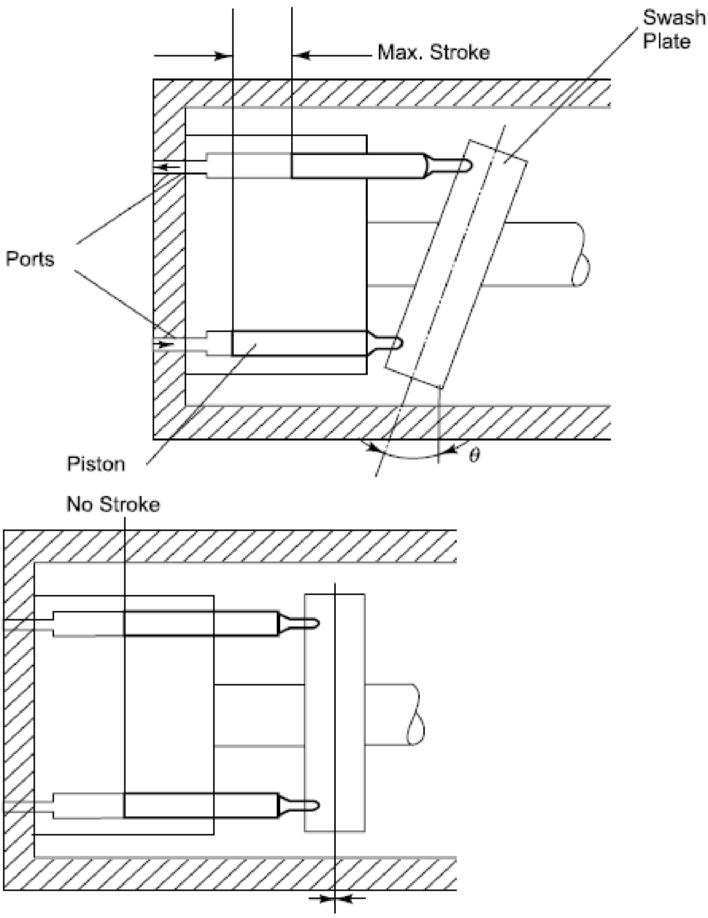
D = piston circle diameter

N = rpm of pump

θ = offset angle

Swash Plate Axial Piston Pump Swash plate design [Figs 3.14(a) and (b)] is termed as in-line axial piston pump as the input drive shaft is in line with the cylinder. The pistons are connected to a swash plate that can be swung. As the pistons are withdrawn from the bore, fluid is taken in at the inlet and when they are forced out, the fluid is delivered through the outlet port. The displacement can be varied with the swing of the swash plate. For zero swash, there is no flow.

Figure 3.14 Swash plate design in-line axial piston (a) Maximum displacement at maximum swash plate angle, θ. (b) Zero displacement at zero swash plate angle



A variable displacement pressure-compensated axial piston pump can be fitted to a pressure compensator which is a small cylinder connected to the swash plate. There is a spring inside the cylinder. When the spring pushes the piston inside the cylinder, the swash plate is tilted to the maximum possible extent and the discharge becomes maximum. When the pressure rises in the system, the fluid through the delivery port enters the cylinder at the head end, and pushes the piston against the spring. The swash plate is inclined in the opposite direction resulting in reduced flow from the pump. This is automatic compensation.

3.3.3. Hydraulic Actuators

Actuators are devices that convert energy extracted out of a fluid to mechanical work. Actuators are of two types: (i) Linear actuator or hydraulic cylinder and (ii) Rotary actuator or hydraulic motor.

3.3.3.1. Linear Hydraulic Actuator

Linear hydraulic actuator is a hydraulic cylinder that may be single acting or double acting. A single acting cylinder exerts a force in only one direction when the piston moves inside the cylinder or barrel due to the fluid pressure exerted on the blank or blind end. Fluid (oil) from the pump enters through a port on the blank end and the piston rod extends through the gland at the rod end. Retraction of piston takes place earlier by a compression spring or by gravity. Figure 3.15 illustrates the representation of a single acting cylinder with piston rings that prevent oil leakage from the cylinder sides. A gland also seals the oil and supports the piston rod.

Figure 3.15 Single acting hydraulic cylinder

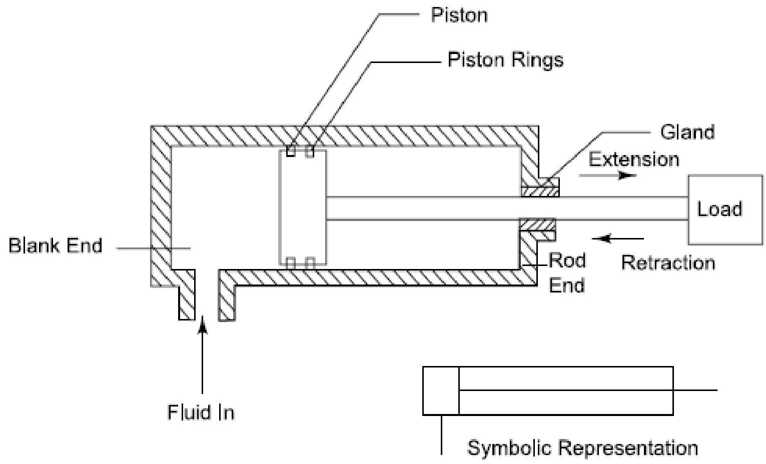


Figure 3.16 shows a double acting cylinder in which the fluid may enter through either the blank end or the rod end. Extension of the piston rod occurs when the fluid is pumped into the blind end. Retraction of the piston occurs when the fluid is pumped into the rod end of the cylinder. A double acting double rod cylinder is shown symbolically in Fig. 3.17. The piston rod is extended due to the fluid pressure exposed on the blind end of the piston. The area exposed to fluid towards the rod end of the cylinder reduces due to the presence of the piston rod and so the extending force is greater than the force of retraction. However, the speed of retraction is higher compared to the speed of extension. In the case of double acting double rod cylinder, force and speed are equal in both directions due to the extension of piston rods on both sides of the piston inside the cylinder. Double acting cylinders sometimes contain cylinder cushions built in to help absorb the shock of the piston when it moves towards the ends of the strokes. When the piston is pushed towards the end, a tapered plunger or spear enters the main opening in the cap, thus restricting the exhaust flow from the cylinder to the port. Finally the spear closes off the main opening and the fluid is forced to go out of the cylinder through a small opening that can be adjusted by a needle valve. The cushioning or deceleration thus takes place. During the reverse motion, fluid can pass to cylinder freely through a check valve placed at the opposite end of the needle valve. Figure 3.18 illustrates the action of cushioning of a cylinder.

Figure 3.16 Symbolic representation of double acting cylinder

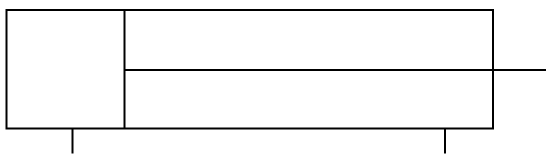


Figure 3.17 *Schematic diagram of double acting double rod cylinder*

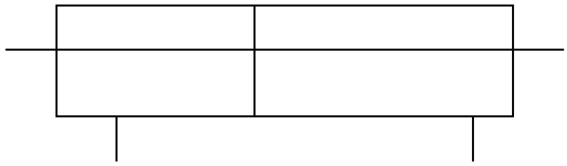
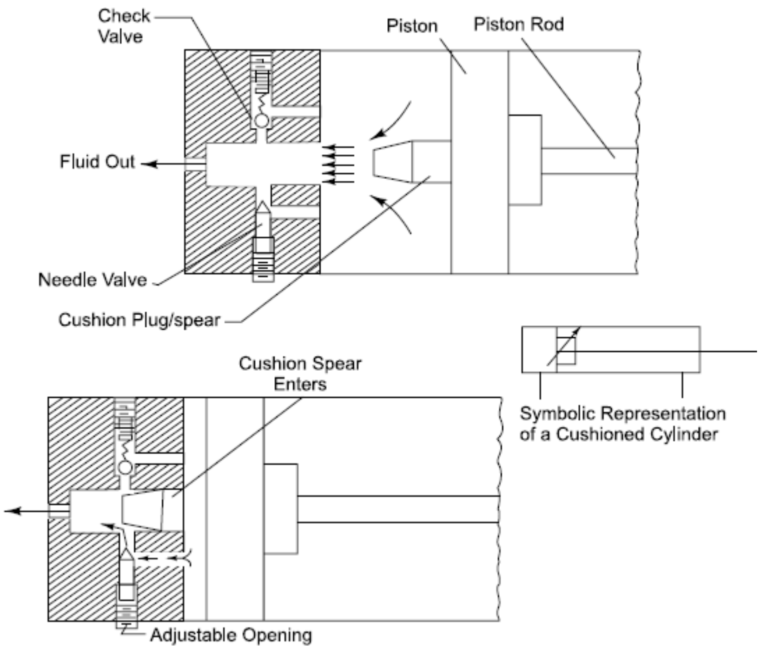


Figure 3.18 *Action of cushioned cylinder*

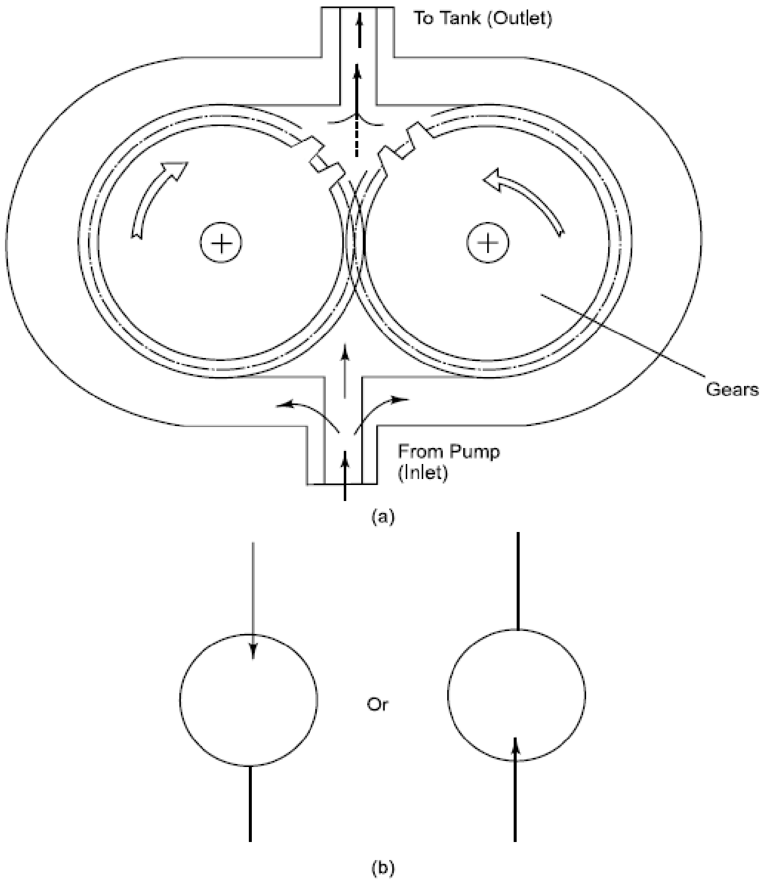


3.3.3.2. Hydraulic Rotary Actuators

Hydraulic rotary actuators sometimes called hydraulic motors create rotary motion and torque instead of linear motion. There are mainly three types of rotary actuators: (i) Gear motors, (ii) Vane motors and (iii) Piston motors.

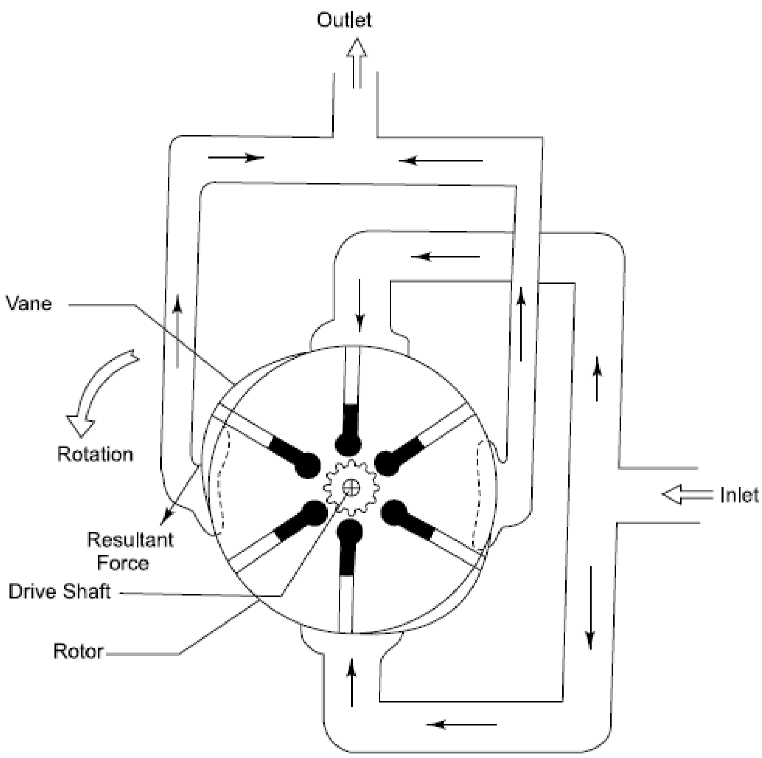
Gear Motors Gear motors unlike gear pumps (discussed earlier) develop torque and rotary motion when they are acted upon by the fluid. Fluid enters the inlet port and is carried around the outside of the casing and finally flows out of the outlet port. The direction of rotation of a gear motor can be reversed by changing the direction of inlet and outlet flow. The volumetric displacement of a gear motor is fixed. Due to the difference in pressure between inlet (high pressure) and outlet (low pressure) side thrust occurs. The shaft drives the load, when it gets power from one of the gears in the gear motor. Figure 3.19 illustrates a gear motor.

Figure 3.19 (a) Gear motor (b) symbolic representation of a gear motor



Vane Motors Torque is developed in vane motors by the force due to the hydraulic pressure acting on the vane. The vane slides in and out of the motor connected to the drive shaft connected to the load. The motor rotates and the vanes follow the surface of the ring. Usually the vanes are sealed tightly against the vane motor case with the help of either springs or by pressure exerted at the bottom of the vanes when fluid is directed to pass through a small passage cut into the motor. If the rotor is mounted off-centre in the casing, the side thrust comes due to unequal pressure on the shaft. Hence vane motors are designed such that side loads on the rotor are balanced when the pressure at the inlet/outlet ports is distributed by the passage of the fluid through two interconnected cavities located 180° apart. The rotor in a hydraulically balanced vane motor is centrally placed and is a fixed displacement unit. Figure 3.20 illustrates the balanced design of a vane motor.

Figure 3.20 Balanced design of vane motor



Piston Motors Piston motors are variable displacement motors (Fig. 3.21). The swash plate can be tilted towards right or left past the central position. The direction of a piston motor can be reversed by tilting the swash plate. The symbolic notations are shown in Fig. 3.22.

Figure 3.21 Piston motor

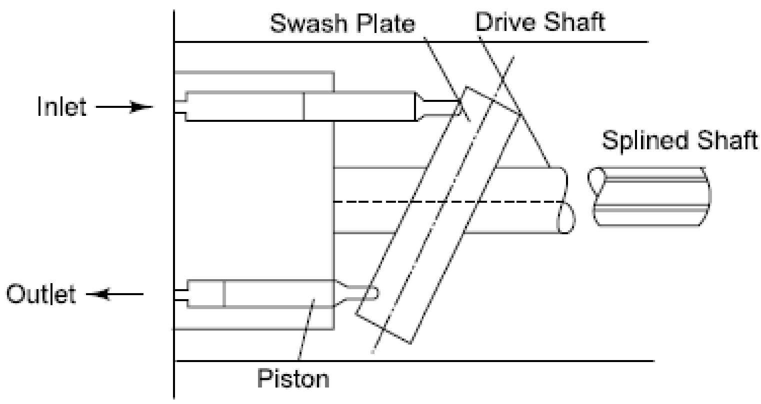
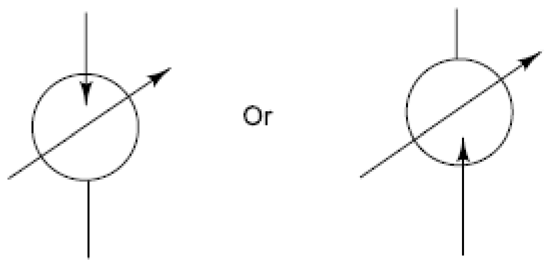
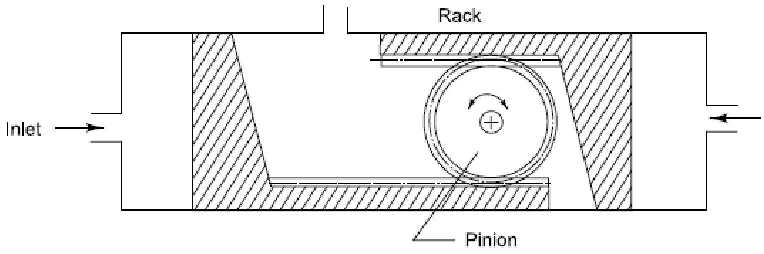


Figure 3.22 Symbolic notation of a variable displacement motor



Rack and Pinion Actuator Rack and pinion actuator as illustrated in Fig. 3.23 gives uniform torque in both directions. Rotational motion at low speed and high torque can be derived using such actuators.

Figure 3.23 Rack and pinion actuator



3.3.4. Basic Elements Used in Hydraulic Circuits

Basic elements like hydraulic tanks, filters and accumulators are used in a hydraulic system. Besides, various control components are used. The control devices are directional control valves, pressure control valves and flow control valves.

Directional control valves establish the direction of motion of an actuator through check valves or shuttle valves. Pressure control valves control excessive pressure and protect the hydraulic system against overpressure. Such valves are pressure relieving valves, pressure reducing valves etc. Flow control valves such as needle valves control fluid flow in various hydraulic lines of a circuit and thus speed control of actuators is possible.

3.3.4.1. Directional Control Valve

Check valve is a control valve used to control the fluid flow in one direction only.Figure 3.24 indicates a check valve in which the poppet (spool) held by a light spring is in closed position. When the fluid flows in the free flow direction, the fluid pressure overcomes the spring force and when the fluid flow occurs in the opposite direction, the fluid pressure pushes the poppet to the closed position and flow is blocked. The symbolic notation is shown in Fig. 3.25.

Figure 3.24 Check valve (a) No flow (b) Free flow

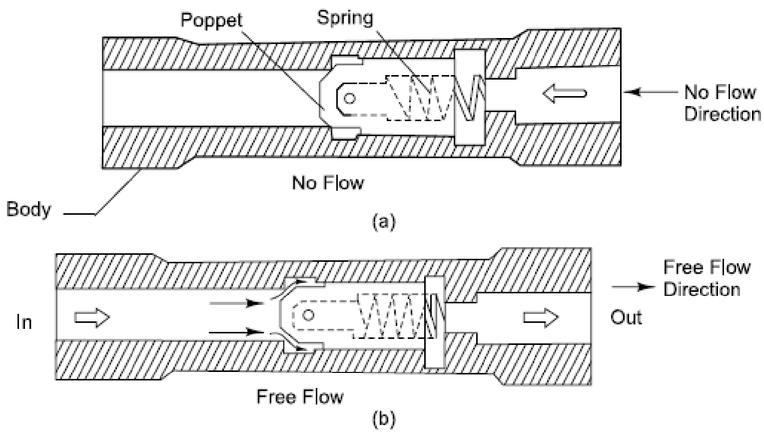


Figure 3.25 Symbolic notation for a check valve

Pilot operated check valve includes a pilot line and a pilot piston and is shown in Fig. 3.26. The symbolic notation is indicated in Fig. 3.27.

Figure 3.26 Pilot operated check valve: (a) no flow (b) fluid flow

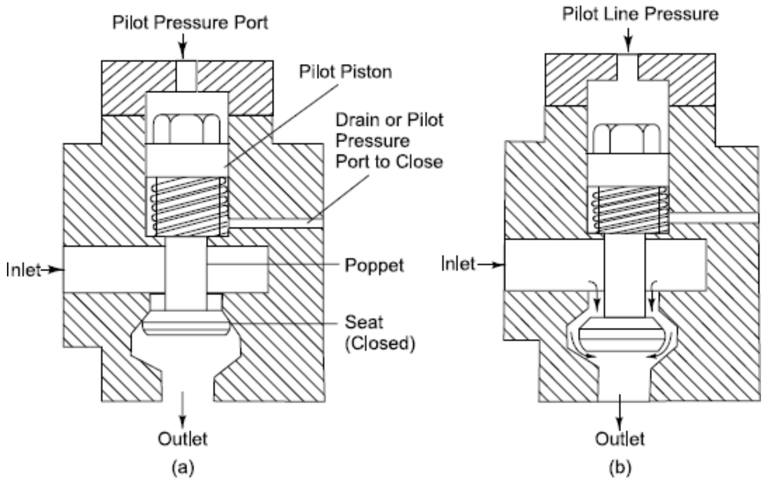
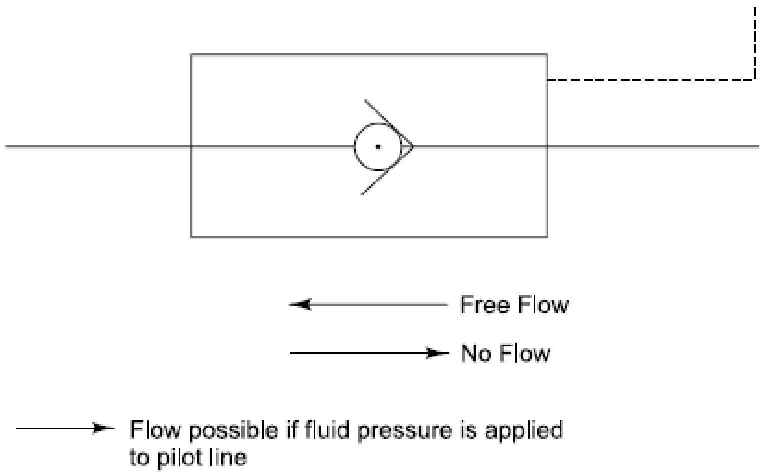


Figure 3.27 Symbolic notation of a pilot operated check valve



When the fluid enters from left end, the poppet closes the outlet port and the flow is blocked. But when the fluid pressure is employed on the pilot pressure port, it pushes a pilot piston against the spring below and the poppet is pushed down allowing the fluid to pass through the outlet port. In this way, an actuator can be put into action by locking the hydraulic cylinder in position.

Counterbalance valve is a special type of pilot operated check valve that may be mounted directly on the actuator.

In Fig. 3.28 a fluid pressure is employed through line B and the fluid enters the cylinder through the check valve at the bottom and the piston is pushed up. In order to move the piston down, fluid pressure is employed through line A and fluid enters the pilot line, exerts pressure on the poppet or spool of the counterbalance valve and pushes it down, when the fluid from the blind end of the cylinder is allowed to pass through the line B. The symbolic notation is illustrated in Fig. 3.29.

Figure 3.28 Counter balance valve (a) Piston pushed up (b) Piston pushed down

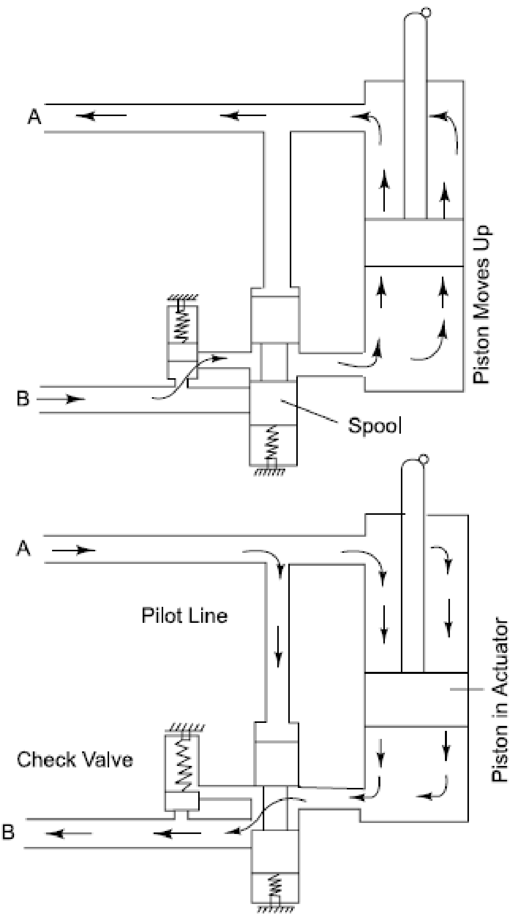
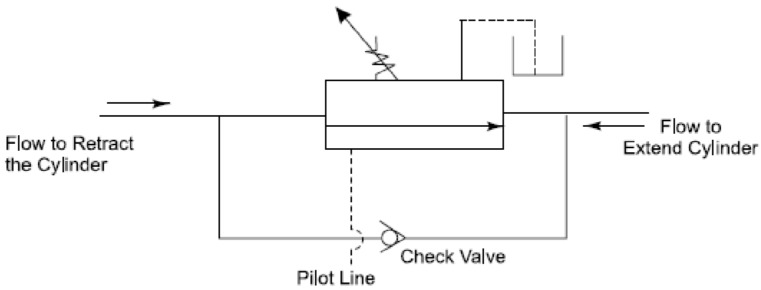


Figure 3.29 Symbolic notation of counter balance valve

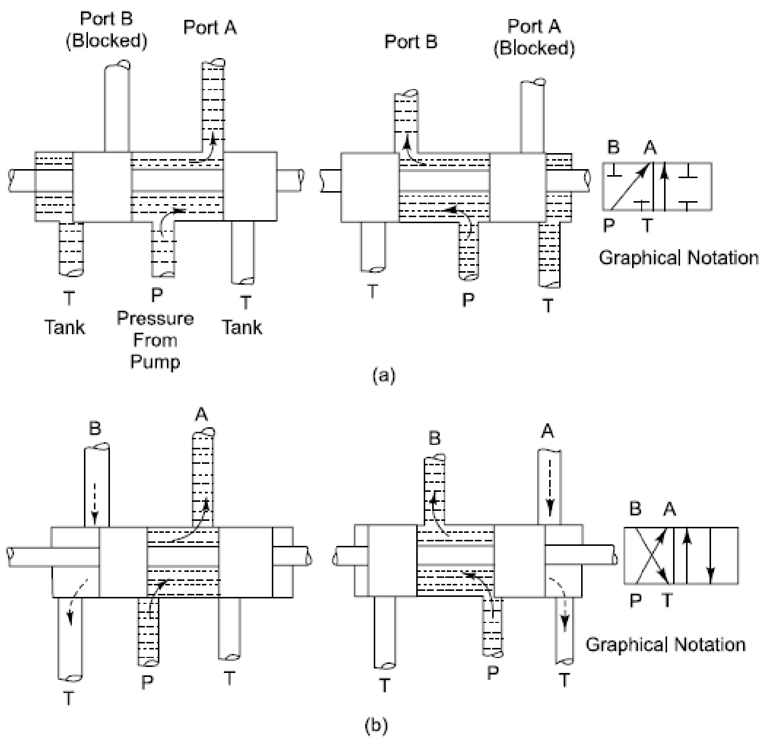


The other types of directional control valves may be two-way and four-way valves used to direct inlet flow to either of two outlet ports. The valves use a spool that slides for changing the path of flow through the body of the valve. The spool may have either two or three positions. The valves may have either two-ways or four-ways. Figures 3.30(a) and (b) illustrate two positions of the two-way and four-way valve respectively.

In Fig. 3.30(a), pressurized fluid from the pump passes through the valve and enters the cylinder through port A while the other cylinder, port B and tank pipe T leading to the hydraulic tank are closed. The graphical notation on the left of the rectangular block indicates the flow path for spool position at the right. Similarly when the spool is shifted to the left, pressurized fluid can go to the cylinder through port B; and port A and tank T are closed.

Figure 3.30(b) illustrates four-way valve configurations in which fluid from P can go to port A while the fluid from the cylinder can pass from B to T, when the spool is on the right. When the spool is shifted towards left, fluid can pass from P to B and from A to T. Four-way valves are used to control double acting hydraulic actuators.

Figure 3.30 Directional control valve (a) Two-way directional control valve (b) Four-way directional control valve



Since the directional control valve has two inlet ports namely P and T and two outlet ports levelled A and B, sometimes the inlets to the directional control valve are termed as the *centre* and the outlets of the directional control valve are called *ports*.

The directional control valve may have three positions. If the spool is at the centre of the valve, the valve is said to be in neutral. The other two spool positions are extreme left or extreme right. When the valve is in neutral, fluid can be blocked from entering the valve and this condition is called the *closed centre* position. When the valve is in neutral, fluid can be allowed to enter the valve and return to the tank and this condition is called the *open centre* position. Figures 3.31(a) and (b), illustrate the path of an open centre-open port three position directional control valve and a closed centre-closed port three position directional control valve respectively. Thus various centre flow paths for three-position four-way directional control valve may include:

1. open centre, open port valve
2. open centre, closed port valve
3. closed centre, closed port valve
4. closed centre, open port valve

and are illustrated symbolically in Figs 3.32(a), (b), (c) and (d), respectively.

Figure 3.31 Three-position four-way directional control valve: (a) open centre directional control valve with graphical notation; (b) closed centre directional control valve with graphical notation

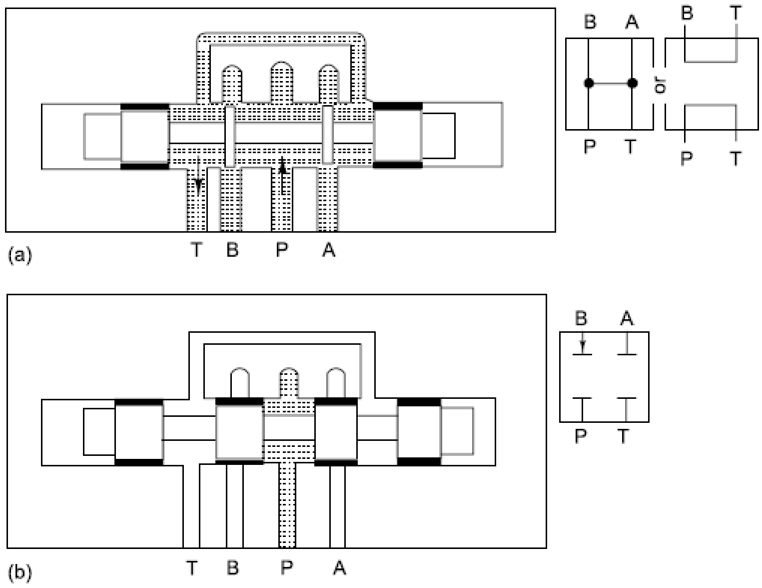
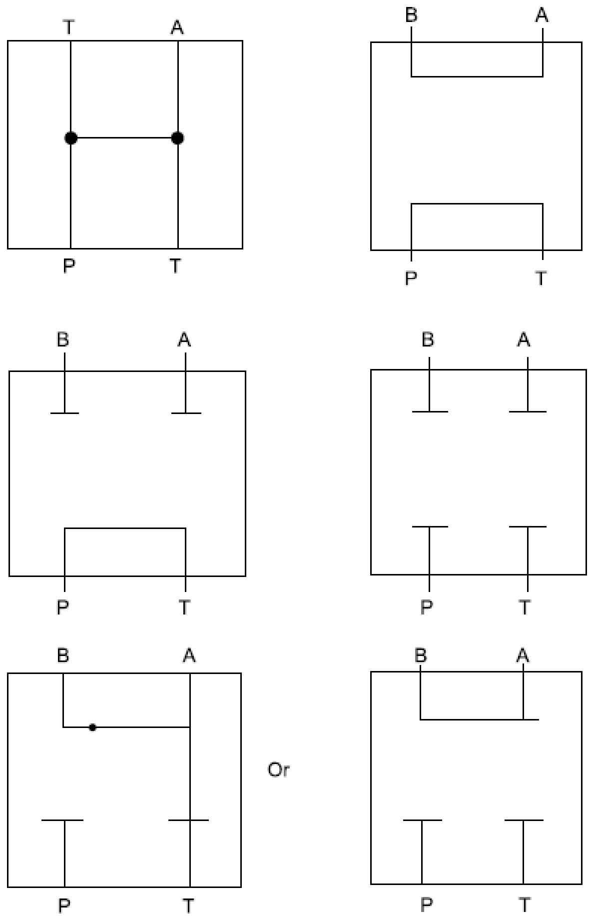


Figure 3.32 Various centres flow paths: (a) Open centre–open port, (b) open centre–closed port, (c) closed centre–closed port and (d) closed centre–open port



It may also include the configuration shown in Figs 3.33(a) and (b).

Figure 3.34(a) illustrates three-position four-way open centre, closed port directional control valve in which the spool is shifted to the right. Fluid from the pump enters the valve and moves to the blind end of the cylinder while the fluid from the rod end of the cylinder is returned to the tank. Figure 3.34(b) illustrates the same valve when the spool is shifted to the left and the direction of the fluid is reversed.

Figure 3.33 Other centres flow paths: (a) pressure and A dosed, B open to tank; (b) A closed and pressure, tank and B open

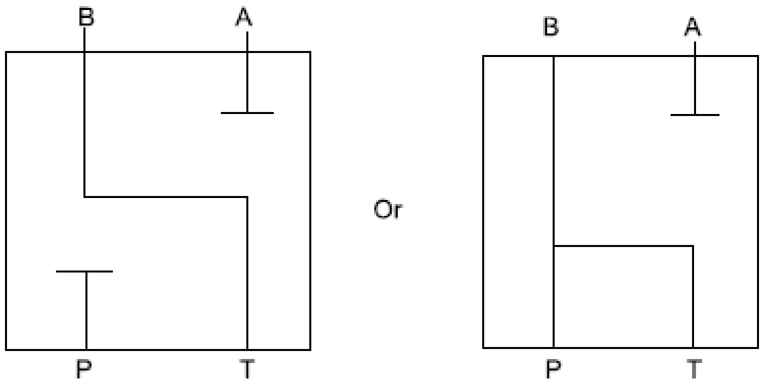
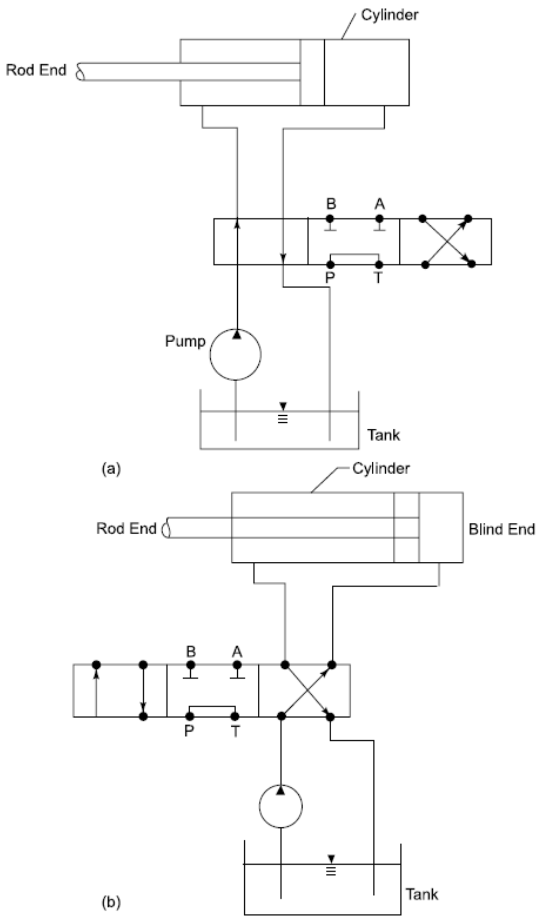


Figure 3.34 Directional control valve allowing the fluid to shift the spool towards either left or right. (a) Fluid entering the blind end of the cylinder shifting the spool to the left. (b) Fluid entering the rod end of the cylinder shifting the spool to the right



The spool of the directional control valve can be shifted and positioned by a hand lever, a foot pedal, by cam using pilot air pressure against the piston at either end of the valve spool or by using electrical solenoids. Figures 3.35(a)–(d) illustrate the various schemes.

Figure 3.35 Three-position four-way directional control valve with different spool control: (a) spring centred valve with spool manually actuated (b) spring centred valve with spool actuated by cam (c) spring centred valve with spool actuated by pilot air pressure (d) spring centred valve with spool actuated by solenoid

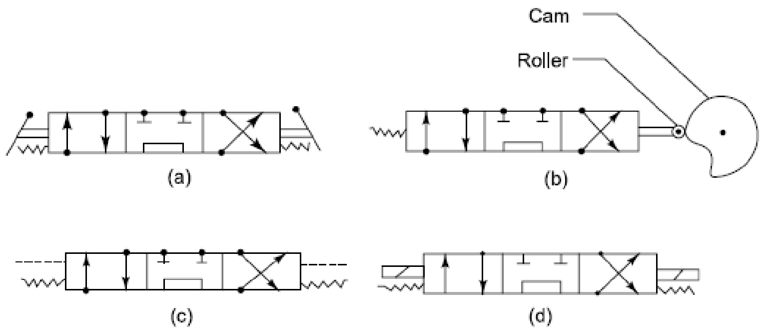


Figure 3.36 indicates a single solenoid actuated two-position, four-way, spring centred directional control valve.

Figure 3.36 Single solenoid directional control valve

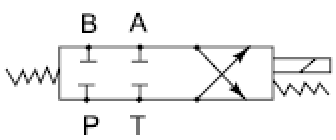
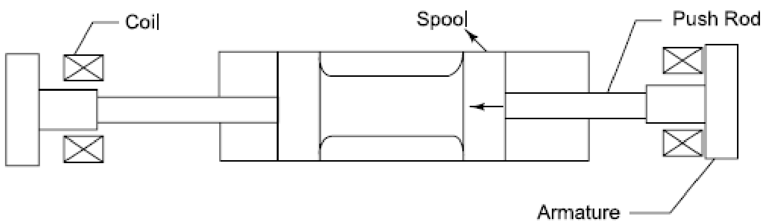


Figure 3.37 shows the directional control valve in which the spool is actuated by a solenoid consisting of a coil of wire. A magnetic field is created when an electric field is applied to the coil. The spool is held in neutral by springs. When the solenoid is energized the magnetic force pulls the armature into the coil resulting in a push on the push-rod to move the spool of the valve out of the centre.

Figure 3.37 Solenoid controlled directional control valve



3.3.4.2. Servo Control Valves

There are three types of servo valves: (i) spool type, (ii) flapper type and (iii) jet pipe type. Usually two stage servo valves are used. In the first stage, there is a pilot valve which directs the fluid to the main spool valve. The movement of the main spool valve is controlled by the amount of torque that can be developed by the torque motor connected to the pilot spool. The torque motor can be connected to the flapper which can be shifted closer to, or moved away from the ports, and the pressure is directed to the main spool that changes its position. In case of jet pipe valve, the torque motor can be connected to the jet pipe that can be deflected towards either of the control ports to move the spool back and forth. When the pilot spool valve or flapper or the jet pipe is in neutral position, no pressure is directed to the main spool valve and as a result, the main spool valve is neutral.

An amplified command electrical signal (voltage) drives the torque motor of the servo valve. This actuates the main spool of the directional control valve to direct the fluid to the hydraulic actuator driving the required load with respect to its desired position and velocity. The position and velocity of the load is fed back in the form of electrical signals to the input of the servo valve via a feedback device. The feedback signal is then compared to the command signal and their difference, i.e., the error voltage, (if any) is amplified to drive the torque motor till the command position and desired position of the load become equal. The amount of rated hydraulic flow is proportional to the valve pressure drop which, in turn, can be influenced by servo type spool or flapper or jet pipe.

In case of solenoid controlled valve, the directional control valve is moved to the left or right, say to close or open fully, but a servo control valve is used to move the valve by a small amount proportional to the electrical signal (voltage) applied in either direction to the torque motor. When the voltage is increased, hydraulic pressure can be increased and the valve can be further shifted from the neutral position.

A schematic diagram of a servo system is illustrated inFig. 3.38.

Figure 3.38 Closed loop feedback servo system

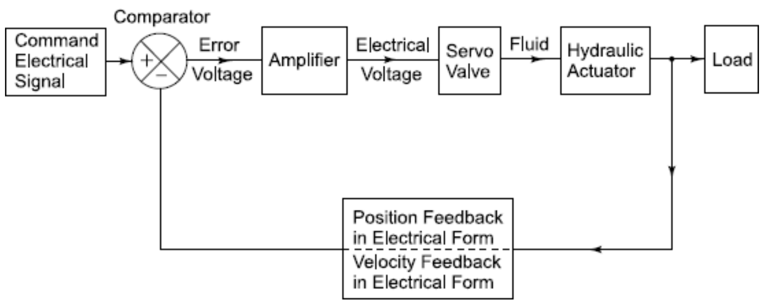
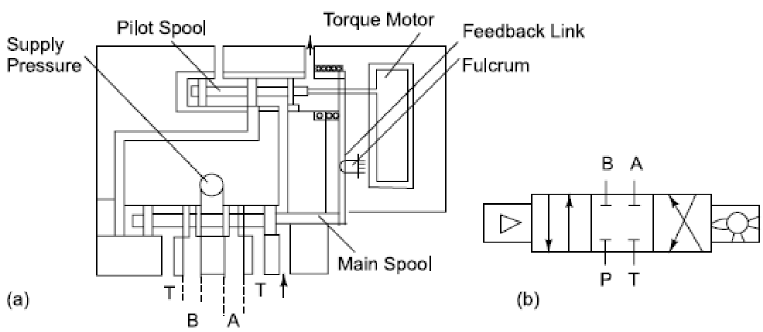


Figure 3.39 shows a scheme of a pilot spool type servo valve. There are two spools—namely pilot spool and main spool. The pilot spool is connected to the torque motor armature and is shifted towards (say) left. The fluid enters the left end of the main spool valve. With increased pressure at the left, the fluid from the pump enters the port B. Now on reversing the voltage to the torque motor, the pilot spool moves to the right allowing the fluid to pass through the right end of the main spool. As the pilot spool moves to the right, the main spool moves to the left. The pilot spool and the main spool is linked by a feedback linkage having a fulcrum at a variable position in between the spools. With the movement of the main spool towards the left, the fluid from the pump enters the port A and the fluid from the left of the main spool is drained out to the tank. The feedback linkage controls the movement of the main spool thus controlling the fluid to pass through the necessary ports.

Figure 3.39 (a) Pilot spool type servo valve (b) Symbol



In some cases, the torque motor can directly be coupled to the main spool valve. For better control, the main spool is moved by the pilot spool to have a controlled and directed motion.

Figure 3.40 indicates the scheme of a flapper type servo valve. The flapper is coupled to the torque motor and the flapper can be swayed (say) to the right or left and can be brought closer to the right or left nozzle. When the flapper is kept closer to the left nozzle, pressure on the left of the main spool increases and pressure on the right end of the main spool decreases. As a result the main spool shifts to the right. When the flapper is midway from both the nozzles, the pilot pressure is not directed to the main spool. As soon as the flapper moves towards right nozzle, the pressure at the left end of the main spool drops and pressure on the right side of the main spool increases and this causes a shift towards left.

Figure 3.40 Flapper type servo valve

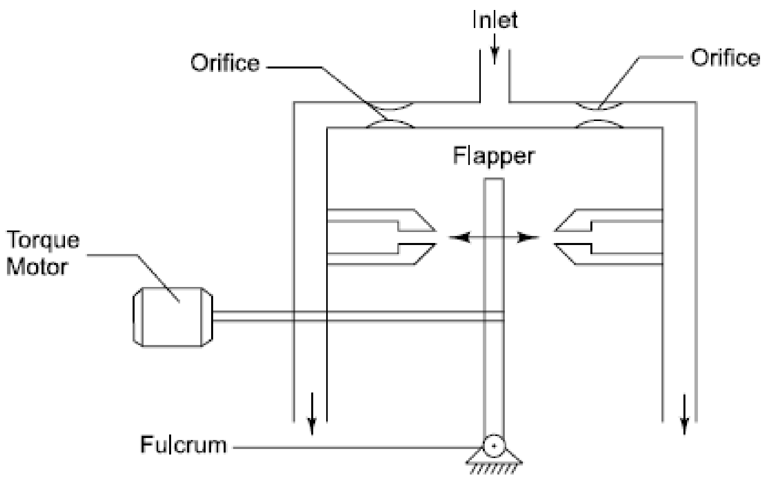
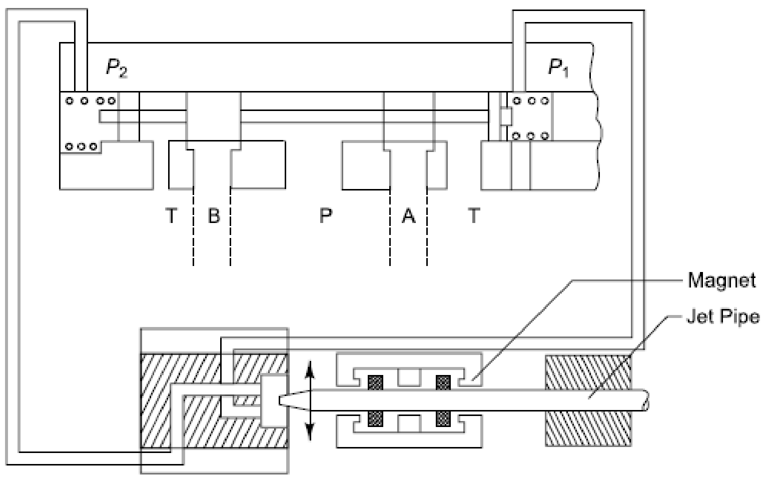


Figure 3.41 illustrates a jet pipe servo valve. If the small jet pipe is at the central position, the pressure on the control lines is neutral and the spool is in neutral position. A small d.c. current to the magnet pulls the jet to one side and creates more pressure to one of the control lines and causes the movement of the main spool. The movement of the spool allows the fluid to run the hydraulic motor and thus the robot arm moves. Two magnets are placed on two sides of the jet pipe. Feedback sensing allows the voltage to be applied on either coil and shifts the jet from the neutral position.

Figure 3.41 Jet pipe servo valve



3.3.4.3. Flow Control Valves

Flow control valves are used mainly to control the flow rate to the actuators and for regulating the speed of the hydraulic cylinder. Fluid flow takes place under pressure differential. This pressure differential can be created by a restrictor with an orifice through which the fluid is allowed to pass, can be made either fixed or variable. The needle valve is a common type of such variable orifice restrictor.

Figure 3.42 shows a servo controlled hydraulic circuit consisting of a pump, relief valve, needle valve and a hydraulic cylinder. Figure 3.43 illustrates a needle valve in which a sharp conical disk can be adjusted to be fitted into its matching seat for allowing free passage of fluid for a given valve setting. The flow can be increased or decreased by rotating the valve in either direction.

Figure 3.42 Hydraulic servo system

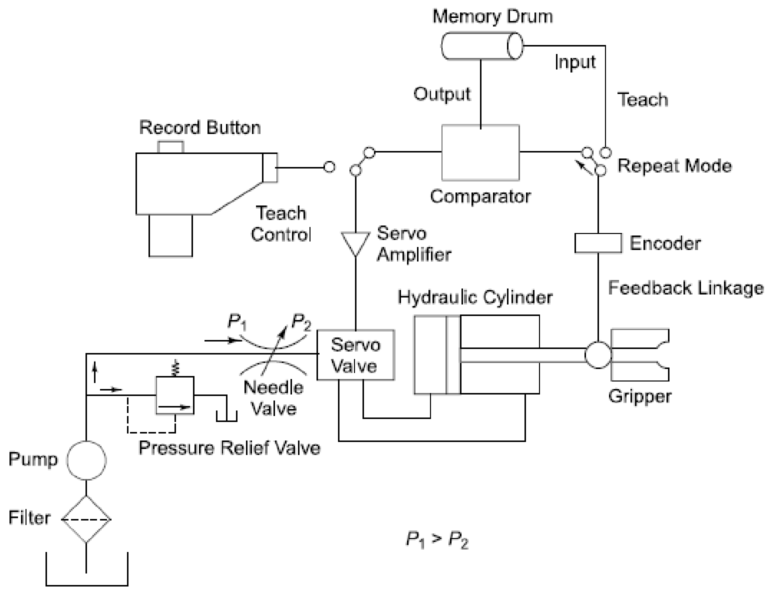
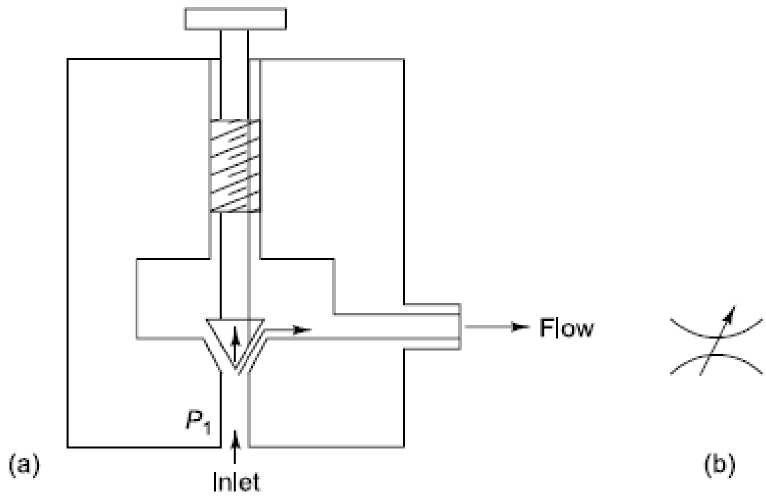


Figure 3.43 Needle valve with graphical notation: (a) needle valve (b) schematic diagram

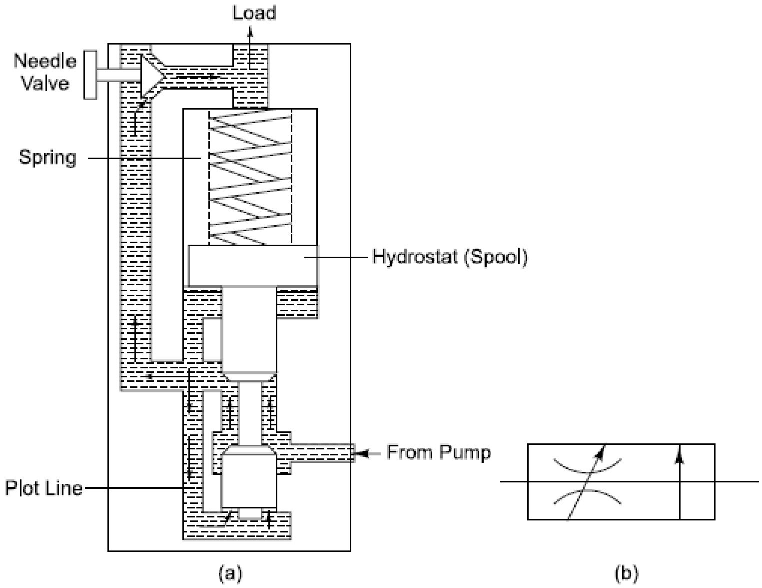


If the load in the system is increased, the speed of the hydraulic cylinder piston decreases because of the drop in the pressure differential across the needle valve. As the pressure differential ($P_1 - P_2$) decreases, the flow of fluid also decreases. To maintain the speed, the pressure on the pump inlet line must be increased so that the pressure differential is kept constant. To overcome the problem of fluctuations of the load, a pressure-compensated flow control valve is preferred.

3.3.4.4. Pressure Compensated Flow Control Valve

Figure 3.44 illustrates a pressure-compensated flow control valve in which the spring pushes the spool downwards to open the passage through which fluid from the pump can enter. The fluid entering through the needle valve actuates the hydraulic actuator to take up the load. The hydrostat maintains a constant pressure differential across the needle valve. The spool or hydrostat is normally opened by a light spring. If the inlet pressure increases, pressure at the pilot line, i.e. at the lower end of the spool increases and if the pressure is in excess, to overcome the spring force, the spool slides upwards and partially closes the passage to the needle valve. The flow is reduced and the pressure drops. A constant rate of flow can be maintained, however, by providing another pilot passage at the top. If the load increases, the increased fluid pressure acting through the spring pushes the hydrostat downwards and thus opens the passage from the pump inlet to the needle valve allowing more fluid flow. This increases the pressure in the fluid line before the needle valve. Thus, a constant pressure differential is maintained across the needle valve.

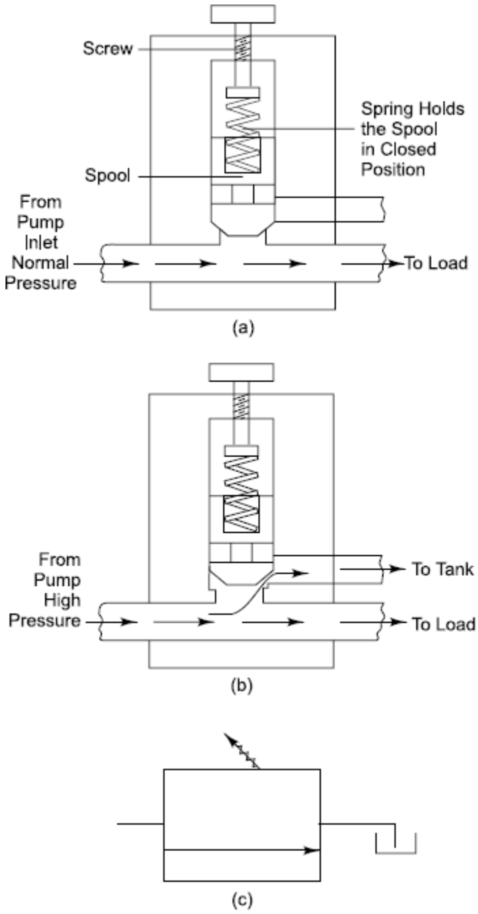
Figure 3.44 Pressure compensated flow control valve with graphical notation (a) Pressure compensated flow control valve (b) Graphical representation



3.3.4.5. Pressure Control Valve

The main purpose of pressure control valve is to limit the pressure to a specified maximum value. If the pressure exceeds the maximum value, a valve known as pressure relief valve diverts the fluid back into the tank. A simple relief valve which is normally closed is illustrated in Fig. 3.45.

Figure 3.45 Simple relief valve. (a) Closed valve (b) Open valve (c) Graphical representation

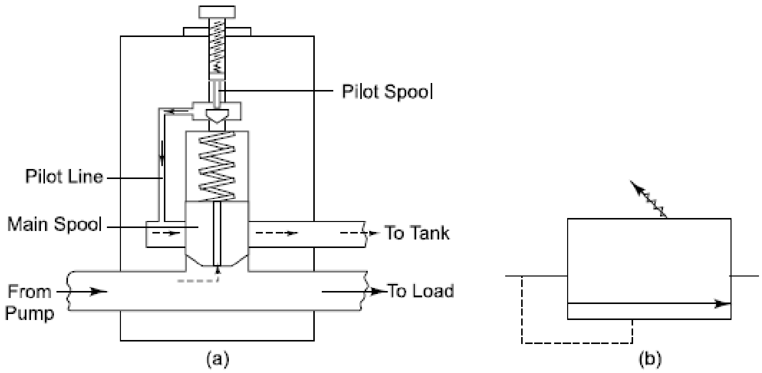


When the pressure is normal, the spool closes the opening to the passage to the tank. But if the system pressure increases, then the pressure acts on the spool on its lower side and pushes up the spool against the spring force that can be adjusted by the screw. The pushing up of the spool opens the passage through which fluid under high pressure is diverted to the tank. The pressure is reduced and the valve closes the opening due to the downward spring force.

3.3.4.6. Pilot Operated Relief Valve

The simple relief valve operates on either fully closed or fully open condition, causing excessive wear and vibrations of the spool. This causes instability because of frequent opening and closing due to the fluctuation of load and system pressure. The simple relief valve is also noisy. The pilot operated valve on the other hand modulates and maintains the system pressure constant. Figure 3.46 illustrates a pilot operated relief valve.

Figure 3.46 Pilot operated relief valve with graphical notation (a) Pilot operated relief valve (b) Graphical representation



The main spool contains a small hole in the centre. The fluid can pass through the bored hole and reach the pilot line if the pilot spool opens. A spring holds the pilot spool closed. Spring force can be adjusted by the screw on the top of the valve. The main spool is also held in a closed position by a spring. If the system pressure increases, the fluid passes through the hole in the main spool and fills the chamber between the pilot spool and the main spool. If the pressure in the chamber becomes high, it lifts the pilot spool. The opening of the pilot spool allows the fluid to be directed to the tank. The chamber pressure falls. The system pressure below the main spool increases further due to the high pressure differential. The main spool thus opens and now a large passage is open to the fluid line leading to the tank. The modulation of the main spool movement will depend on the pressure differential between the chamber pressure and the system pressure. Thus pilot operated pressure relief valve is able to maintain the system pressure at a preset constant level and adjusts itself through the modulation.

3.4. INTRODUCTION TO PNEUMATIC SYSTEMS

The word pneumatic comes from the Greek word *pneuma* meaning breath. Pneumatic systems use pressurized gases; here compressed air is the fluid medium to transmit and control power.

There are some advantages and disadvantages of pneumatic systems over hydraulic systems. The major advantage is economy, i.e. pneumatic systems are less expensive than hydraulic systems as the air used in the actuators is exhausted into the surrounding atmosphere and there is no need of any extra reservoir or tank. Besides, oil being more viscous and heavier than air poses problems while suddenly opening and closing the valves, due to the greater magnitude of accelerating or decelerating force required to control the fluid.

Air like any other gas is compressible while hydraulic fluid compresses very little. The compressibility of air helps in absorbing shock or load.

But the precise control of velocity and position in pneumatic systems is rather difficult as the arm of a pneumatically driven robot will sag and impair the repeatability of the robot. Pneumatic pressure is quite low compared to higher hydraulic pressure and therefore pneumatic systems are restricted to low power applications.

Air molecules are such that they will leak between the spool and the valve body easily and so seals like O-rings are necessary to avoid leakage.

Free air from atmosphere contains moisture that is harmful. Air is not a good lubricant and causes wear inside the actuator. Air creates a lot of noise. As the air is compressed, it causes change of state due to the heating and cooling effects.

3.4.1. Properties of Air

3.4.1.1. Gas Laws

The perfect gas laws are controlled by Boyle's law and Gay-Lussac's law. The general gas law is defined by

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

by combining Boyle's law and Charles' law.

Boyle's law:

$$\frac{V_1}{V_2} = \frac{P_2}{P_1}$$

Charles' law:

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}$$

Gay-Lussac's law:

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}$$

where *P* is the pressure, *V* is the volume and *T* is the absolute temperature.

$$\begin{aligned} \text{Absolute pressure} &= \text{Gauge pressure} + \text{constant} \\ &= \text{Gauge pressure} + 14.7 \text{ (FPS)} \end{aligned}$$

or

$$\text{Absolute pressure} = \text{Gauge pressure} + 1 \text{ bar}$$

$$\begin{aligned} \text{Absolute temperature} &= \text{Temperature} + \text{constant} \\ &= \text{Temperature } ^\circ\text{F} + 460 \\ &= \text{Tempreature } ^\circ\text{C} + 273 \end{aligned}$$

3.4.1.2. Flow and Pressure

When there is a pressure difference, flow takes place from high pressure to low pressure till the pressure differential is zero. The rate of flow determines the speed. So flow causes speed while pressure causes force.

3.4.2. Compressors

An air compressor is a machine to compress air from atmospheric pressure to a higher level of pressure at the expense of reduction of volume. Compressors are of two types: positive displacement compressor and rotary vane or screw compressor.

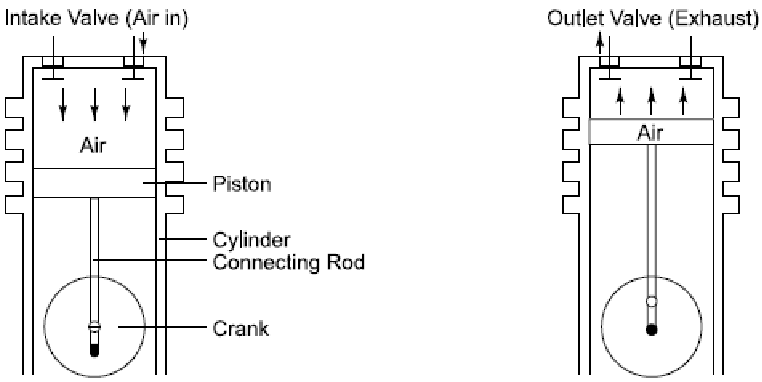
3.4.2.1. Positive Displacement Compressor

This is basically a reciprocating piston type compressor. The piston compressor may have a single stage, i.e. one cylinder in which the piston sealed with the piston-rings operates. The piston type compressor may have multistage compression in successive cylinders with effective intermediate cooling between stages to take away heat of compression.

A precision bored cylinder with deep thin fins for dissipation of heat is used for the piston type compressor. There are intake and exhaust valves on the top of the cylinder. The piston is fitted with crank-connecting rod mechanism for reciprocation.

When the piston as shown in Fig. 3.47 is pulled downward by the crank shaft in the crankcase, a vacuum is created above the piston and atmospheric air rushes in through the intake valve that opens to fill the vacuum. The intake valve is closed as the piston reaches the bottom. The crankshaft pushes the piston upward and the air in the cylinder is compressed. When the piston approaches the top of the cylinder, the outlet valve opens and the compressed air is delivered. At the top position of the piston, the outlet valve closes and intake valve opens. The cycle is repeated. This is the basic principle of compression. A compressor is, of course, fitted with many other elements like silencer, oil gauge, filter, lubrication systems, fly wheel, intercoolers etc.

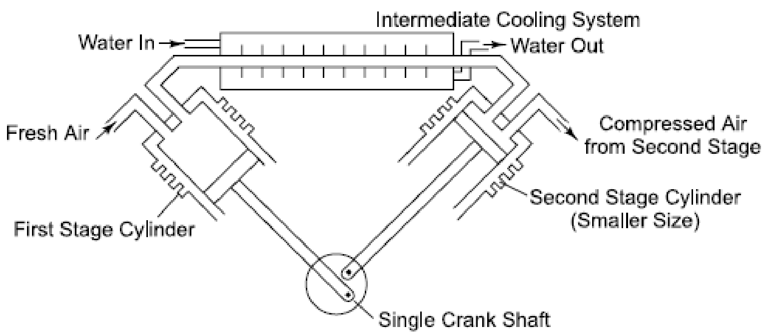
Figure 3.47 Reciprocating piston type compressor



Multistage Compressor and Cooling The temperature of air rises as it is compressed. With the increase of heat in the air, it tries to expand. Then compression poses a great difficulty. So multistage compression divides the total pressure among two or more cylinders by feeding exhaust air from one cylinder into the inlet of the next cylinder. The pumping efficiency is increased and input power requirement is reduced. The successive cylinder sizes decreases.

Figure 3.48 indicates a two stage compressor with intercooling arrangement. The first stage longer cylinder works to take fresh air in, while the piston goes down and as the piston is pushed upward, the air taken at ambient temperature is compressed and the compressed air passes through a copper tube which is air cooled or chilled with water and enters the second stage cylinder through the inlet valve. As the air is compressed in the first cylinder, temperature of air increases and the pressure of the air increases further. Compression of air in the second stage becomes easier if it is cooled to ambient temperature. This is effected by arranging an intermediate cooling system where either a tube with fine fins may be used or water jacketed tube may be employed for quick cooling. The cold compressed air from the first cylinder is delivered to a second small cylinder in which it is compressed and delivered or further compressed through several stages. Due to the significant heat dissipation, density of air increases and the volumetric efficiency is increased. The output of the piston type compressor is pulsating in nature.

Figure 3.48 Two stage piston compressor



3.4.2.2. Vane Type Rotary Compressor

A vane type compressor uses a rotor that rotates and creates a vacuum. Air is rushed in and compressed. It gives a constant delivery of the compressed air. It is similar to the design of vane pump shown in Fig. 3.10.

3.4.2.3. Screw Type Rotary Compressor

Screw type rotary compressor uses unsymmetrical profile of screw type rotors that mesh. Fresh air enters at one end and flows past the progressively smaller volume and is compressed. Controlled clearance between the teeth profiles and housings is necessitated. Oil is injected to form a thin film to absorb heat of compression besides the sealing of rotor clearance for high compressor efficiency. The profiles of rotors in mesh are shown in Figs 3.49(a) and (b).

Air compressors are rated in terms of free air which is defined as air at standard atmospheric conditions.

A compressor is provided with a receiver that acts as reservoir. The main function of the receiver is to supply air at constant pressure. The size of the receiver depends on the output flow rate of the compressor, rate of demand of pneumatic system, maximum and minimum pressure level in the receiver and time for which the receiver can supply the required amount of air.

The *receiver* size can be determined from,

$$V_{\text{receiver}} = \frac{C.T(Q_{\text{receiver}} - Q_{\text{delivery}})}{P_{\max} - P_{\min}}$$

where C = a coefficient, 14.7 or 1.01 × 10^5 pascal

T = time (min) for which receiver can supply air, s

Q_{receiver} = rate of demand (consumption), cfm (m^3/s)

Q_{delivery} = rate of output to the-receiver by the compressor, cfm (m^3/s)

$P_{\max}$ = maximum pressure level, psi (pascal)

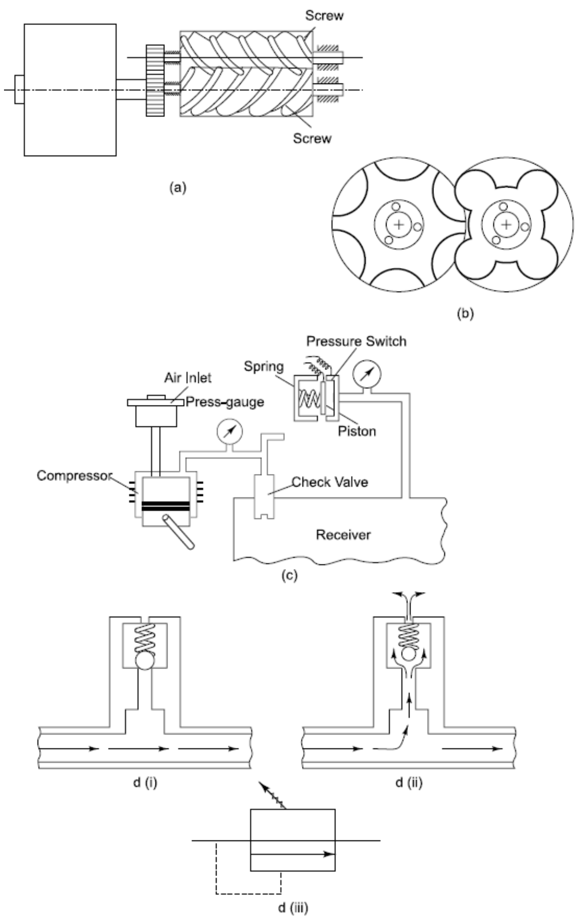
$P_{\min}$ = minimum pressure level, psi (pascal)

V_{receiver} = size of receiver, ft^3 (m^3)

Pressure Switch The compressor stores compressed air in the receiver and the pneumatic system draws it whenever air is needed. When the air is not needed, the receiver pressure may rise. To prevent rise in pressure in the tank, a pressure switch is provided in the receiver. The main function of the pressure switch is to cut off the electrical circuit and switch off the circuit whenever the pressure in the receiver tank exceeds a certain pressure limit. In a pressure switch shown in Fig. 3.49(c), a piston is pushed up by the high pressure and it moves against the spring tension and turns the electrical power switch off and the compressor motor stops. When the pressure in the receiver drops adequately, the spring pushes the piston down and turns the electrical switch on. The spring tension can be adjusted. When the pressure is high, air is bled off to the atmosphere through the release valve.

Safety Relief Valve If the pressure switch somehow fails to turn off the electrical switch of motor of the compressor, the pressure in the tank may continue to rise and the tank may explode. A safety valve is provided, therefore, to release the pressure of the receiver. A safety relief valve is shown in Fig. 3.49(d).

Figure 3.49 Screw type rotary compressor pressure switch and safety valve (a) Single-stage screw compressor (b) Profile of screw type rotors (c) Pressure switch (d) Safety relief valve with graphical notation



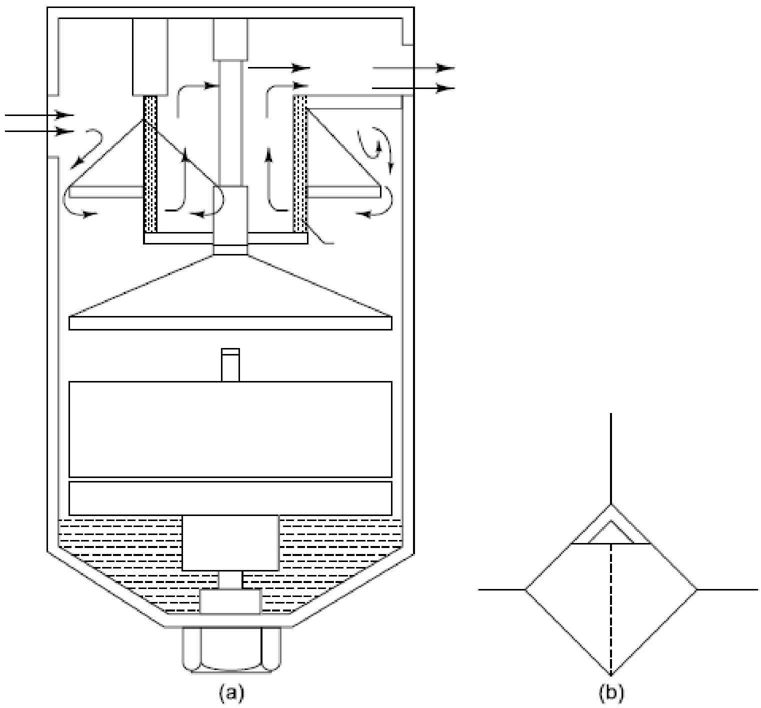
3.4.3. Pneumatic Conditioners

The main function of pneumatic conditioners is to make the air acceptable. The conditioners include air filters, regulators, lubricators and air dryers.

3.4.3.1. Air Filter

An air-filter as shown in Figs 3.50(a) and (b) is required to remove dirt and other contaminants from the air. Airborne dirt and other contaminants damage cylinder walls, valves and other pneumatic elements in the circuit. The air filters use cellulose felt-like reusable elements with gaskets. The baffling system installed within the air filter separates the dirt particles from the air. At the bottom, a drain port is provided.

Figure 3.50 Air filter with graphical symbol (a) Air filter showing dirt separation (b) Air filter symbol



3.4.3.2. Pressure Regulators

Pressure regulators are used to deliver air at a constant pressure to the pneumatic actuators. Figure 3.51 illustrates the schematic diagram of pressure regulator in which a spring pushes a diaphragm to lower a poppet or a spool down. The poppet can be opened or closed depending on the demand of load on the actuator. Air entering the regulator passes through the orifice that can be provided by opening the poppet. Due to the back pressure created by the load on the actuator, the diaphragm is pushed up against the spring force and the poppet is raised up to close the orifice and the flow of air to the outlet pipe is stopped. When the back pressure drops, the spring again pushes the diaphragm and the poppet downward to allow the air to pass through. The spring tension may be adjusted to set the air pressure. The symbolic representation is shown in Fig. 3.52.

Figure 3.51 Air pressure regulator (a) Poppet open (b) Poppet closed

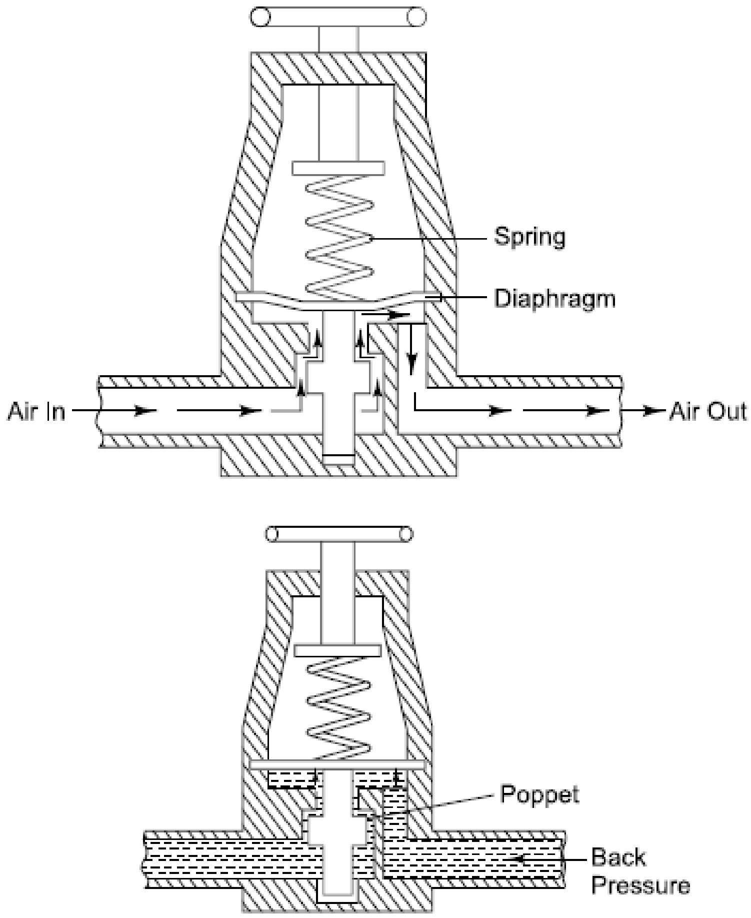
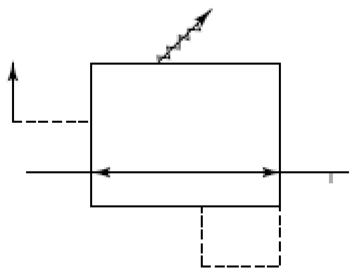


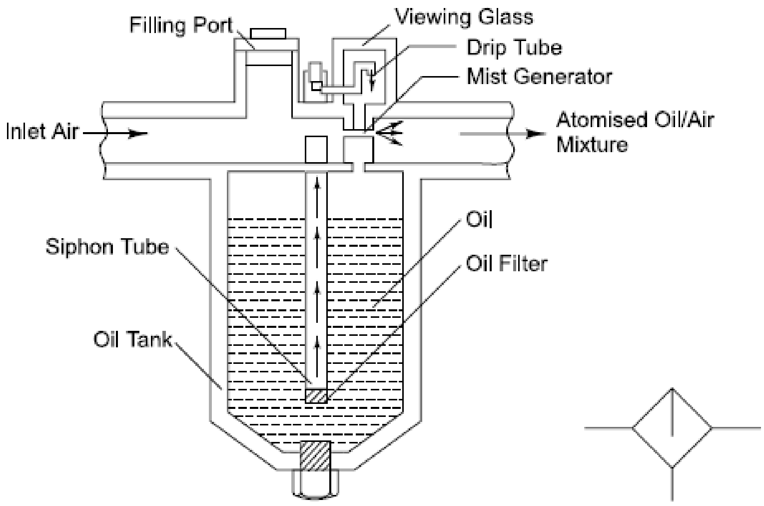
Figure 3.52 Symbolic representation of air pressure regulator



3.4.3.3. Lubricators

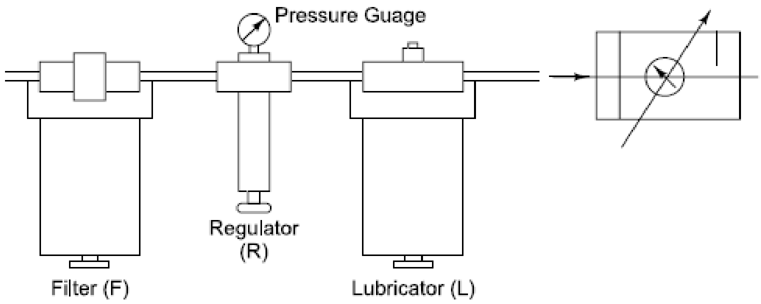
Lubrication is necessary for the internal moving parts of pneumatic components. Oil reaches the drip tube by siphonic action. When the air passes through the variable control orifice, an oil delivered by the drip tube is mixed with air to form an oil-mist that contains coarse and fine particles. The oil-mist is carried out and it lubricates the moving components of the pneumatic circuit. The lubricator is shown schematically in Fig. 3.53. Oil can be filled in the bowl without turning off air supply pressure. After refilling the bowl, the filling plug is replaced. This allows the bowl to be pressurized by the automatic opening of the bowl pressure control valve, mounted on top of the air pressure line. A sight dome is provided on the top of the lubricator.

Figure 3.53 Air lubricator with symbolic notation



A combination filter–regulator–lubricator (FRL) is shown in Fig. 3.54. The filter removes dirt and water; the regulator controls the air pressure to the actuators and the lubricator sends an oil–air mist to lubricate the valves and moving elements of the actuator. FRL includes a pressure gauge to indicate the operating pressure.

Figure 3.54 Combination filter-regulator-lubricator (FRL) with symbolic notation



3.4.3.4. Driers

The compressed air after passing through the aftercooler is retained in the receiver. Though aftercooler removes most of the moisture from the air, the air is still not suitable for use. Air driers are used for removing virtually all moisture. A drying agent (chemical substance) may be used. Air passes through the drying agent, say calcium chloride, a chemical reaction takes place with the water vapour and water vapour is absorbed. The chemical agents may corrode the parts. Sometimes heated air is passed through the chamber and dried.

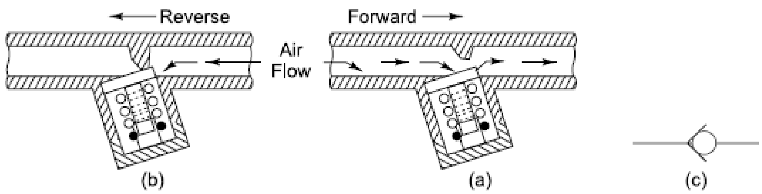
3.4.4. Pneumatic Valves

There are different types of valves used to control the pressure, flow rate and direction of air in the pneumatic circuit. Sometimes from the air line, two or more different pressure levels for separate actuators are required for which pressure regulators are installed in the line to get the desired operating pressure. The principle of operation of pressure regulator has been discussed in Sec. 3.4.3.

3.4.4.1. Check Valve

Pneumatic check valve is employed to shut off air flow instantaneously if it attempts to flow in the reverse direction. It allows free flow of air in the forward direction. A schematic diagram of a check valve is shown in Figs 3.55(a), (b) and (c).

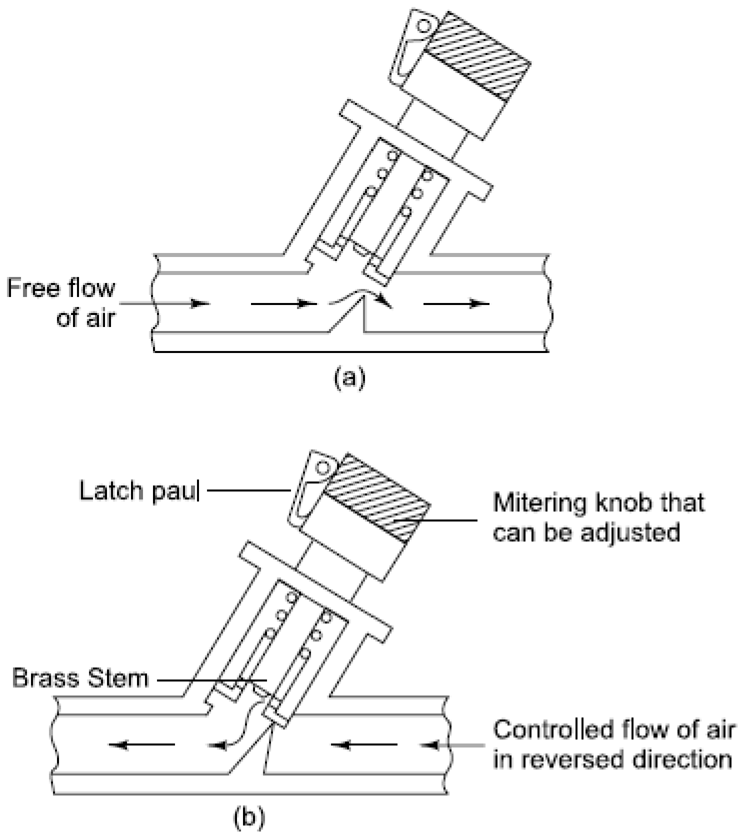
Figure 3.55 Pneumatic check valve with graphical representation: (a) forward air flow (b) reverse air flow (c) symbol



3.4.4.2. Flow Control Valve

Flow control valve is used to allow free flow in one direction and metered or controlled flow in the opposite direction. The flow control valve is illustrated in Fig. 3.56.

Figure 3.56 Flow control valve: (a) free flow of air (b) controlled flow of air



3.4.4.3. Directional Control Valve

Directional control valve used in pneumatic systems functions in a way similar to that of hydraulic systems except for a small change in design features of the O-rings.

There are different types of directional control valves. They may be 3-way or 4-way push button valve as shown inFig. 3.57, 3-way or 4-way roller lever type limit valves as shown in Fig. 3.58 and lever operated 4-way directional control valves as illustrated in Fig. 3.59 and Fig. 3.60. 4-way 2-position single solenoid or 3-position double solenoid directional control valves are shown respectively in Figs 3.61(a) and (b). 3-position valves remain in the spring centred position until one of the solenoids being energized shifts the valve towards one end. The spool remains in the shifted position until the solenoid is de-energized. The spool returns to the centre position after the solenoid is de-energized.

Figure 3.57 Push button valves: (a) 3-way button valve (b) 4-way button valve

Figure 3.58 Limit valves: (a) 3-way limit valve (b) 4-way limit valve

Figure 3.59 2-position lever operated directional control valve

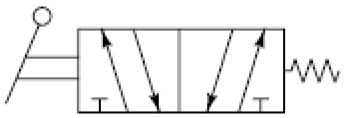


Figure 3.60 3-position blocked centre directional control valve

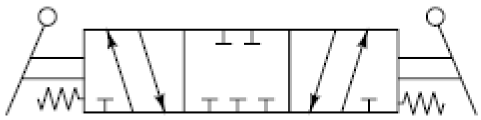
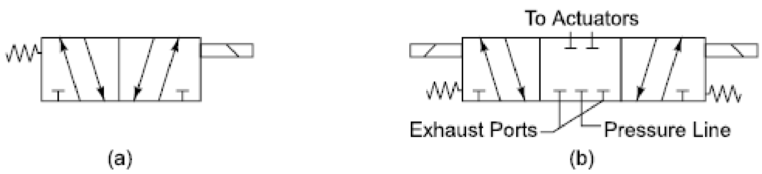


Figure 3.61 Solenoid controlled directional control valve (a) 2-position single solenoid valve (b) 3-position double solenoid valve



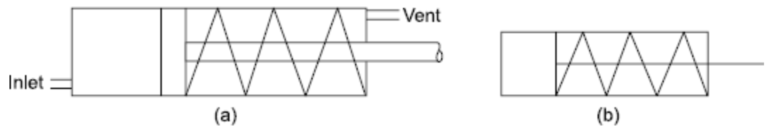
3.4.5. Pneumatic Actuators

Pneumatic actuators are similar to those used in hydraulic systems. Light aluminium cylinders are common in pneumatic systems. A typical pneumatic cylinder described in Chapter 1 may be reviewed. Pneumatic actuators are of two types: linear actuators—pneumatic cylinders and rotary actuator—piston motor or vane motor.

3.4.5.1. Linear Actuators

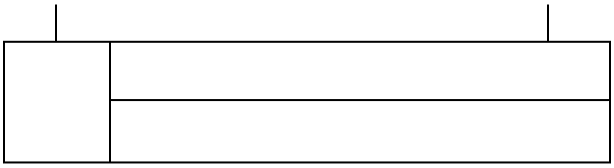
Pneumatic cylinders may be single acting cylinder or double acting cylinder. A single acting spring return cylinder is schematically shown in Fig. 3.62.

Figure 3.62 Linear actuator: (a) single actuating cylinder (b) symbolic representation



A typical double acting cylinder is symbolically shown in Fig. 3.63.

Figure 3.63 Double acting cylinder

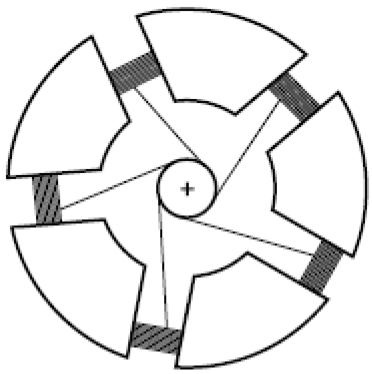


3.4.5.2. Rotary Actuators

Rotary actuators are similar to the hydraulic rotary actuators. There are two types of rotary actuators: low speed piston motor and variable speed vane motor.

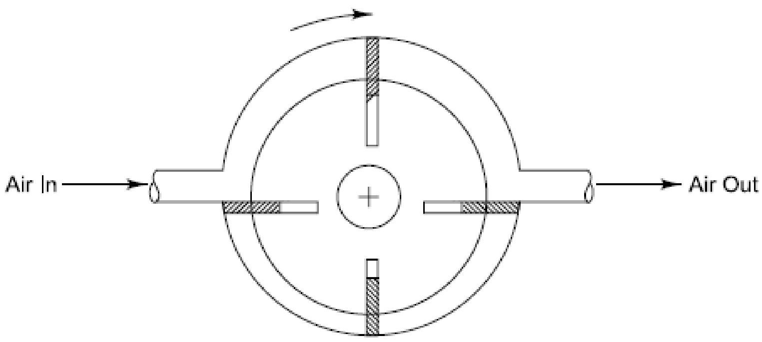
Piston motors are of radial type and shown in Fig. 3.64.

Figure 3.64 Piston motor



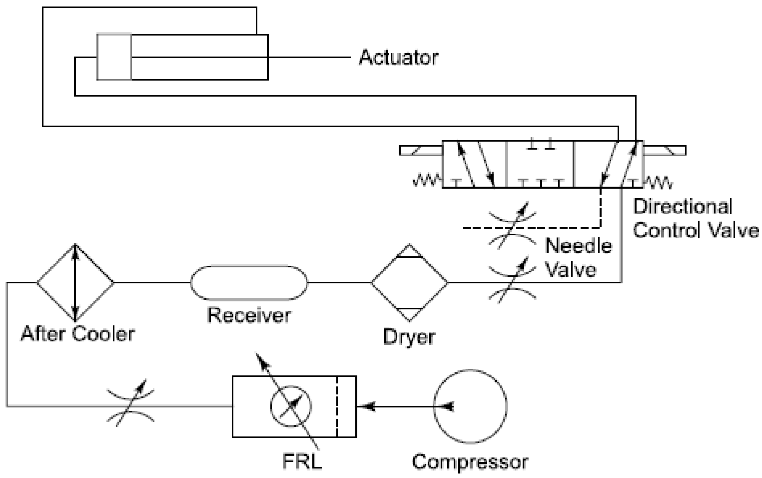
Vane motors are bidirectional and can rotate in either clockwise or counterclockwise directions. The speed depends on the volume of air inducted in and the torque depends on the pressure of the air. Unlike in the electrical motor, torque is not a function of speed. A typical vane motor is illustrated in Fig. 3.65.

Figure 3.65 Vane motor



A typical pneumatic system is illustrated in Fig. 3.66 to show the use of different pneumatic elements.

Figure 3.66 Scheme of a pneumatic system



3.5. ELECTRICAL DRIVES

Electrical drives use d.c. electrical motors for robot articulation. DC motors can supply power to carry desired loads. DC motors have high torque-to-volume ratios. For high precision, d.c. motors are suitable with closed loop servo controls. They provide clean drives in comparison to hydraulic and pneumatic drives. Electrically driven robots exhibit good repeatability. DC motors convert electrical energy into mechanical energy by developing suitable torque on the motor shaft. There are usually two types of motors used in the field of automation and robotics: permanent magnet motors and motors with wound field coils. However, for the non-linearity in the speed-torque characteristics of wound field motors, permanent magnet motors are conveniently used in robots. For the purpose of understanding d.c. motors, wound field motors are discussed first. DC motors have a stator and a rotor. The torque developed on the motor shaft depends on the magnetic (or electromagnetic) field flux in the stator field and the current in the motor armature.

3.5.1. Electrical Motors

3.5.1.1. d.c. Motors

Permanent magnets are used to generate the stator magnetic field by supplying directly the electrical current into the armature winding of the rotor through brushes and commutators.

In the shunt wound motor, a stator field winding is connected in parallel with the armature winding.

In the series wound motor, the stator winding (electromagnet) is connected in series with the armature winding.

In the compound wound motor, two stator windings are connected—one in series and the other in parallel with the armature winding.

In brushless d.c. motors, electronic commutation in matching with the rotor and the stator magnetic fields is made replacing the conventional brush-commutation system.

3.5.1.2. Shunt Wound Motors

Figure 3.67 indicates a schematic diagram of a shunt wound motor. Instead of using a permanent magnet in the stator field, a field coil is used. When direct current is applied to the field coil, a magnetic field is created. The armature coil begins to turn in the magnetic field and a voltage is generated. When the armature is static, a voltage is applied to the armature that draws heavy current. As soon as the armature rotates, the coil cuts through the magnetic line of flux and a back emf or a counter emf is generated. This opposes the applied voltage. The armature draws little current during its rotation when it generates counter emf and develops a torque. The higher the armature current, the higher is the torque. The speed-torque characteristic for a shunt wound motor is shown in Fig. 3.68. The shunt wound motor has good speed regulation.

Figure 3.67 Shunt wound electrical d.c. motor

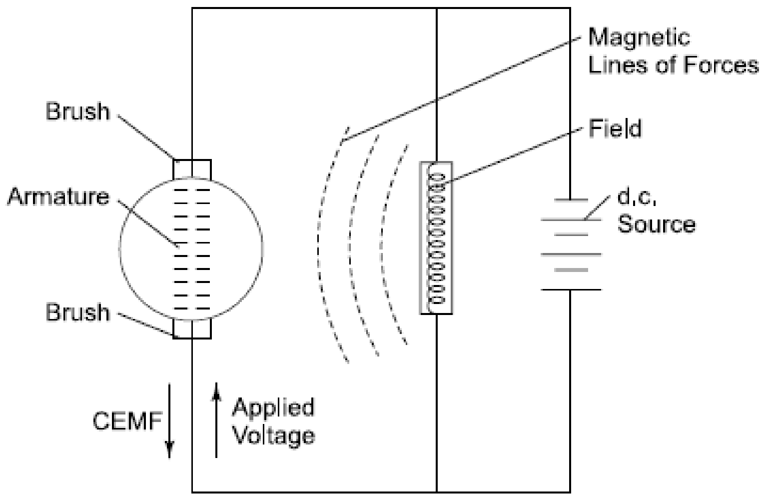
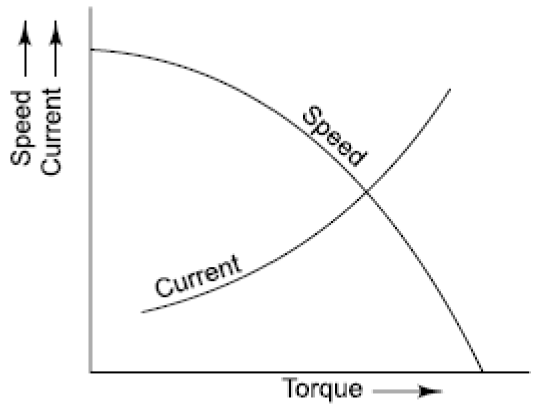


Figure 3.68 Speed–torque characteristics of a shunt wound motor



The speed of a shunt wound motor can be controlled by either controlling the field current as shown inFig. 3.69 or controlling the current in the armature circuit as shown in Fig. 3.70.

Figure 3.69 Speed control of a shunt wound motor with rheostat in series with the field

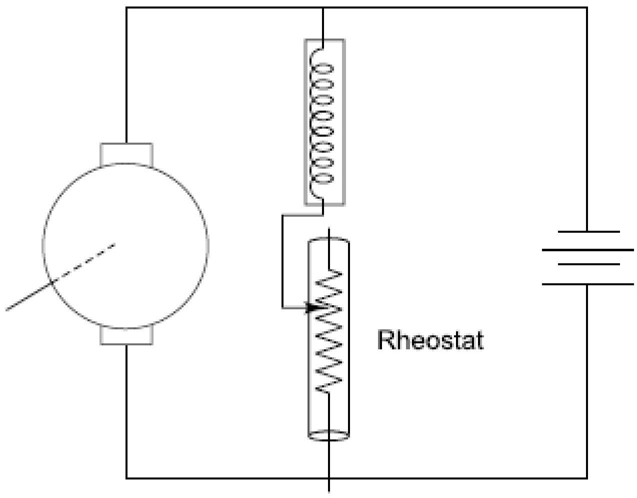
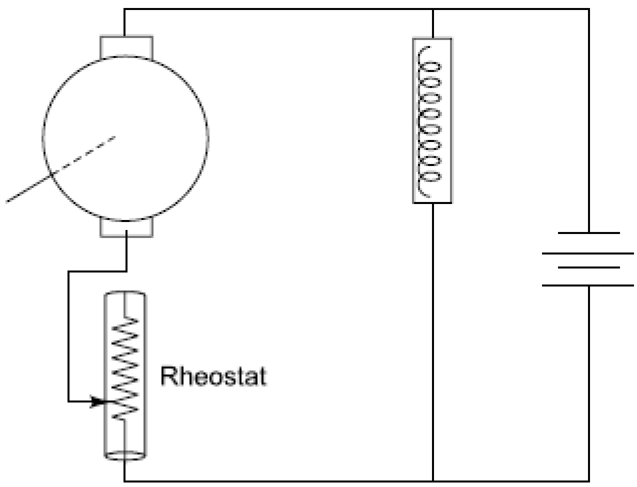


Figure 3.70 Speed control of a shunt wound motor with a rheostat in series with armature



3.5.1.3. Series Wound Motors

Figure 3.71 indicates a series wound motor. Here, the field winding is in series with armature winding. When the voltage is applied, high current is drawn by both the field and armature. The torque becomes high. But with the rotation of the armature, counter emf is generated which opposes the applied voltage. The current goes down and the motor runs faster. Of course the load restricts the speed of the motor; otherwise it will run away and the motor may be damaged. Figure 3.72 shows the speed-torque curves for a series wound motor.

Figure 3.71 Series wound motor

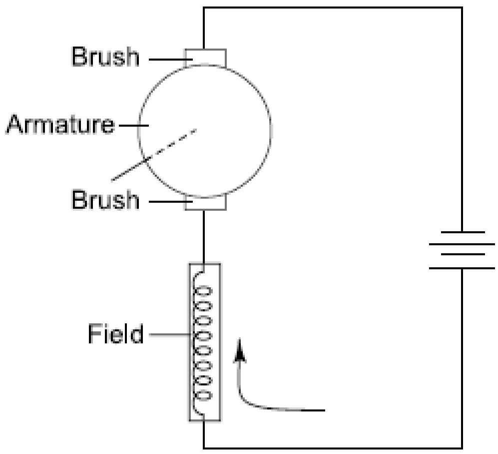
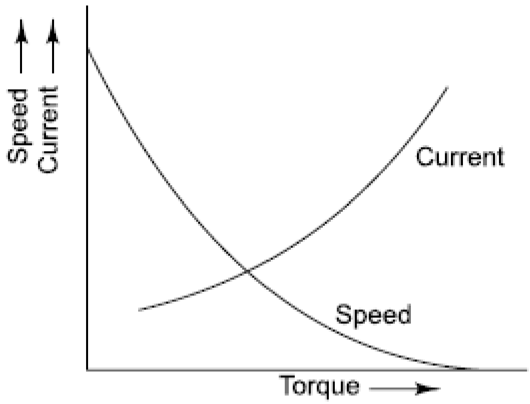


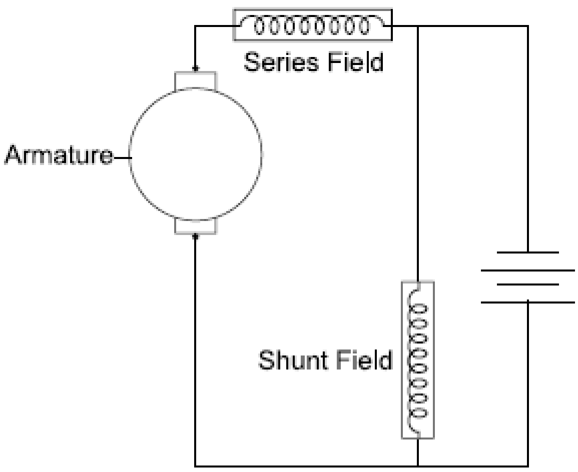
Figure 3.72 Speed–torque characteristics of series wound motor



3.5.1.4. Compound Motors

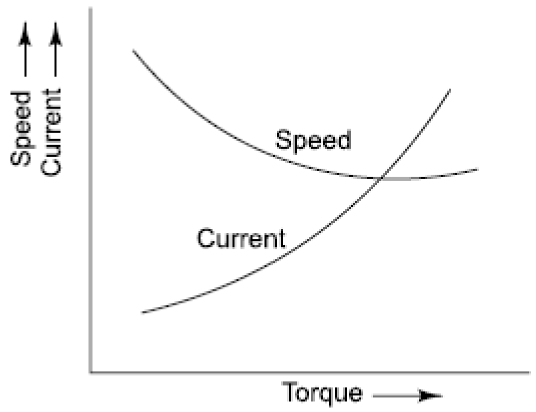
The speed regulation of a shunt wound motor is good and the series wound motor has higher starting torque. The advantages of the shunt wound motor and the series wound motor can be combined to form a motor known as compound motor, shown in Fig. 3.73.

Figure 3.73 Compound motor



[Figure 3.74](#) indicates the speed-torque curve of compound motors.

Figure 3.74 Speed–torque curve of a compound motor



3.5.1.5. Permanent Magnet Motors

Permanent magnet motors are of three types. They are: Iron core permanent magnet d.c. motors, Surface-wound permanent magnet d.c. motors, and Printed armature motors.

Iron Core Permanent Magnet Motors The armature shaft rotates within a strong and stable magnetic flux provided by a permanent magnet made of alnico, ferrite, ceramic or rare earth alloys. The wound field is substituted by a powerful permanent magnet. Iron core d.c. PM motors have a laminated iron rotor with slots in which the windings are located as shown in Fig. 3.75. Since there are slots, there is a tendency of starting and stopping as each slot passes through the edge of the magnetic field.

Figure 3.75 Iron core permanent magnet d.c. motor

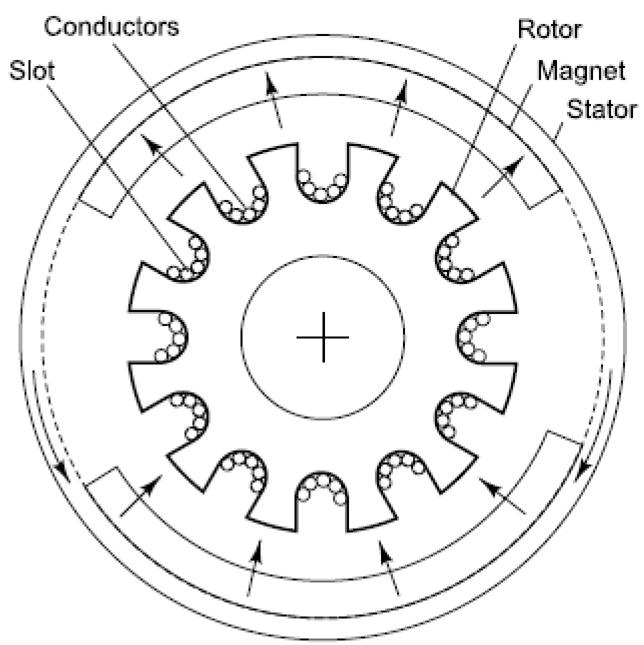
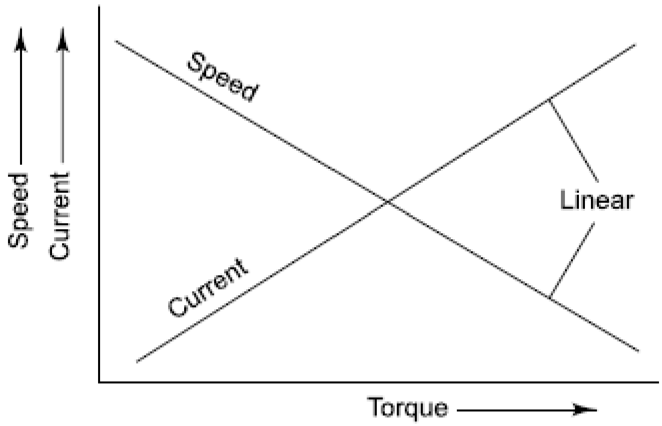


Figure 3.76 illustrates linear speed-torque characteristics of a permanent magnet motor. When the speed of a motor increases, torque decreases.

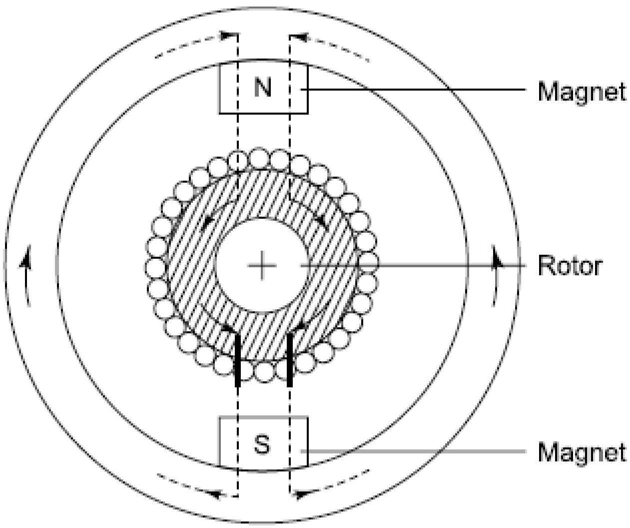
Figure 3.76 Speed–torque curves of permanent magnet d.c. motor



Surface Wound Permanent Magnet d.c. Motors In this motor, armature conductors are bonded to the surface of a cylindrical rotor. Since there are no slots, the starting and stopping effect as in the case of iron core PM d.c. motors does not occur. The magnets used in this motor are more powerful than in the iron core PM d.c. motors. The motor is shown in Fig. 3.77.

At the time of reversal of the motor, the applied voltage acts in the same direction of counter emf and as a result, the armature current increases and a strong armature field is created, which in turn, attempts to demagnetize the motors. The armature current is, in fact, restricted in this case and possibility of demagnetization is less.

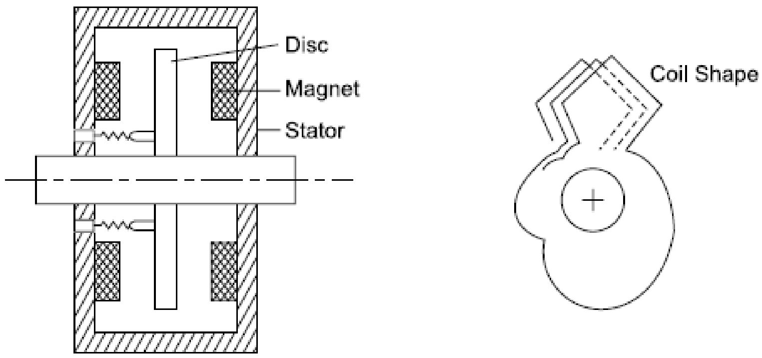
Figure 3.77 Surface wound permanent magnet d.c. motor



Printed Armature or Moving Coil PM d.c. Motors In the robots, it is often necessary to position the manipulator instantly by immediately bringing the motor to full speed from the starting or it may be necessary to stop it and reverse the motor. In the permanent magnet motor, the armature made of soft steel is heavy and difficult, to accelerate or dead stop due to the inertia effect. To overcome these difficulties, disc armature motors or printed-circuit motors are used. These provide good response and good reliability.

Figure 3.78 indicates disc armature motor in which flat discs of copper are stamped out and the stampings are laminated together with insulation between the sheets. The copper laminations are connected together to form a continuous wire.

Figure 3.78 *Disc armature d.c. motor*

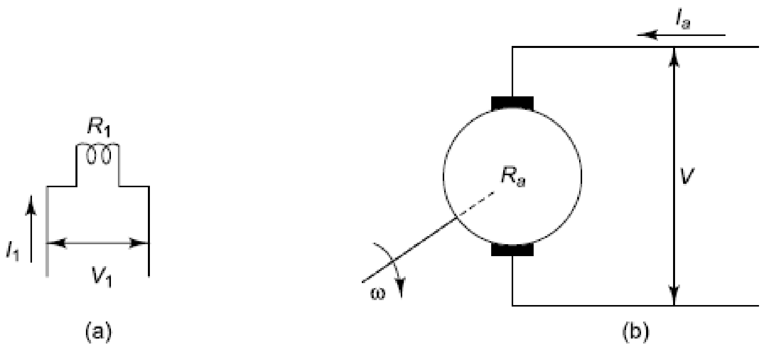


The model of a d.c. motor in steady operation is shown in Fig. 3.79.

The torque, T_m varies with time and is given by $T_m - KI_a$ where I_a is the time varying current in the armature.

The time varying counter emf (back emf), E_b is a function of flux created by the magnet and the speed of rotation, ω.

Figure 3.79 *Schematic representation of a disc armature d.c. motor (a) Schematic diagram of applied voltage (b) Scheme of a d.c. motor*



$\therefore E_b = k\omega\phi = k_b\omega$

where k_b = back EMF constant.

From Fig. 3.79(a),

$$V_1 = I_1 R_1$$

If the voltage applied to the motor is V, the armature current can be calculated from,

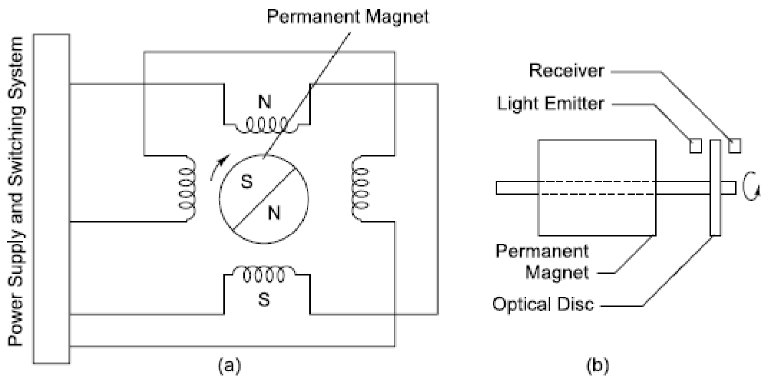
$$I_a R_a = V - E_b$$

3.5.1.6. Brushless d.c. Motors

The d.c. motors have brushes and a commutator to transmit power to the armature. During the rotation of the armature, the brushes make repeated contacts on the split sectors of the commutator. The making and breaking of contacts creates electrical noise besides pitting of the surface due to continuous rubbing and generates problems in the computer-controlled robots.

Brushless d.c. motors are therefore developed and the scheme is illustrated in Fig. 3.80. A permanent magnet is mounted on the armature shaft instead of on the field and the field is wound. The switching of the voltage in the field is reversed by electronic commutation. When north pole faces the south pole, rotation stops. When the north pole faces north, rotation take place. If the field is reversed at the moment when unlike poles face each other, the armature begins to rotate. An optical disc mounted on the armature rotates between the receiver and the light transmitter. When the light path is broken by the disc, the output from the receiver sends a signal to the electronic control to switch on the applied voltage. When the light transmitted reaches the receiver, a signal is also sent to the electronic control that activates the electronic switching to reverse the field. Thus without using the brushes and the commutator, it is possible to organize electronic switching and power supply to have continuous rotation of the armature. However, the position of the armature can also be sensed by other types of sensors. Hall effect is one such device. An advantage of brushless d.c. motors is that they have longer lives.

Figure 3.80 Brushless d.c. motor (a) A shematic diagram of electronic commutation (b) Optical disc on an armature



3.5.2. Control Loops

There are two loops namely (i) open loop and (ii) closed loop. Feedback is the essence of any automatic control. For any electromechanical system in which an output is obtained for a given input, designed output is controlled by adopting the principles of either an open-loop or a closed-loop system.

Figure 3.81 shows an open loop control of maintaining liquid level in a cistern. Liquid is allowed to pour into the cistern by opening the control valve. Figure 3.82 is the corresponding block diagram of the open loop system in which setting of the valve is the input. Control valve represents the controller, controlled variable is the desired level of liquid in the cistern and the process is the rate of liquid inflow. By changing the setting, the liquid level is maintained. There may be environmental disturbance (say), a change in temperature causing a change of viscosity that may influence the rate of liquid inflow.

Figure 3.81 The cistern being filled with liquid

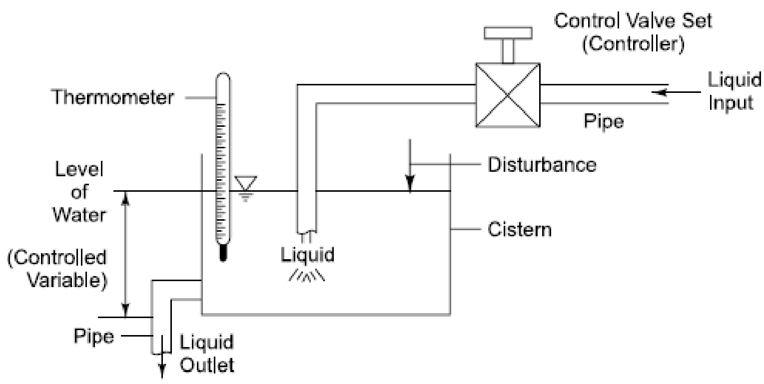


Figure 3.82 Open loop system

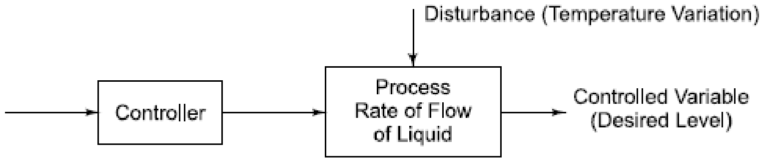
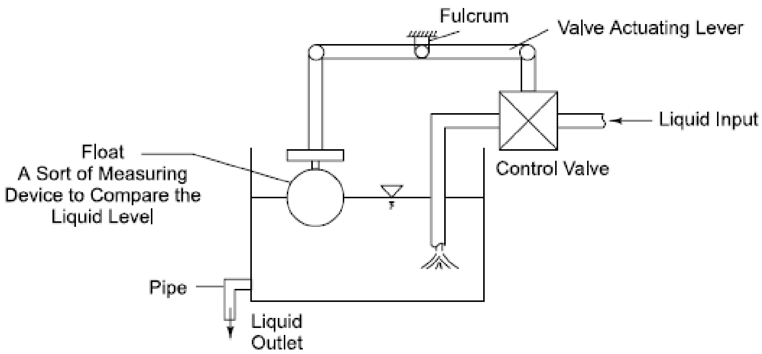


Figure 3.83 indicates the closed loop control of the set-up shown in Fig. 3.81.

Figure 3.83 The cistern fitted with a float to control the liquid level



In Fig. 3.83, a cistern is provided with a float that is connected to a hinged lever. The lever is connected to the stem of the control valve. Depending on the level of liquid in the cistern, the float is raised up or lowered down and accordingly, the valve setting is actuated by the lever, causing opening and closing of the valve. If the level of liquid is influenced by change in temperature and is high depending on the flow of the liquid through the output pipe, the valve will be closed preventing the inflow of the liquid. On the other hand, if the level of liquid goes down, the valve setting is such that more liquid will pour in to maintain the liquid level as before.

Figure 3.84 shows the block diagram of the closed loop control of flow of liquid. Figure 3.85 indicates the block diagram corresponding to "the diagram shown in Fig. 3.83. Setting is changed according to the height of the level of liquid. The difference between the desired liquid level and actual liquid level is known as error. This error on the output level is fed back to the input (setting) and is corrected till the error in the liquid level becomes zero. Here the error or change in the level of liquid may be caused due to the external disturbance, i.e. change in the temperature. The float is a sort of measuring device that measures the liquid level and sends the information to the controller to bring in necessary changes in the setting.

Figure 3.84 Closed loop system

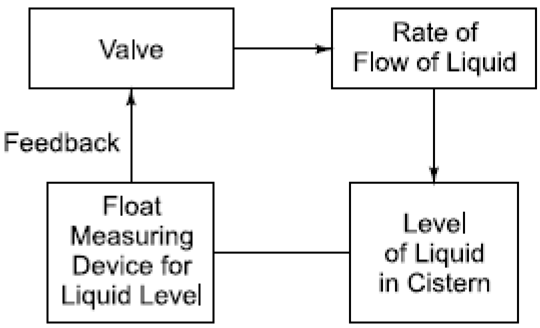
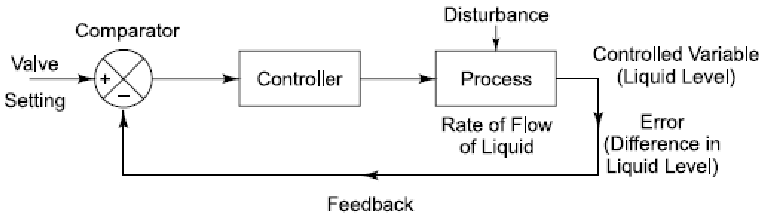


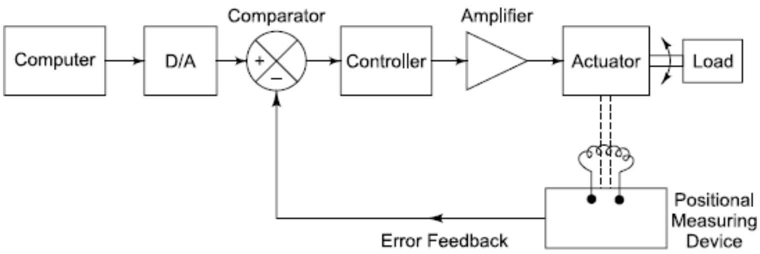
Figure 3.85 Block diagram of a closed loop control



3.5.2.1. Principles of Servo Control in a Robot

Closed loop servo control systems are activated by the error signal. For a servo system, the output expressed in the form of either position or speed of a robot arm is constantly servoed by an input command. Figure 3.86 illustrates the block diagram of a positional feedback of a robot arm. The desired position of the robot arm is given through a computer that sends a digital signal. Finally the robot's arm is shifted to a new position by a d.c. servo motor fitted to the arm. The digital signal from the computer is converted to an analog signal by a digital to analog (D/A) converter. This analog voltage is fed to the positive input of a comparator (an operational or differential amplifier). The output of the comparator is fed to the controller which in turn, sends its output to the actuator (a servo motor) through a variable gain power amplifier. A measuring device (a potentiometer or a shaft encoder or a resolver) is fitted on the output shaft. The measuring device produces an electrical signal indicating the current position of the robot arm and the signal of the current positional information is fed back to the negative input of the comparator. The comparator compares the desired input signal (setting signal) and the actual output signal obtained through measuring device. Their difference (error signal) is amplified and fed to the actuator. When the comparator output is zero, the robot arm stops moving as it has reached the desired position. This is the principle of servo control system in a robot.

Figure 3.86 Positional feedback system



In a servo actuated robot, the controlled variable may be position (angular or linear), speed (angular or linear) or torque (or force).

For controlling position or speed, either a positional servo system or a tachometric servo system is used.

Figure 3.87 shows a relationship between the input voltage signal, V and the angular speed ω of an output shaft of a robot actuator for a given load, L. Let there be a variation of speed, $\Delta\omega$ due to the external disturbance in load, ΔL. As soon as the load changes, the angular speed changes for which the input voltage, V is modified by an amount ΔV proportional to the variation in the angular speed. This is illustrated in Fig. 3.88. As the load (disturbance) varies, there is an increase of speed beyond set point, ω_0. Due to this disturbance, the input voltage V reacts.

Figure 3.87 Influence of input voltage on speed for a given load

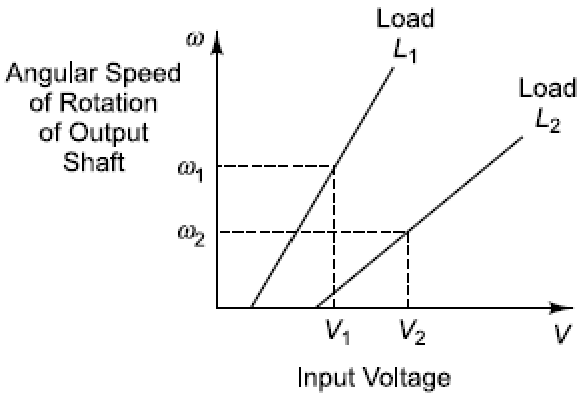
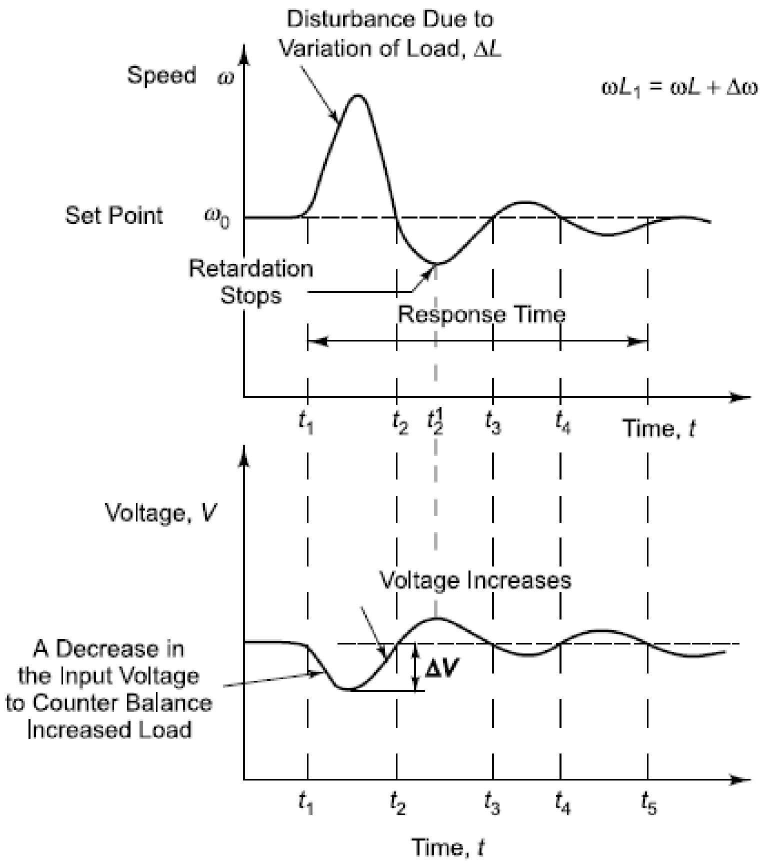


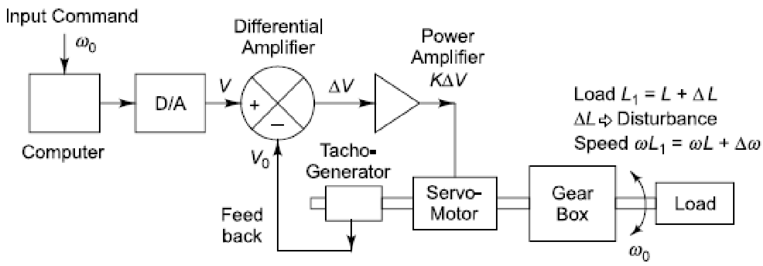
Figure 3.88 Change of voltage due to proportional variation of angular speed with respect to time



The voltage opposes the speed and counter balances the effect of the disturbance. As a result, the motor speed reduces, voltage gain increases and attempts to reach the set point. But due to inertia, the motor speed further decreases beyond the time t_2 and retardation stops at a time . By then the input voltage increases. Thus due to the variation of the output speed, input voltage will alter proportionately. After a few oscillations, the system will stabilize or achieve steady state depending on the interaction of inertia and friction, i.e. the response time of the system.

Figure 3.89 shows the closed loop speed servo system. A tachogenerator fitted to the output spindle of the servo motor generates a voltage proportional to the speed. The voltage, V_0 is fed to the input, V and the difference $(V - V_0) = \Delta V$ is input to the power amplifier and rotates the motor in either direction.

Figure 3.89 Closed loop speed servo system



3.5.2.2. Accuracy and Stability

In a servo system, accuracy refers to zero error in steady operation. When the difference between the output and input signals reduces to zero level, accuracy is achieved. By increasing the gain of the differential amplifier, accuracy is enhanced.

During transient operation, oscillations of the servo system occur due to variations of input in opposition to the output disturbance specially of load in an interacting environment of inertia and friction (damping). A high gain of the differential amplifier may disturb the stability of the system, though it may introduce more accuracy. The higher the gain, the faster will the system respond to the disturbance, but on the other hand higher the gain, the higher the probability that the system will become unstable. Thus there is a value of critical gain, below which the system is stable.

3.5.2.3. Servo Control Modes

There are four servo control modes by which a closed loop servo control system reacts to errors with sufficient accuracy and stability.

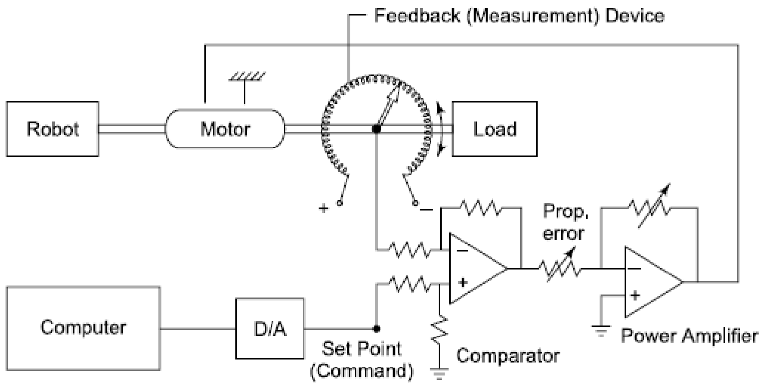
- Proportional control
- Proportional and integral control
- Proportional and derivative control
- A combination of all three, namely PID control

In fact a PID control in conjunction with a tachometric control is the most suitable solution for servo-controlled robots.

3.5.2.4. Proportional Control System

Figure 3.90 shows a schematic diagram of a proportional control system of an electrical actuator. Usually a shaft encoder or a resolver is employed as a measuring device on the feedback line, but in this figure a simple potentiometer has been shown for simplicity. As the wiper of a potentiometer moves, the output voltage varies. In a robot, command voltage indicating the set point is given by a computer through a digital to analog converter. The command voltage from D to A converter is given on the positive input of an operational amplifier (OP Amp), i.e. the comparator. The feedback voltage from potentiometer is brought to the negative input of the OP Amp. The OP Amp compares the command voltage and feedback voltage. The difference in the voltage is the error that is further amplified by a power amplifier and the output of the power amplifier drives the motor mounted on the robot. When the robot moves to the set point given by the command voltage, the difference between the command voltage and feedback voltage becomes zero; movement of the robot arm stops.

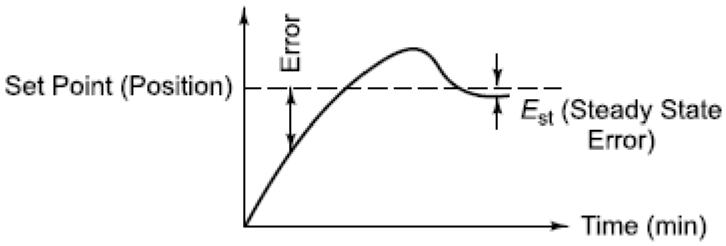
Figure 3.90 Proportional control system



However, the robot will not precisely stop at the set point due to transmission losses and other disturbances and hence in the proportional control system, there will be an error called steady-state error, i.e. there will be a difference between the command voltage and feedback voltage from the positional measuring device. However, the speed with which the robot moves upto the set point depends on the gain of the power amplifier.

Figure 3.91 shows the error due to proportional control. A steady-state error is found to exist.

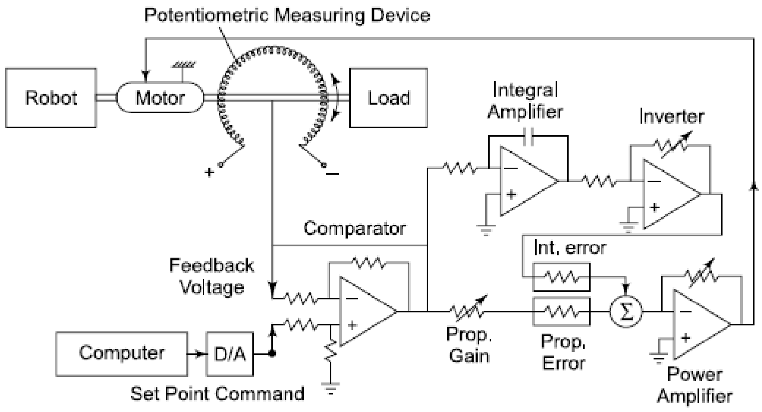
Figure 3.91 Steady state error due to proportional control



3.5.2.5. Proportional and Integral Control

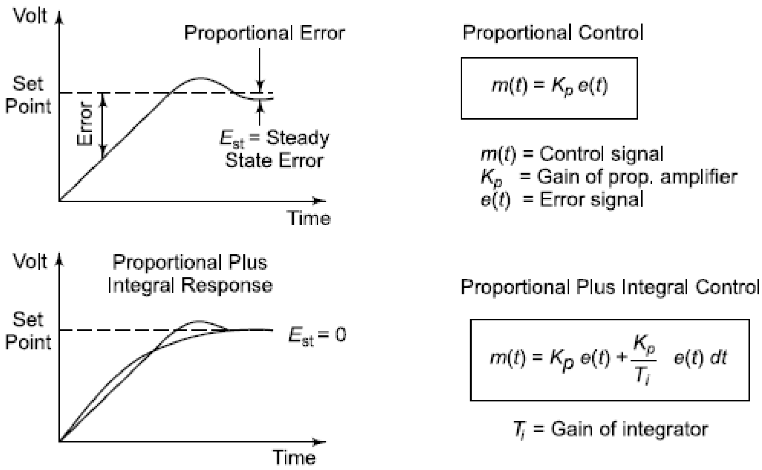
To compensate for the steady-state error, an integral amplifier is added to the proportional system as shown inFig. 3.92. The command or set point voltage is given to the positive input and feedback voltage from the positional potentiometer is given to the negative input of the OP Amp (comparator). Their difference gives the error signal and is indicated by the output of the comparator. The error signal is sent to one of the inputs of the summing junction. The same error signal from output of the comparator is fed to the inverting input of the integral amplifier. The output of an integral amplifier is always inverted. To invert the signal again, the output may be connected to an inverter. Thus, if positive input is given to the integral amplifier, its output will be inverted. If this inverted output of the integral amplifier is connected to the inverter, the output of the inverter will follow the input, i.e. the output of the inverter will be the positive signal. The reverse is true, i.e. a negative input to the integral amplifier will be the same as a negative output signal of the inverter. The output of the inverter is connected to the other input of the summing junction. The summing signals of proportional control error plus the integral control error are sent to the power amplifier that drives the motor of the robot.

Figure 3.92 *Proportional plus integral control system*



The error signals are shown in Fig. 3.93. The steady-state error is eliminated by the combined effect of proportional and integral control.

Figure 3.93 *Response of proportional plus Integral control*



3.5.2.6. Proportional and Derivative Control

In the proportional control, depending on the positional feedback, the robot arm on which the motor is mounted is found to oscillate about the set point and a steady-state error is found. This steady-state error due to the proportional control can be eliminated by adding an integral control. But the compensation for the rate of change of an error signal is very important. The rate of change of error is influenced by introducing derivative control. The derivative amplifier, in fact, slows down the response of the system and introduces damping. The degree of damping controls motor oscillations caused by the proportional control.

Figure 3.94 illustrates the circuit diagram of proportional plus derivative control. The command or set point voltage and the feedback voltage from the potentiometer are fed to the comparator. The difference in voltage, i.e. the error undergoes proportional gain and is sent to one of the inputs of the summing junction. The output from the comparator is also sent to the inverted input of a derivative amplifier. The derivative amplifier is an inverting amplifier. If the input to the derivative amplifier goes more positive, the output of the derivative amplifier goes more negative. For a constant input voltage to the derivative amplifier, it gives zero output. For a ramp input, the output is the rate of change of ramp input with a negative sign $\left(-\frac{d}{dt} \text{ of error}\right)$. Therefore a rising input error from the comparator gives a negative output voltage. Thus, a rising error voltage from the comparator and a negative error voltage from the derivative amplifier are the two inputs to the summing junction and the summed error becomes an input to the power amplifier. The output of the power amplifier is connected to the motor actuating the robot.

Figure 3.94 Proportional plus derivative control

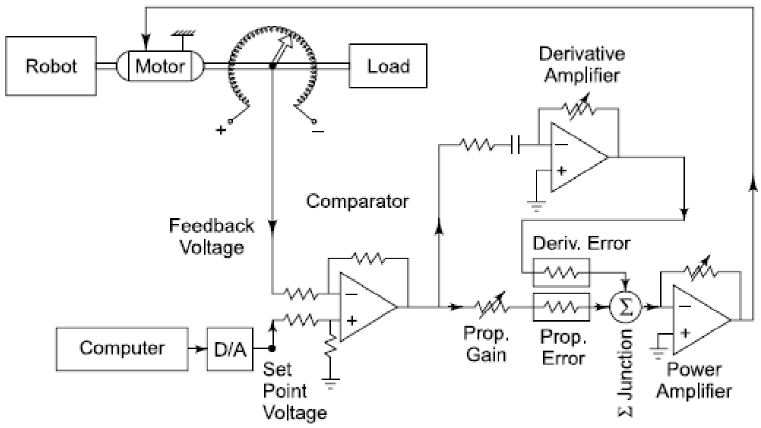
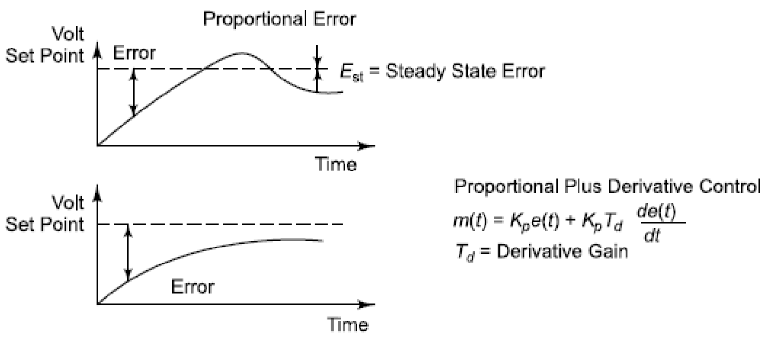


Figure 3.95 illustrates the response curves of proportional and derivative control.

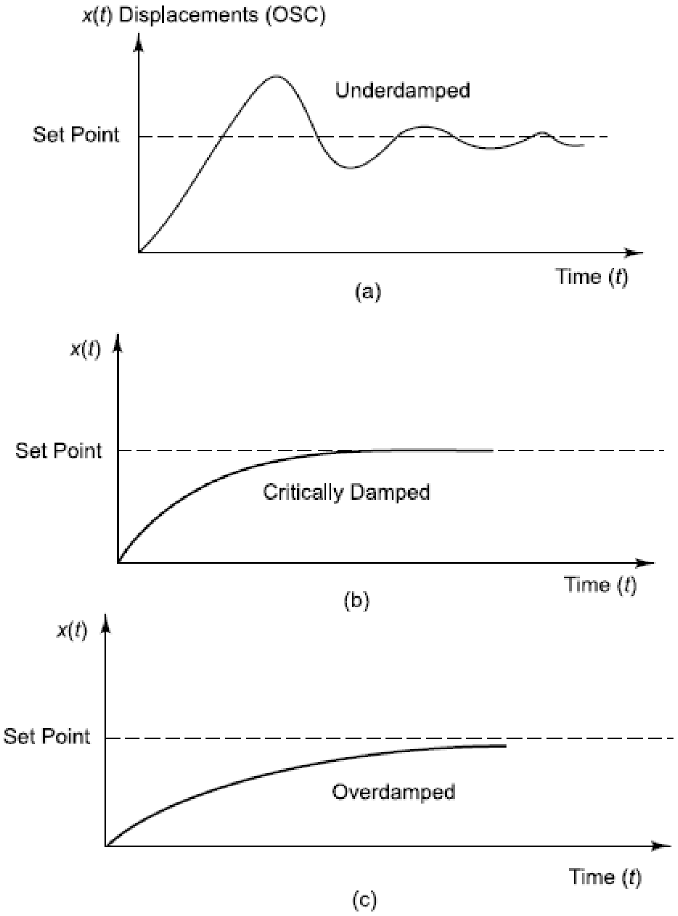
Figure 3.95 Response curves of proportional plus derivative control



There are three possible conditions of oscillations in a closed loop servo system. They are (i) undamped (ii) critically damped and (iii) over damped oscillations.

When the oscillations are underdamped, the response is as shown in Fig. 3.96(a).

Figure 3.96 System damping characteristics: (a) underdamped system (b) critically damped system (c) overdamped system



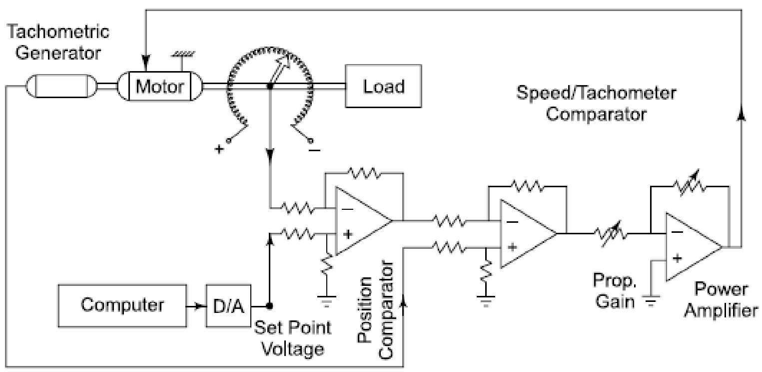
When it is critically damped, the response is shown in Fig. 3.96(b), i.e. the motor and robot mass moves in the shortest time period without overshoot.

When the system is overdamped, the response curve is shown in Fig. 3.96(c).

3.5.2.7. Proportional-Integral-Derivative (PID) Control with Tachometric Feedback

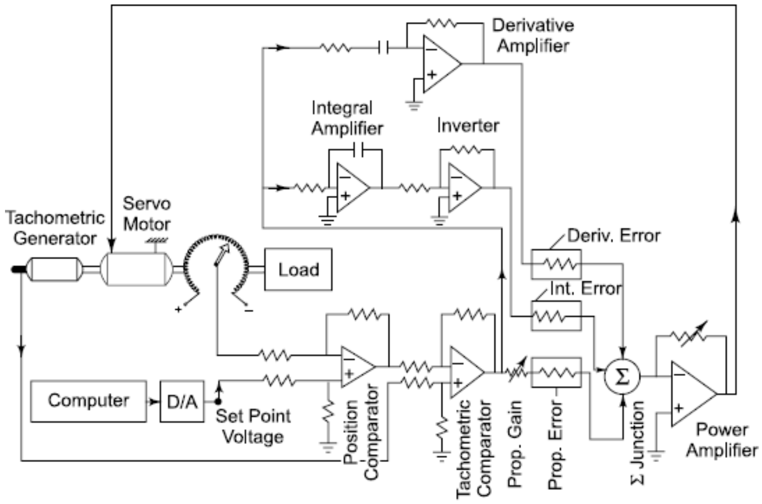
The servo system with velocity feedback has been illustrated in Fig. 3.89. A combined tachometric (velocity) and positional feedback system is shown in Fig. 3.97.

Figure 3.97 Velocity and proportional feedback systems



[Figure 3.98](#) shows a combined PID and tachometric control used in robotics. The servo motor moves at a given controlled speed and is regulated in position. Integral control eliminates steady state error caused by proportional control only and the system oscillations or stability is monitored by derivative control. Thus, combined PID drives and tachometric compensation ensures positional control at controlled speed.

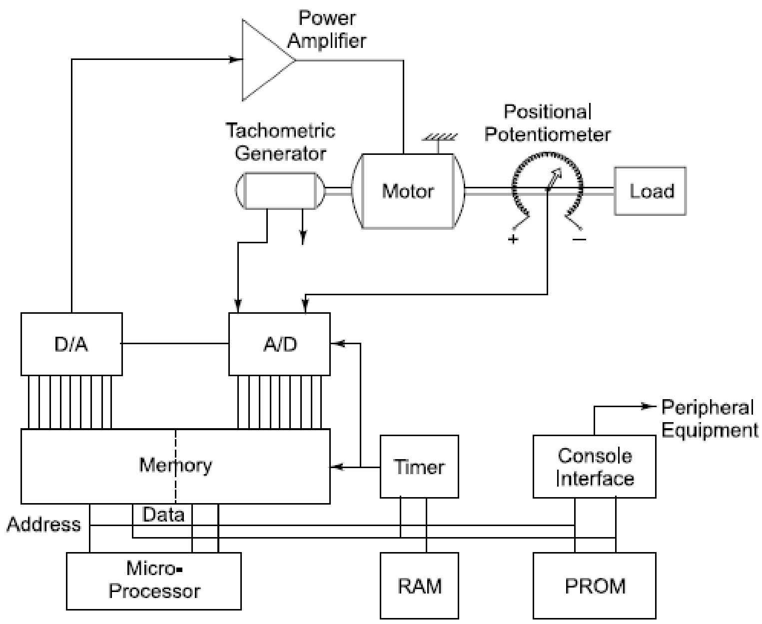
Figure 3.98 Digital servo system



3.5.3. A Microprocessor-Controlled Digital Servo System

[Figure 3.99](#) indicates a digital servo system controlled by a microprocessor. The microprocessor receives signals from the tachogenerator and the potentiometer through analog-to-digital converter (A/D) and sends the signals to the power amplifier through digital-to-analog converter (D/A). The main memory, random access memory (RAM), programmable read only memory (PROM), timer and console interface are connected with address and data buses.

Figure 3.99 Digital servo system



3.6. DC MOTORS AND TRANSFER FUNCTIONS

3.6.1.1. DC Motors

DC motors currently used in electrically powered robots are generally separately excited. The two adjustable parameters are the armature current and the field current, and hence there are two modes of operation of a d.c. servo motor:

i. Armature controlled mode (with fixed flux)

ii. Field controlled mode (with fixed armature current).

3.6.1.2. Transfer Functions and Block Diagrams

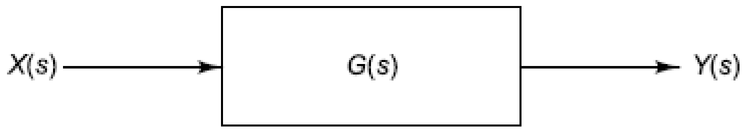
The transfer function of a system is defined as the ratio of the Laplace transform of the output of the system to that of the input with zero initial conditions, and is designated by the symbol, $G(s)$.

$$\text{Transfer function,} \qquad G(s) = \frac{Y(s)}{X(s)}$$

where, $X(s)$, $Y(s)$ are input and output functions.

The functional relationship in a transfer function is often expressed by a block diagram as shown in Fig. 3.100.

Figure 3.100 Representative block diagram of transfer function



3.6.1.3. Armature Control Motors

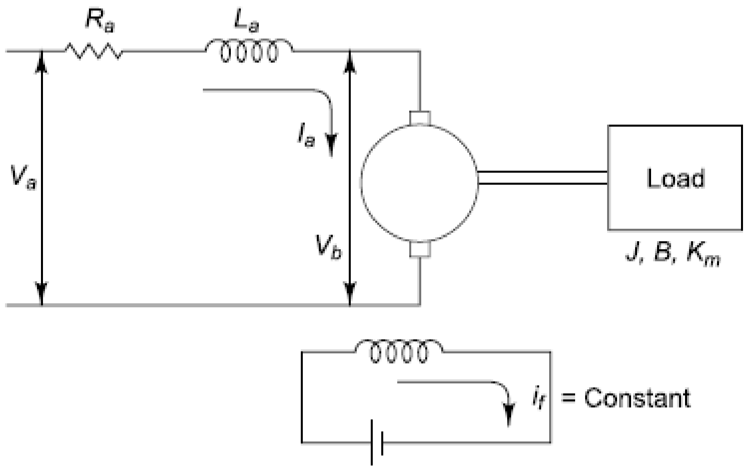
The schematic diagram of armature control motors is shown in Fig. 3.101. Since the field is assumed to be constant, the developed torque can be expressed as

$$T = K_T i_a$$

(3.3)

where, K_j = torque constant. The torque is used to drive the system having a total inertia J, damping constant B and torque coefficient, K_m.

Figure 3.101 *Scheme of armature control motor*



So,

$$T = J\ddot{\theta}_m + B\ddot{\theta}_m + K_m\theta_m$$

(3.4)

where θ_m = angular position of the motor shaft

$\dot{\theta}_m$ = $d\theta_m/dt$ = angular velocity of the motor shaft

$\ddot{\theta}_m$ = $d^2\theta_m/dt^2$ = angular acceleration of the motor shaft

The voltage equation of armature circuit is

$$v_a = R_a i_a + L_a i_a + v_b$$

(3.5)

where v_b = back emf and can be expressed as,

$$v_b = K_b\,\theta_m$$

(3.6)

where K_b = voltage constant of the motor.

Taking Laplace transform of the Eqs (3.3) through (3.6), the following relations can be obtained.

$$T(s) \;=\; K_T I_a(s)$$

(3.7)

$$\theta_m(s) \;=\; \frac{T(s)}{Js^2 + Bs + K_m}$$

(3.8)

$$V_b(s) \;=\; K_b s\theta_m(s)$$

(3.9)

$$I_a(s) = \frac{V_s(s) - V_b(s)}{R_a + sL_a}$$

(3.10)

The block diagram may now be obtained as shown in Fig. 3.102.

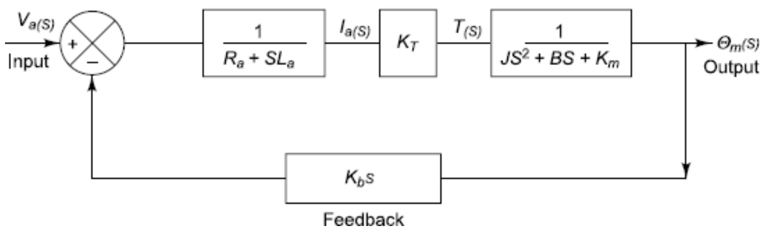


Figure 3.102 Block diagram showing relations between output and input

The transfer function $G(s) = \theta_m(s)/V_a(s)$ may be obtained, either from the block diagram or from Eqs (3.7) to (3.10), as

$$G(s) = \frac{\theta_\mu(s)}{V_a(s)} = \frac{K_T}{J\,L_a\,s^3 + (R_aJ + L_aB)s^2 + (R_aB + K_bK_T + L_aK_m)s + R_aK_m}$$

3.6.1.4. Field Control Motors

The schematic diagram of field control motors is shown in Fig. 3.103.

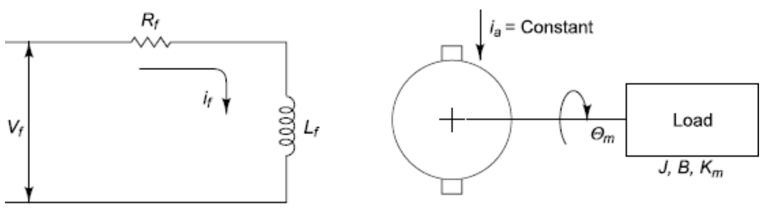


Figure 3.103 Scheme of field control in a motor

Since, the armature current is constant, the torque is

$$T = K'_T i_f$$

(3.11)

where K_T = torque constant

As before,

$$T = J\ddot{\theta}_m + B\dot{\theta}_m + K_m\theta_m$$

(3.12)

The equation for the field circuit is

$$v_f = R_f i_f + L_f i_f$$

(3.13)

The Laplace transforms of the above equations give:

$$T(s) = K'_T I_f(s)$$

(3.14)

$$T(s) = (Js^2 + Bs + K_m)\ \theta_m(s)$$

(3.15)

$$V_f(s) = (R_f + sL_f)\ I_f(s)$$

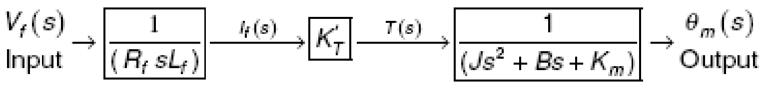
(3.16)

From the block diagram as shown in Fig. 3.104, the transfer function $G(s)$ can be obtained as

$$G(s) = \frac{\theta_m(s)}{V_f(s)} = \frac{K'_T}{(R_f + L_f\ s)(Js^2 + Bs + K_m)}$$

(3.17)

Figure 3.104 Block diagram indicating relations between output and input



3.7. A.C. MOTORS

A.C. motors may be single-phase or polyphase synchronous motor. In the single-phase type, rotor is a permanent magnet and rotor winding is provided with slip-ring commutation like d.c. machine. The synchronous motor rotates at the speed of a rotating magnetic field. The stator may consist of three 120° apart stator coils supplied with a three-phase current. The motor operates at only one speed depending on the frequency of the supply current and number of pole pairs. Since there is no starting torque, the rotor field is run upto synchronous speed by some means for which a d.c. voltage is applied to rotor winding. The rotating magnetic field is induced by the stator coils. The rotor aligns to the rotating flux created by the stator. But due to mechanical loading of the motor connected to one end of the rotor, some misalignment takes place due to the difference of the field produced by the rotor and the field produced by the stator. The angle of misalignment is known as 'load' angle and torque produced by the motor is a function of load angle, δ and the maximum rated torque, T_{max}. An a.c. synchronous type machine is shown in Fig. 3.105 with rotor and stator configurations. Figure 3.106 illustrates the half section of an a.c. synchronous motor with windings and slip rings-brushes.

Figure 3.105 Single-phase synchronous motor

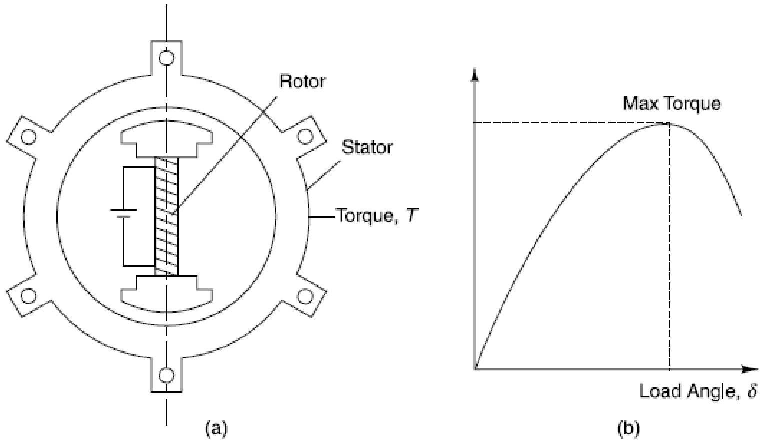
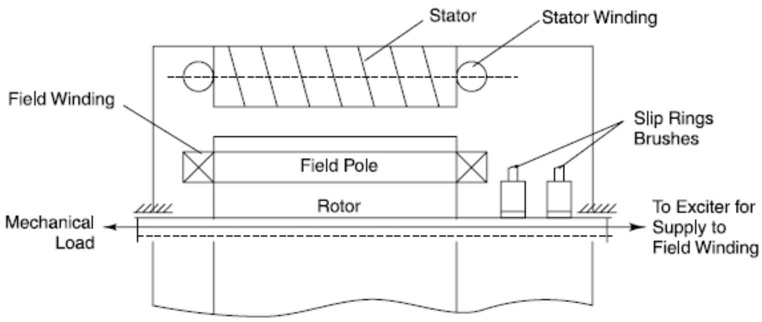


Figure 3.106 AC synchronous machine with slip-rings brushes



The polyphase synchronous motor is similar to single-phase synchronous motor but with multiple stator windings for smoother operation.

3.7.1.1. Induction Motor

Induction motors may be single-phase or polyphase.

Induction motor consists of a stator properly wound for three phases connected in star-delta. All the six leads are brought out for changing the connection from the star to delta. Star connection is used at the time of starting, and delta connection is used during running.

The rotor is also properly wound for three phases with three connecting leads brought out through slip rings and brushes. Squirrel-cage rotor has slots, and conducting bars are placed in slots and permanently shorted at each end. A schematic diagram of an induction slip-ring motor is shown in Fig. 3.107(a).

Figure 3.107 Induction motor

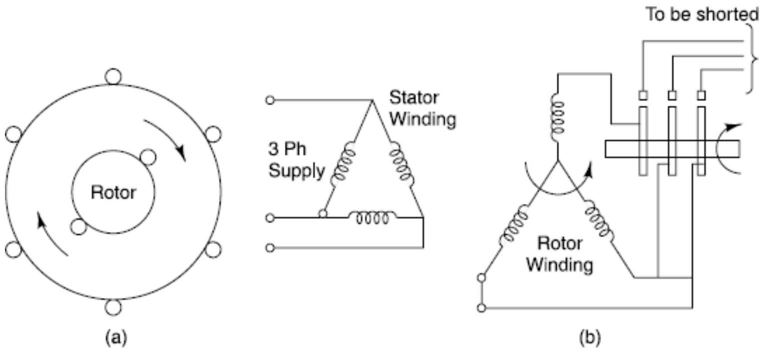
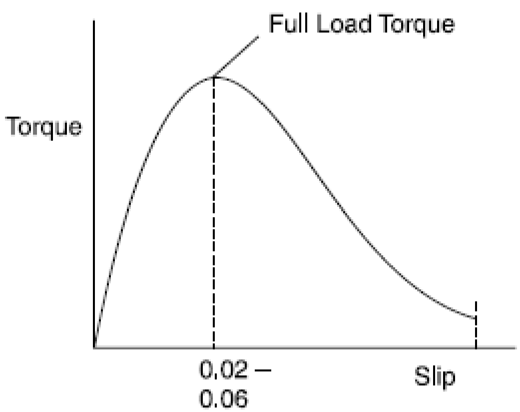


Figure 3.107 shows rotor and stator windings for a slip-ring motor with delta-connected stator and star-connected rotor connected to slip rings to be shortened externally. With stator coils electrically connected to three phase currents, a rotating magnetic field is produced in the stator. The rotating magnetic field will induce a voltage in the rotor coil and induced emf will circulate a current in the coil. A resultant force on the current carrying conductor will produce a torque accelerating the rotor. The rotor speed will increase until electromagnetic torque is balanced by the torque due to mechanical load. However, the motor will never run at synchronous speed, but a lesser speed resulting in always a slip. The slip is defined as the ratio of the difference between the synchronous speed (N_S) and the rotor speed (N) to the synchronous speed.

$$\text{So, slip } s = \frac{N_s - N}{N_s}$$

The torque-slip characteristic is shown in Fig. 3.108.

Figure 3.108 Torque-slip curve for induction motor



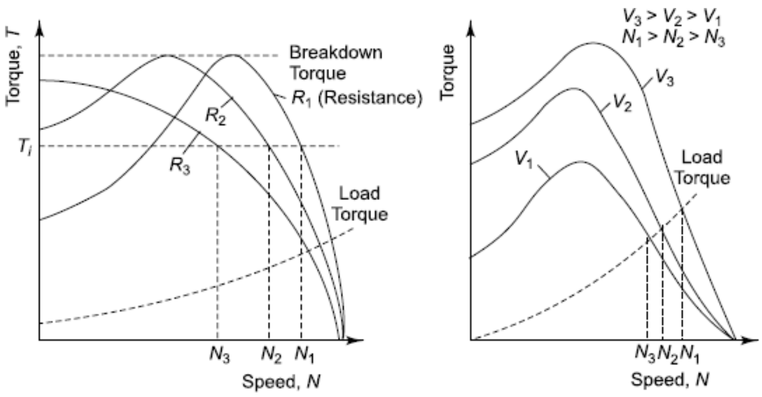
At no slip (s = 0), $N_S = N$ and the torque is 0.

An alternative method of starting induction motor is to use autotransformer starter. During starting up, a star connection is supplied from a midpoint tapping. The supply voltage becomes halved, and current and the torque are much reduced. After the motor has been accelerated, the starter device is moved to the run position. An additional resistance may be added in series with rotor circuit for reducing starting current and improving the starting torque.

Induction motors are stopped by reversing the direction of the rotating magnetic field, i.e. reversing any two of the supply leads to the stator. It can be stopped by dynamic braking in which the stator is connected to a d.c. source instead of a.c. source.

Speed control of induction motors is possible either by changing the frequency of the supply current or by changing the number of poles. The torque–speed characteristics for the changes in the rotor resistance and reduction of stator voltage are illustrated in Figs 3.109(a) and (b), respectively.

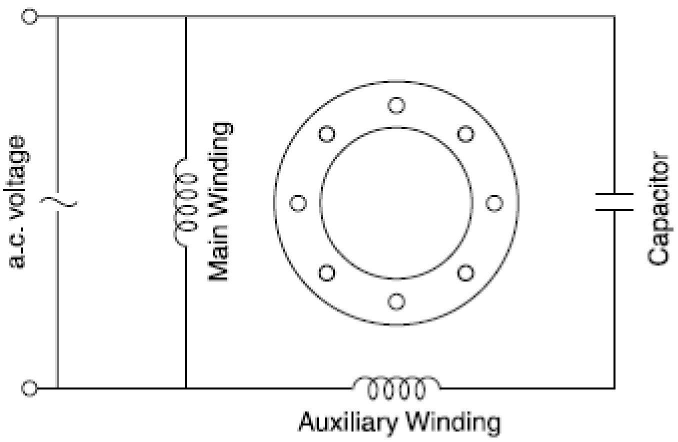
Figure 3.109 Torque–speed curves at different stator resistances and stator voltages



3.7.1.2. Capacitor Motor

The capacitor motor very closely resembles to three-phase induction motor when the two windings of the stator are physically displaced by 90°. A capacitor is connected in series with the auxiliary winding as shown in Fig. 3.110. A.C. motors have the advantages over d.c. motors due to lesser maintenance cost. But the speed control poses difficulties for a.c. motors.

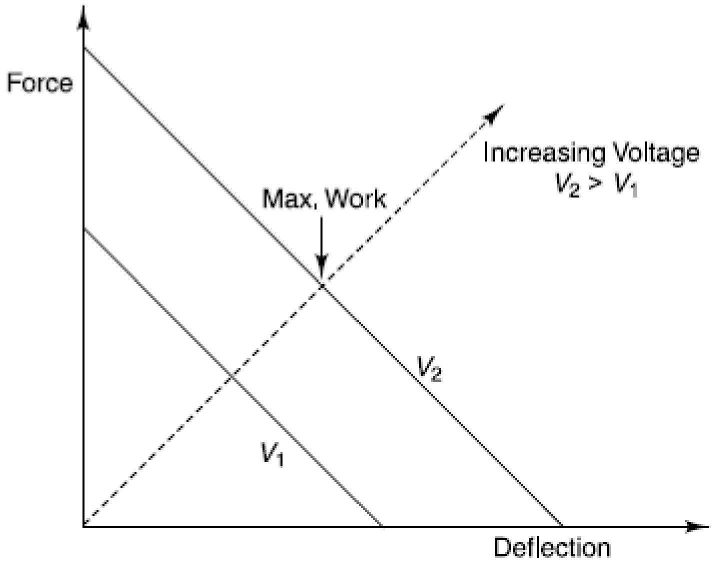
Figure 3.110 Capacitor motor



3.8. PIEZOELECTRIC ACTUATORS

Due to the unique properties of piezoelectric materials, piezoelectric elements can be used as actuators or sensors. It has the ability to generate electrical charge in proportion to externally applied force. It has an inverse piezoelectric effect. Piezoelectric properties depend on the direction of electrical/mechanical-inputs/ outputs. Typical piezoactuating elements are produced in shapes of squares, hemispheres, rings, discs, cylinders and bars in the range of thickness of 0.2–20 mm and up to 100 mm length or diameter. The piezoelectric effect is dependent on the applied electrical field. The relative change in length of piezoelement is about 0.1%. The most popular piezomaterial is PZT (lead zirconate titanate). The other materials are ferroelectric ceramics. Piezopolymer—PVDF (Polyvinylidene Fluoride) is a special class of polymer showing piezoelectric activity and is used in the form of piezo films with which structural materials are laminated. This is suitable for sensor development. The other types of materials like single crystal lead, magnesium niobate lead titanate, lithium niobate, lead zirconate, niobate lead titanate, lithium tetraborate, etc. are attractive materials for actuators and transducers. Typical force–deflection curves for piezoelectric actuators are shown in Fig. 3.111.

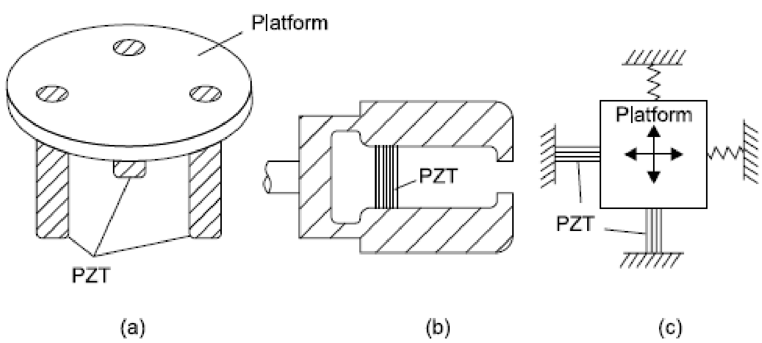
Figure 3.111 Force–deflection graphs



An optimized actuator delivers force at half of its free deflection.

Piezoelectric elements are used for micromanipulators, motors, positioning devices and industrial automation systems due to their compactness, light weight, rapid response, no magnetic field, high stability and broad frequency range. Piezolegs as shown in Fig. 3.112 made of PZT are used in microrobot platform. For fine movement, the legs can be lengthened, shortened or bent in any direction [Fig. 3.112(a)]. Other platform and cylindrical parts can be made of PZT as illustrated inFigs 3.112(b) and (c).

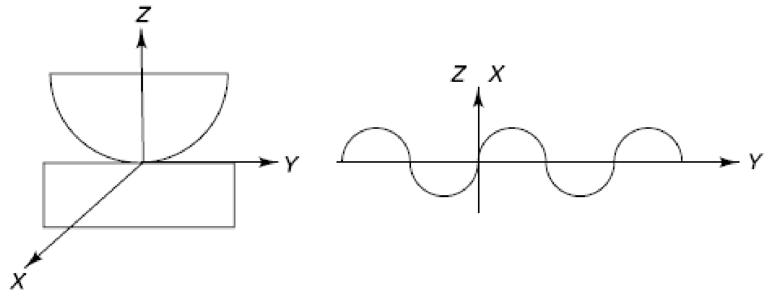
Figure 3.112 Piezoactuators



Piezomotors have wider scope of applications in robotics due to large troque at low speed range with higher power/weight ratio, no speed reduction gears and no electromagnetic induction.

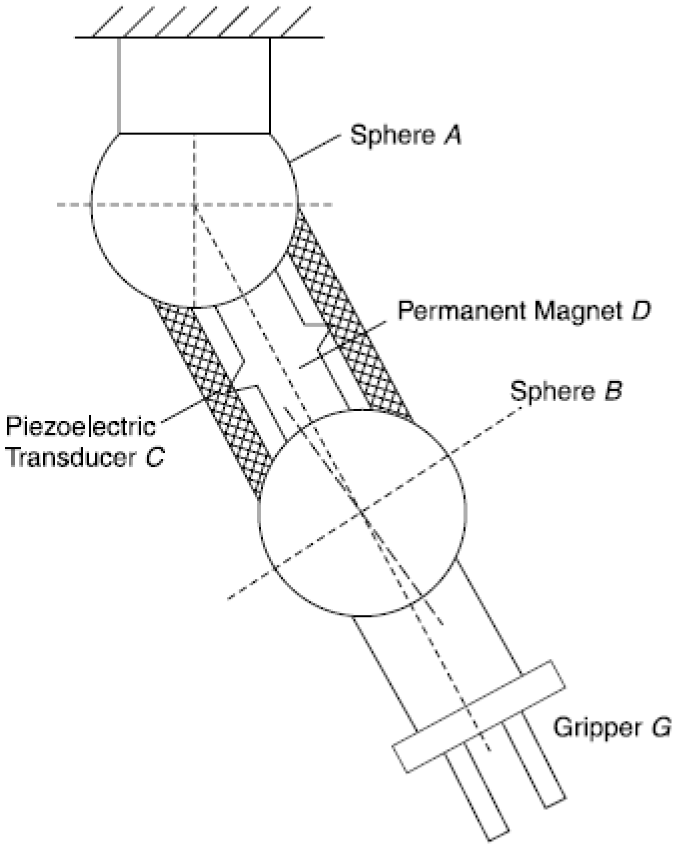
Active kinematic pairs can be built up of piezoelectric motors and several degrees of freedom can be obtained. Due to the use of piezoelectric links, static displacements and resonant oscillations are possible. In the contact area of links made of piezomaterials, relative motions are generated and forces and torque are developed in the contact area. Friction in the contact area of the pairs can be controlled by varying frictional coefficient or the magnitude of the force executing the closure, and this has been made possible by excitation of high-frequency tangential or normal oscillations in the contact area of the pairs as shown in Fig. 3.113.

Figure 3.113 *Frictional anisotropy of contact by superimposition of oscillations of higher frequency in perpendicular direction*



A piezoelectric robot manipulator as shown in Fig. 3.114 built by using two kinematic pairs of spheres *A* and *B* made of steel with a piezoelectric transducer *C* between them. A permanent magnet *D* is located inside the piezo tube and contact forces are ensured. The robot has 6 DOFs due to two spheres. The positional errors or motion trajectory can be realized on the gripper, *G*, due to the forces/torque acting on the gripper.

Figure 3.114 *A piezoelectric robotic manipulator*



3.9. STEPPER MOTOR

The increasing trend toward digital control has generated a demand for mechanical devices capable of delivering incremental motions of predictable accuracy. The stepper motor can be considered as a digital device which converts electrical pulses into proportionate mechanical movement. Each revolution of the stepper motor's shaft is made up of a series of discrete individual steps. Being bidirectional, it is ideally suited for a wide variety of control and positioning applications in the industrial world. A typical application is positioning a work table in two dimensions for automatic drilling. The stepper motors may be used in educational and hobby robots which can take lighter loads. Conventional a.c. and d.c. motors have a free turning shaft. The stepper motor shaft rotation is incremental. It is designed to rotate a specific number of degrees, (usually 7.5° or 15°) for each electrical pulse received by its control unit. This increment is known as step angle. It is used in digital control systems where the motor receives open loop commands as a train of pulses to turn a shaft or move a plate by a specific distance. The basic feature of a stepper motor is that upon being energized it will move and come to rest after some number of steps in strict accordance with the digital input commands provided. The repeatability (the ability to position through the same pattern of movements a number of times) is very good. With a stepper motor, a position sensor or feedback system is not normally required to make the output member follow the input instructions.

Stepper motors are usually designed with multipole, multiphase stator windings. They typically use three or four phase windings with the number of poles determined by the required angular change per input pulse. The rotors are of the permanent magnet type.

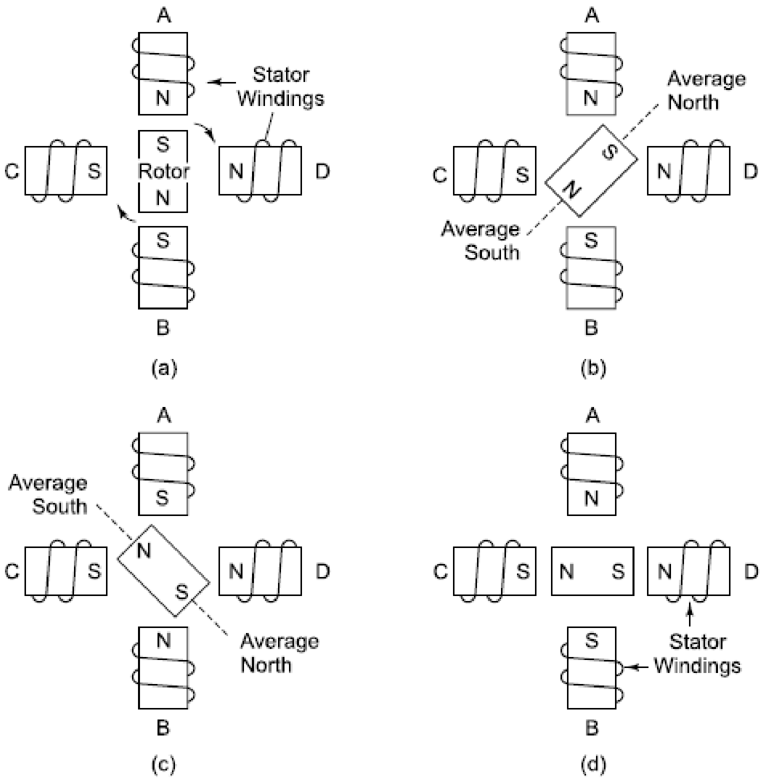
3.9.1.1. Principle of Operation

A stepper motor's operation is based on the basic magnetic principle: like magnetic poles repel and unlike poles attract. A simplified representation of a stepper motor is shown in Fig. 3.115(a). If the stator windings are energized so that the stators *A* and *D* are north poles and the permanent magnet rotor positioned as shown in Fig. 3.115(a) a torque will be developed to position the rotor as shown in Fig. 3.115(b) with the rotor aligning itself between the 'average' south pole and the 'average' north pole. As indicated in the figure, the rotor's direction of rotation would be clockwise. Reversing the polarity of the pair of poles *AB* draws the rotor 90° clockwise to its new position of Fig. 3.115(c). This is known as full step. If poles *AB* had been turned off, instead of being reversed, the rotor would rotate 45° clockwise to line with the field of the pair of poles *CD*, as shown in Fig. 3.115(d). This is known as half step. So, if the windings are excited in a particular sequence, the stepper motor of Fig. 3.115, would have either four steps per revolution (with 90° step angle) or eight steps per revolution (with 45° step angle). In the first case, two pairs of poles have to be energized all the time, and their polarities reversed one by one. In the second case, either one or two pairs of poles are energized at a time in a proper sequence with their polarities reversed as above.

In the half step sequence, the rotor moves half its normal distance per step. For example, a 3.6° step angle, 100 steps per revolution motor would become a 1.8° step angle, 200 steps per revolution motor. The advantages of operating in this mode include finer resolution and greater speed, but with less available torque.

If the stator windings are excited in the reverse sequence, the direction of rotation would be counterclockwise.

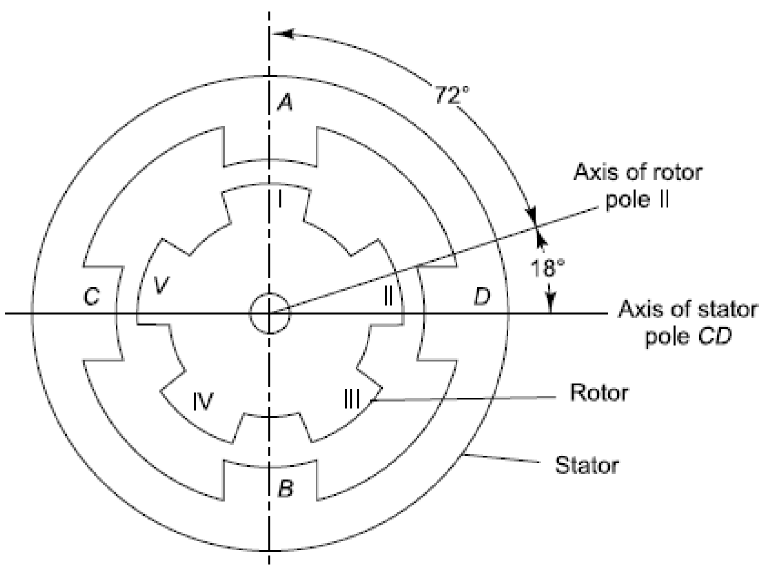
Figure 3.115 Stepper motor rotation



The simple stepper motor shown in the figure would have only four full steps or eight half steps per revolution. Actual stepper motors obtain small angle increments by using large number of poles (using a differential construction). One such stepper motor using differential construction is shown in Fig. 3.116. The stator has a 2 phase winding while the rotor has five projecting poles. The position shown is for poles *AB* energized with pole *A* as north pole, where pole-I is aligned with *AB* axis. If only the pair of poles *CD* is energized, the rotor will rotate by $\theta = 90° - 72° = 18°$ to align pole-II with *CD* axis.

There are many stable positions for any given stator energization pattern. Proper selection of the energizing sequence of the stator windings allows the stable positions to be made to rotate smoothly around the stator poles, establishing the rotational speed and the direction of the rotor.

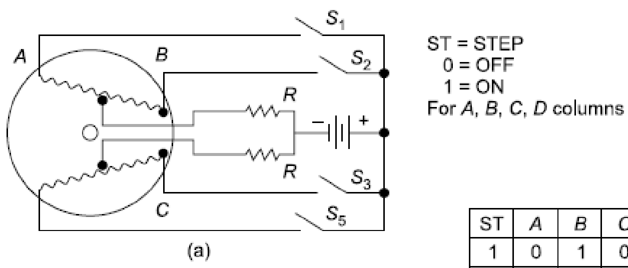
Figure 3.116 Cross-section of stepper motor for differential operation



3.9.1.2. Drive Circuit

In the previous examples, there were one phase of windings per pair of poles, so that the current should be reversed to reverse the polarities of the stator poles. This is not suitable for using with solid state transistor switches. The most common stepper stator windings are, therefore centre tapped dual windings, known as bifilar windings, which simplifies the drive circuitry using electronic switches. Figure 3.117(a) shows a bifilar-wound stepper motor, its power supply, and the switching points. In bifilar windings the current always flows in one direction only, and also in one, but not both, of the bifilar windings. The windings are so made that a current in one or the other of the bifilar windings causes magnetization in opposite directions. There are as many bifilar winding as there are pairs of stator poles. Only a single polarity power supply is needed with the centre tapped windings whereas the stepper motor of Fig. 3.115 would require a dual power supply for reversal of the poles. In this figure *AB* (and *CD*) are such centre tapped bifilar windings where a unidirectional current in either phase *A* or *B* (also, in *C* or *D*) reverses the polarities of stator poles. The rotor which may have many permanent magnet poles is not shown in the figure.

Figure 3.117 Bifilar stepper motor (a) Circuit diagram (b) Full step sequence (c) Half step sequence



CW ↓ / CCW (Counter clockwise) ↑

ST	*A*	*B*	*C*	*D*
1	0	1	0	1
2	0	1	1	0
3	1	0	1	0
4	1	0	0	1
1	0	1	0	1

(b)

CW ↓ / CCW ↑

ST	*A*	*B*	*C*	*D*
1	0	1	0	1
2	0	1	0	0
3	0	1	1	0
4	0	0	1	0
5	1	0	1	0
6	1	0	0	0
7	1	0	0	1
8	0	0	0	1
1	0	1	0	1

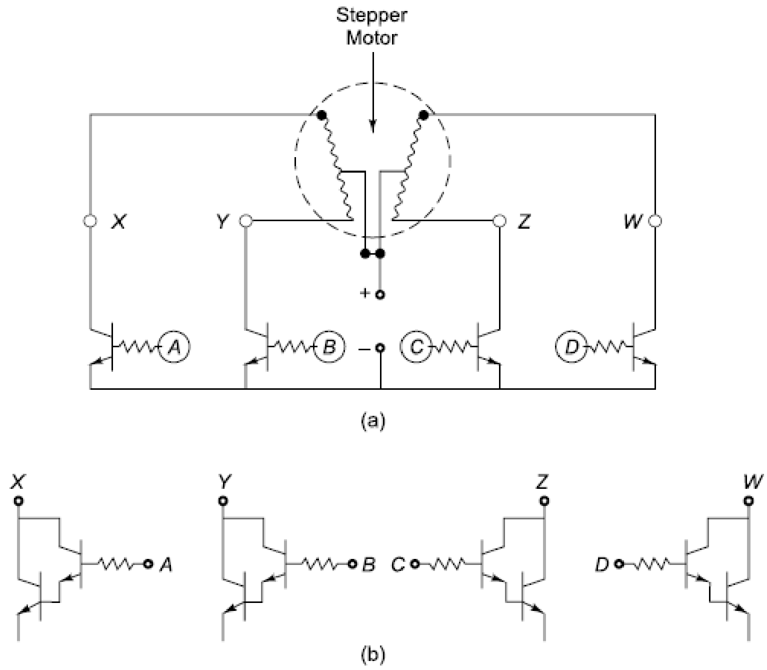
(c)

The four-step switching sequence shown in Fig. 3.117(b) is called a full step sequence, where both pairs of poles are magnetized at a time (but with different polarization) by switching 'on' one phase of windings always from both the bifilar windings *AB* and *CD*. To reverse the direction of rotor rotation, the sequence should be reversed and the chart should be read bottom up, instead of top down. Series resistors are used in the common leads to limit the current and improve the L/R time constant for better performance.

The eight-step switching sequence in Fig. 3.117(c) is called half step sequence, in which case the rotor moves half its normal distance per step. Here, either one or both of the bifilar windings *AB* and *CD* are 'on' at a time.

The switching sequence for these motors was originally achieved by mechanical switches. Electronic switches are now used, as shown in Figs 3.118(a) and (b).

Figure 3.118 Stepper motor drive devices (a) Transistors (b) Darlington transistors



Current will pass through the collector of the transistors when the base (at *A*, *B*, *C* or *D*) receives a positive pulse (high level logic) from a suitably designed logic circuit or microprocessor port in proper sequence. As most stepper motors require currents from hundreds of milliamperes up to a few amperes, which is too large for logic circuitry to provide, power drivers (Darlington transistor pairs) are required.

3.9.1.3. Interfacing with a Microprocessor

The advantage of a stepper motor is the ease with which it can be controlled by a microprocessor by sending digital pulses directly via the power amplifier. Four lines from an output port are connected to the bases of four transistor switches at points *A*, *B*, *C*, *D* of Fig. 3.118. The speed and direction of the motor can be changed by using suitable software to send digital pulses from the output port to switch on and off the phases in proper sequence. Feedback signal can also be taken, if necessary, to some input port using limit switches or similar mechanisms for providing information regarding limit positions.

Other advantages of stepper motors are the smaller size and power, cost of the motor-drive unit compared to the corresponding parts of a proportional position or velocity servo system.

Stepper motors come in a wide variety of sizes, types and styles, but the basic stepping principle for all is the same.

Applications include positioning of the table for machine tools, tape drives, recorder pen drives, *X*–*Y* plotters, robotics etc.

3.10. DRIVE MECHANISMS

When the various driving methods like hydraulic, pneumatic, electrical servo motors and stepping motors are used in robots, it is necessary to get the motion in linear or rotary fashion. When motors are used, rotary motion is converted to linear motion through rack and pinion gearing, lead screws, worm gearing or ball screws.

3.10.1.1. Rack and Pinion Movement

The pinion is in mesh with rack (gear of infinite radius). If the rack is fixed, the pinion will rotate. The rotary motion of the pinion will be converted to linear motion of the carriage.

3.10.1.2. Ball Screws

Sometimes lead screws rotate to drive the nut along a track. But simple lead screws cause friction and wear, causing positional inaccuracy. Therefore ball bearing screws are used in robots as they have low friction. The balls roll between the nut and the screw. A cage is provided for recirculation of the balls. The rolling friction of the ball enhances transmission efficiency to about 90%.

3.10.1.3. Gear Trains

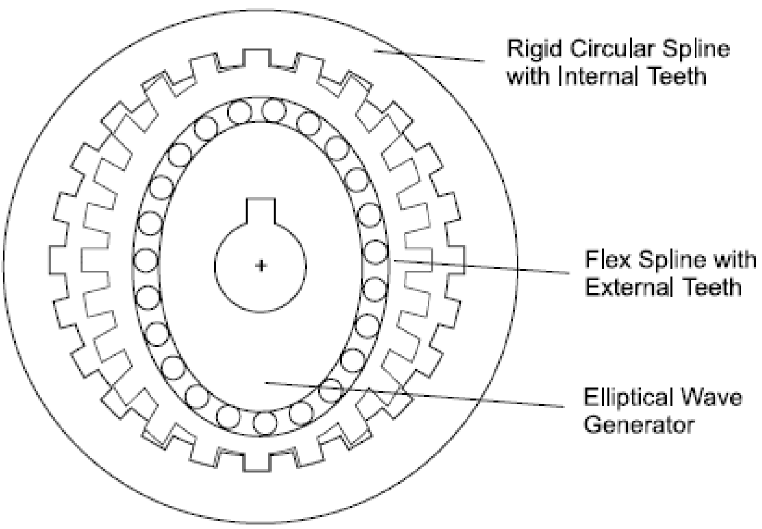
Gear trains use spur, helical and worm gearing. A reduction of speed, change of torque and angular velocity are possible. Positional errors are caused due to backlash in the gears.

3.10.1.4. 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.

The harmonic drive as shown in Fig. 3.119 is made up of three major elements: the circular spline, the wave generator and the flex spline. The circular spline is a rigid ring with gear teeth machined on the inside diameter. The flex spline is a flexible ring with the teeth cut on its outside diameter. The flex spline has fewer teeth (say 2 teeth less) than the circular spline. The wave generator is elliptical and is given input motion. The wave generator is assembled into the flex spline. The entire assembly of wave generator and flex spline is placed into the circular spline such that the outer teeth of flex spline is in mesh with the internal teeth of circular spline.

Figure 3.119 Harmonic drive elements



If the circular spline has 100 teeth and the flex spline has 98 teeth, and if the wave generator makes one complete revolution, the flex spline will engage 98 teeth of the circular spline. Since circular spline has 100 teeth and only 98 teeth have been in engagement for one complete rotation, the circular spline's position has been shifted by 2 teeth. Thus after 50 revolutions of the wave generator, the circular spline will have made one full rotation. The ratio of harmonic drive is 2 : 100 or 1 : 50. The gear ratio is influenced by the number of teeth cut into the circular spline and the flex spline. The harmonic drive has high torque capacity.

3.11. EXERCISES

3.1 Classify hydraulic pumps.

What are the different types of positive displacement pumps? Using diagrams briefly describe the working of

a. gear pump

b. piston pump

3.2 What are the types of hydraulic actuators used in robotics?

3.3 Using a schematic diagram represent a hydraulic circuit to explain the drive system of a bang-bang robot having waist rotation, shoulder and arm expansion respectively.

3.4 With the aid of diagrams, explain the working principle of

a. directional control valve

b. pressure control valve

c. flow control valve

3.5 Classify air compressors.

State the relative advantages of different types of air compressor.

3.6 Sketch a pneumatic circuit to control different motions of

a. cylindrical coordinate robot

b. cartesian coordinate robot

3.7 Distinguish between shunt wound motor and series wound motor. Sketch their speed-torque characteristics.

3.8 What are the advantages and disadvantages of moving coil d.c. motors? How does a brushless d.c. motor function?

3.9 A d.c. electric motor is used to drive a robot joint with a torque of 5.6 Nm. If the torque constant is 0.25 Nm per ampere, how much current is required from the drive amplifier at peak torque?

3.10 A stepper motor is used to drive a linear axis of a robot. The motor is connected to a screwed shaft having a single start thread of pitch 2.5 mm. The resolution desired for the controlled motion is 0.5 mm. Determine:

a. step angles that are required on the motor to obtain the resolution

b. pulse rate required to drive the axis if the velocity is 80 mm/s

3.11 What are the advantages and disadvantages of stepper motors over d.c. servo motors?

3.12 What are the major types of control for robots?

3.13 What do you mean by 'open loop and closed loop servo' systems? Illustrate through block diagrams.

3.14 What do you mean by

a. proportional control

b. integral control

c. derivative control?

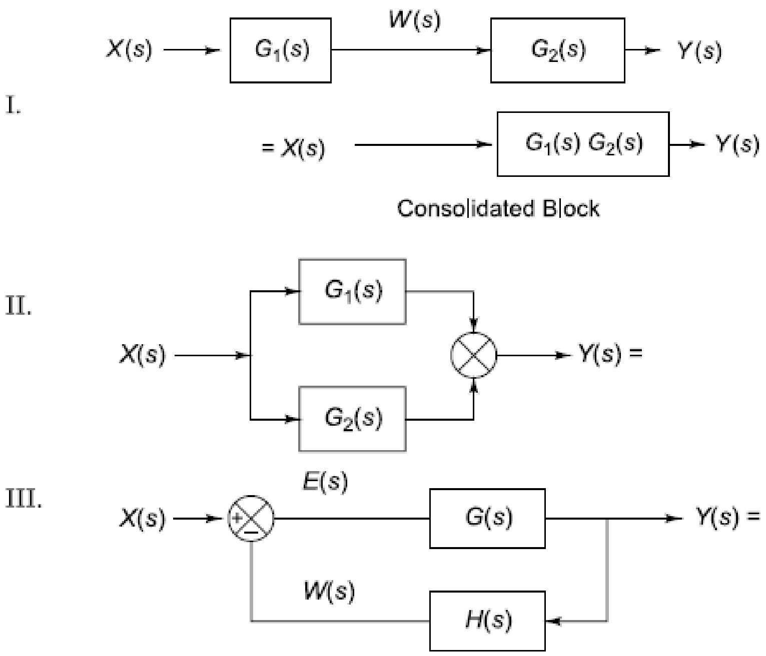
3.15 What is meant by a PID control? Explain with the aid of a diagram the working principle of PID control of a robot.

3.16 What is positional feedback?

What is tachometric (velocity) feedback?

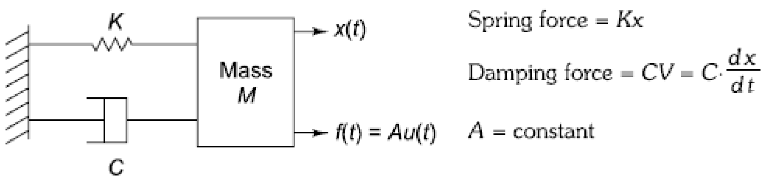
3.17 What are the advantages of PID plus tachometric control over only proportional (positional) control?

3.18 Prepare consolidated block diagrams from the following input-transfer functions-output elements.



Assume, $X(s)$ = input; $G1(s)$ = Control elements, $G2(s)$ = system elements, $H(s)$ = Feedback elements, $Y(s)$ = output.

3.19 A simple spring-mass-damper system is illustrated below:



The overall force equation is given by

$$M\frac{d^2x}{dt^2} + C\frac{dx}{dt} + Kx = Au(t) = f(t)$$

a. Find the characteristic equation and the roots.

b. Indicate the system response under the following conditions:

   i. underdamped

   ii. critically damped

   iii. overdamped

c. Find the transfer function for spring-mass-damper system.

3.20 Find the transfer function of a PID control if the controller functions are represented by

$$m(t) = K_p e(t) + \frac{K_p}{T_1} \int e(t)dt + K_p T_d \frac{de(t)}{dt}$$

where $m(t)$ = Control signal produced by the controller

$e(t)$ = Error signal

Kp = Proportional gain

Ti = Integrator gain

Td = Derivative gain

$\frac{de(t)}{dt}$ = Rate of change of the error

3.21 What is an induction motor? Indicate the slip-torque and speed-torque characteristics of the motor.

3.22 What is a capacitor motor?

3.23 What are the common piezoelectric materials used for actuators and sensors? What is PZT material?

3.24 How are the piezoelectric transducers used for building micro-robot manipulators? Sketch the set-up for a six degrees–of–freedom micro–robot manipulator.

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