

## Chapter 2

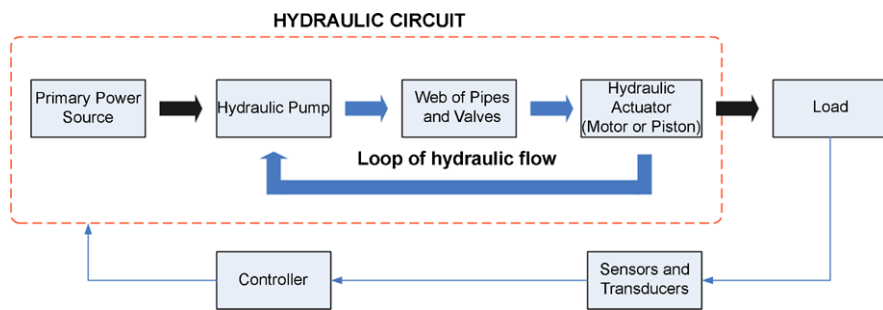
# Servo Hydraulic and Pneumatic Drive

Among the various drives available, the hydraulic drive ranks at the forefront in terms of application history. The history of hydraulic power dated to the beginning of civilization, where artefacts show the applications of water turbines in power generation [132]. However, more significant progress in this field is generally achieved following Pascal's pioneering work which was later known as Pascal's law of hydrostatic. Bernoulli's discovery of the hydrodynamic law in 1750, and the Industrial Revolution in 1850 further catalysed the development of servo hydraulic drives. They led to the first applications of hydraulic equipment as a power source to power industrial machines such as the press, the crane, and the jack, as they also contributed to the development of hydraulic pumps, driven by steam engines, which produce hydraulic energy to run hydraulic systems. In the early 20th century, a revolutionary design of hydraulic drives used the oil, instead of water, as the hydraulic liquid, which greatly expanded the applications of hydraulic drives to more devices. World War II also contributed to the development of hydraulic drives, especially in the development of submarine control systems, radar/sonar drives, and military cargo transportation.

Hydraulic drives are still being used today, and, in fact, their applications are expanding to loads of increasing mass and power requirements, yet with higher speed and control precision. The main attraction of a hydraulic drive is its high power-to-weight ratio, rendering it the natural servo drive to use for heavy applications found in the aircraft and space shuttle. Moreover, it possesses several desirable characteristics such as accuracy, flexibility in applications, and simplicity of operations, as it also allows for fast, smooth, and precise start, stop, and reversal actions.

## 2.1 Overview of Servo Hydraulic and Pneumatic Drive

Hydraulics has been around in human civilization since the ancient times. Historical records provide evidence that water mills had been used around 100 B.C.E. Another remarkable invention was a screw pump developed by ancient Greek's Archimedes around 300 B.C.E. The invention of water clock by Ktesbios around 250 is regarded



**Fig. 2.1** Configuration of a servo hydraulic drive

not only as a remarkable invention in the field of hydraulic system, but also in the field of servo control.

The development of the theoretical foundation of hydraulics and pneumatics is spearheaded by Sir Isaac Newton with his viscosity theory, Daniel Bernoulli with his Bernoulli's equation, and Blaise Pascal with his Pascal's law.

The main events that boosted significantly the development of servo hydraulic and pneumatic drive were the Industrial Revolution and World War II. During the time of Industrial Revolution, the interest of using fluid power was growing rapidly, creating many inventions such as various pumps, mills, and steam engines. This provided a fertile ground for the development of pneumatic power system around 1900. World War II further accelerated the advancement of fluidic power system with the need to develop more powerful military aircrafts. Pneumatic drive proved to be the answer to this demand since it allowed the replacement of the cable-operated flight control, thereby allowing the pilot to operate the aircraft with a push of a button. This in turn enhanced the development of civil aviation technologies, whose working principles have been applied to less sophisticated system such as door-mechanism in public transportation.

Hydraulic and pneumatic systems share many similarities in terms of working principle and theoretical foundation; further discussed in Section 2.2. From this point onward, the term *servo fluidic drive* will be used to refer to both *servo hydraulic drive* and *servo pneumatic drive*.

A servo fluidic drive comprises several fluidic components which work in unison to deliver the functions highlighted in Chapter 1. A typical configuration of a servo hydraulic drive is shown in Figure 2.1, while that of pneumatic drive is shown in Figure 2.2.

In a hydraulic system, the primary power source, usually an electric motor, powers a hydraulic pump, which in turn generates a flow of the hydraulic liquid through a web of pipes, tubes, valves, and other hydraulic components, to a hydraulic actuator (a hydraulic motor or a hydraulic piston). The actuator will, in turn, drive the load. After transmitting the energy to the actuator, the hydraulic liquid will be returned to the reservoir to be recirculated by the pump. In a pneumatic system, a similar process also takes place via a pneumatic compressor, followed by a web of

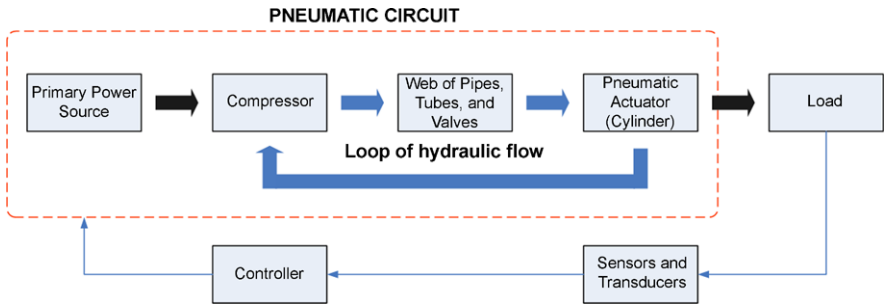


Fig. 2.2 Configuration of a servo pneumatic drive

Table 2.1 Comparison of characteristics of hydraulic and pneumatic drives

| Hydraulic drive                             | Pneumatic drive                         |
|---------------------------------------------|-----------------------------------------|
| Instantaneous reaction                      | Delayed reaction                        |
| Hold load without unwanted movement         | Hold load with some unwanted movement   |
| Provide significant lubrication and cooling | Provide limited lubrication and cooling |
| More complicated design                     | Less complicated design                 |
| More expensive                              | Less expensive                          |
| Pose environmental problems (oil leakage)   | No environmental problems               |

pneumatic circuitry similar to that of its hydraulic counterpart before powering up an actuator to finally drive the load.

The part of the drive within the dotted box is referred to as the hydraulic/pneumatic circuit, where the specific configuration depends on the fluidic characteristic required in each application. Common fluidic circuits will be presented in Section 2.4.

In a servo fluidic drive, sensors and transducers are also installed to yield the measurement signals for the controller. The controller will manipulate the controllable components in the fluidic circuit to achieve the control objectives.

2.2 Fundamentals of Hydraulic and Pneumatic Drives

Hydraulics is the principle of transmitting energy using liquids to achieve useful work. It shares many similarities with pneumatics, which uses gases to transmit energy. Collectively, liquids and gases are also called fluids, both of which exhibit a flow tendency when there is a pressure difference between two points along the flow path.

The main difference between liquids and gases lies in their compressibility; liquids are incompressible while gases are compressible. This difference influences the characteristics of a hydraulic and a pneumatic drive, and in turn, the applications suitable for each of the drives. Table 2.1 presents the main difference between hydraulic and pneumatic drives.

When a fluidic drive is complemented with a control system to achieve better performance, it becomes a servo fluidic drive. A servo fluidic drive measures its own outputs and takes control action so as to force the outputs to quickly and accurately follow a given command signal.

### 2.2.1 Basic Definitions and Principles

Below are fundamental definitions and concepts pertaining to fluidic drives.

#### 2.2.1.1 Weight and Weight Density

Since fluid has mass, it also has weight due to gravity. The SI unit of weight is  $\text{kg}\cdot\text{m}/\text{s}^2$ . Weight  $w$  is defined as follows:

$$w = mg, \quad (2.1)$$

where  $m$  is mass, and  $g$  is acceleration due to gravity.

The ratio of weight to volume is called weight density  $s$  and is a characteristic of fluids. It is defined as follows:

$$s = \frac{w}{V}, \quad (2.2)$$

where  $V$  is volume.

Most hydraulic liquids—the ones used in hydraulic systems—have a weight density of about  $880\text{--}930\text{kg}/\text{m}^3$ .

#### 2.2.1.2 Pressure

Pressure  $p$  is defined as the force applied per unit area, as follows:

$$p = \frac{F}{A}, \quad (2.3)$$

where  $F$  is force, and  $A$  is area.

The SI unit of pressure is  $\text{N}/\text{m}^2$  or equal to Pascal (Pa), although the *bar* (equal to  $10^5\text{Pa}$ ) is also commonly used.

Since every component in a fluidic drive has a fixed area, pressure is equivalently the resultant force to produce useful work. Therefore, a variation of actuator force or shaft torque is achieved by a variation of the fluidic pressure.

#### 2.2.1.3 Flow Rate

Flow rate refers to the volume of moving fluid per unit time. Variation of flow rate in a fluidic circuit results in variation of rod velocity or shaft speed. Flow rate is related to pressure, in the sense that flow is the result of pressure difference in a system. Likewise, without flow there cannot be pressure rise in a system. The SI unit of flow rate is  $\text{m}^3/\text{s}$ .

### 2.2.1.4 Pascal's Law

Pascal's law is a very important principle in fluidics since it describes quantitatively how fluid transmits power in the form of pressure. Pascal's law can be stated as follows:

*Pressure applied to a confined fluid is transmitted undiminished in all directions.*

Pascal's law is often formulated in the form of the following equation:

$$\frac{F_1}{A_1} = \frac{F_2}{A_2}, \quad (2.4)$$

where index 1 and index 2 denote object 1 and object 2, respectively. This equation essentially explains that heavy load can be lifted with small force using fluidics.

In hydraulic drives, the operating pressure ranges from 1MPa to 40MPa, while some special applications may require operating pressures as high as 70MPa. A higher operating pressure can deliver the same amount of power at a reduced equipment size and weight, desirable characteristics for many applications.

### 2.2.1.5 Bernoulli's Equation

Bernoulli's equation is another important equation in fluidic circuit analysis. While Pascal's law describes the behaviour of static fluids, Bernoulli's equation explains the behaviour of dynamic/moving fluids. Bernoulli's equation can be stated as follows:

$$f_1 + p_1 + h_1 = f_2 + p_2 + h_2, \quad (2.5)$$

where  $f$  is flow, and  $h$  is elevation.

Bernoulli's equation relates to the conservation of energy in a fluidic system. All three terms in the equation relates to different forms of energy, which depend on the liquid's flow rate, pressure, and position, respectively.

### 2.2.1.6 Bulk Modulus

Bulk modulus is the measure of fluid incompressibility, where higher bulk modulus means higher incompressibility. Bulk modulus  $B$  is defined as

$$B = -\frac{\Delta p}{\epsilon}, \quad (2.6)$$

where  $\Delta p$  is pressure change, and  $\epsilon$  is volume strain.

The bulk modulus of a fluid changes with pressure and temperature.

### 2.2.1.7 Boyle's Law

This law is strictly valid for gases, although it is relevant to the discussion of the accumulator of a hydraulic drive. Boyle's law states that gases obey the following relationship:

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}, \quad (2.7)$$

where  $T$  is temperature.

According to this law, under constant temperature, pressurization brings about compression, and compression brings about pressurization.

### 2.2.1.8 Viscosity

Viscosity is a concept which is especially useful in hydraulic systems. Theoretically, viscosity is a measure of the internal resistance of a liquid to shear and hence to flow. Lower viscosity signifies that the fluid can flow more easily.

Although the concept of viscosity is simple, the formulation is more complicated compared to other parameters. There are two measures of viscosity:

- absolute viscosity, defined as the force required to move a flat plane of one unit area, separated by a liquid by one unit distance apart from a fixed plane, at one unit velocity; measured in centipoises (cP)
- kinematic viscosity, defined as absolute viscosity divided by its mass density; measured in centistokes (cS)

The measurement of viscosity is conducted with a Saybolt viscosimeter. This device comprises of an inner chamber containing sample liquid and an outer chamber containing standard liquid. A standard orifice is located at the bottom of the inner chamber. The measurement is done by letting the sample liquid fill a standard 60cm<sup>3</sup> container through the orifice. The time (in seconds) to complete the filling is recorded as Saybolt Universal Seconds (SUS), which is the official unit of viscosity.

The viscosity of a liquid depends on the temperature. As the temperature increases, the viscosity decreases. Liquid's viscosity change with respect to temperature change is measured as viscosity index (VI). Oil with a low VI is more sensitive to changes in temperature.

## 2.2.2 Hydraulic Liquid

Hydraulic liquid plays a very important role in a hydraulic drive since it serves as the medium to transmit the power from the power source to the intended load in a manner according to the application requirements. In the early history of hydraulic drives, water was used as the hydraulic liquid due to its wide availability. However, with the ever strengthening requirements for higher pressure following the industrial

revolution, the constraints with using water and problems relating to oxidation and corrosion can no longer be tolerated. Since the early 20th century, oil has replaced water as the transmission medium in hydraulic drives.

Hydraulic drives are designed to operate with a hydraulic liquid having a specified range of viscosity. When a drive is operated with a liquid which has viscosity above the tolerance band, the following problems may occur:

- difficulty in starting-up
- stiff/sluggish operations
- cavitation in the pump
- accelerated wear of pump
- sticky valves and higher pressure drop
- higher temperature and power consumption

On the other hand, when a liquid with a viscosity below the tolerance band is used, the following problems may arise:

- internal and external leakage
- slow and irregular operations of the actuators
- reduction in lubrication

Apart from the hydraulic properties, the chemical properties of the hydraulic liquid are also important features governing the ruggedness of a hydraulic drive. While adequate hydraulic properties will ensure the efficiency and effectiveness of a hydraulic drive, adequate chemical properties will ensure that the components of the drive will not be unduly damaged or corroded over prolonged operations. Typical chemical properties to be observed include the degree of oxidation, water content, and degree of contamination.

Over prolonged time, these properties may change. Various tests are available to check the condition of the hydraulic liquid, *e.g.* the *Fluid Analysis Test* and the *Particle Analysis Test*. These tests will help to determine if the key properties of the hydraulic liquid have deteriorated to a level which will necessitate a replacement.

### ***2.2.3 Benefits of Fluidic Drives***

Fluidic drives have remained an option for motion generation and power generation, despite the wide availability of electric drives. This is even more so in the case of hydraulic drives due to their ability to deliver higher power.

Advantages of the fluidic drives are as follows:

- higher power-to-weight ratio, compared to a servo electric drive
- fluid acting simultaneously as a lubricant and coolant, apart from a power transmitter; a distinct feature of fluidic drives
- flexible in nature, *i.e.* ability to operate under continuous or noncontinuous conditions, at variable (and reversible) speed, with step-less variations

- ability to be stalled (*e.g.* in the case of overloading) without affecting the whole system, with simple circuitry
- both linear and rotational actuators available
- flexibility for interconnection of various fluidic components
- low maintenance cost

Disadvantages of the hydraulic drives are as follows:

- not readily available, compared to electric power
- costly and complicated installation, compared to mechanical or electrical system

Even when fluidic drives have been selected as the driving mechanisms, there are considerations in choosing whether to use hydraulics or pneumatics based on their characteristics. For example, fluidic actuators incur a shorter response time; an important consideration in applications where time precision is critical. In terms of safety, hydraulic liquid poses fire, explosion, contamination, and leakage hazards; rendering requirements of continuous maintenance of hydraulic liquid. Due to their incompressibility, hydraulic drive has poor damping characteristics. Also, hydraulic drive is sensitive to leakage, filtration, and contamination.

## 2.3 Components of Fluidic Drives Systems

The components of a hydraulic drive can be represented by symbols. These symbols are commonly used in circuit diagram, which represents the connections of components in the system. Commonly used symbols of fluidic components are presented in Figure 2.3.

### 2.3.1 Primary Power Source

The primary power source normally consists of a prime mover, *e.g.* an electric motor, serving as the energy source of the fluidic drive. This component typically drives hydraulic pumps in the hydraulic drives or pneumatic compressors in the pneumatic drives.

### 2.3.2 Hydraulic Pump

The hydraulic pump converts mechanical energy into hydraulic energy, which can then be transmitted by the hydraulic liquid to the actuators (hydraulic motors or pistons). In practice, the pump also generates pressure due to hydraulic resistance of other components in the system, thereby maintaining the flow. The input energy source is usually an electric motor.



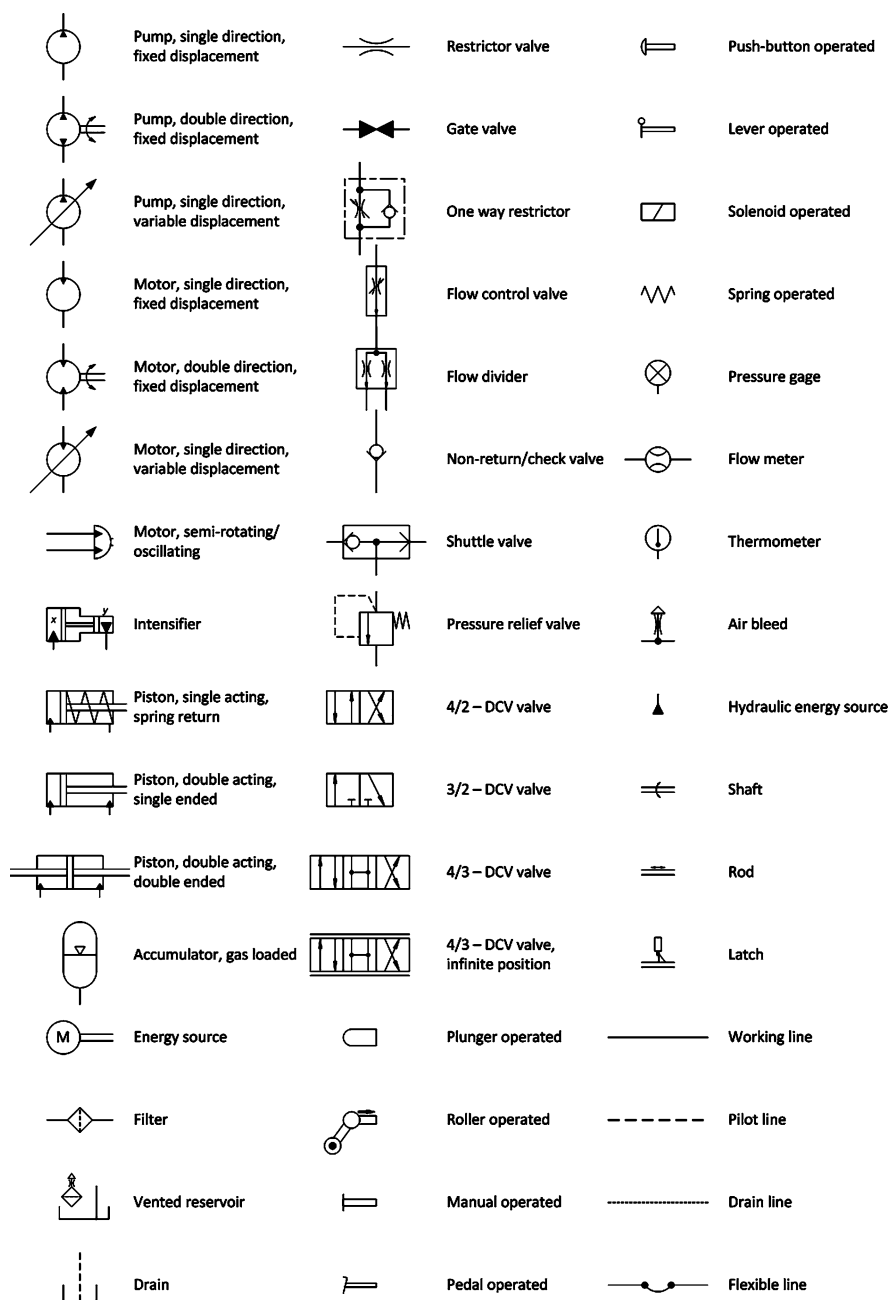


Fig. 2.3 Common symbols of fluidic components

Pumps can be classified based on the variability of the internal volume. Fixed pump refers to a pump with a fixed internal volume such that it always delivers the same flow rate of hydraulic liquid. Variable pump, on the contrary, has a variable internal volume, and hence it allows a variable flow rate of the hydraulic liquid.

Pumps can also be classified into positive displacement and nonpositive displacement pumps. Positive displacement pumps operate by displacing an amount of liquid from the low-pressure chamber (suction side) to the high-pressure chamber (delivery side) using its respective impeller, *i.e.* vane for vane pump, tooth for gear pump, *etc.* The flow is generated by varying the physical size of the pumping chamber, which has a larger volume for lower-pressure chamber and a smaller volume for higher-pressure chamber, so that the liquid is expelled at the high-pressure chamber accordingly. Inlet and outlet valves are installed at the inlet and outlet port, respectively, which is necessary to prevent a backward flow. Furthermore, since the operational pressure can be very high, sealing is important to prevent leakage. Valves and sealing increase the complexity of the construction of a positive displacement pump, and as such these parts have become the common sources of pump faults.

Nonpositive displacement pumps are generally used for generating large flow volume at low pressure. Examples of nonpositive displacement pumps are the centrifugal pump and the axial propeller pump.

Pumps used in hydraulic drives are positive displacement pumps, due to the requirement to generate and maintain a large pressure (typically up to about 13MPa) and high power at a specific certain flow rate.

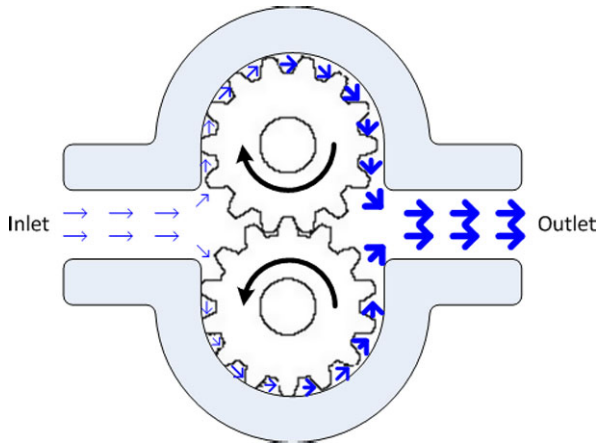
### 2.3.2.1 Types of Positive Displacement Pumps

Examples of positive displacement pumps include gear pump, gerotor pump, screw pump, vane pump, and piston pump. In the selection of a pump for use in the hydraulic drive, several factors should be considered, including the load characteristics (*e.g.* the flow rate), the pump characteristics (*e.g.* the operational pressure), speed of the power source, cost, reliability, maintenance, noise generated, and the environmental condition.

#### 1. Gear pump

In an external gear pump, the pumping action is accomplished by a pair of gears meshed together on their external sides, where one gear is keyed to the motor shaft. As the electric motor drives the pump, the liquid enters the pump through the inlet port, and the teeth of the pump cause the liquid to circulate through the outer diameter of the gears. The liquid is then displaced to the higher-pressure chamber and leaves the pump through the outlet port. Teeth mesh prevents the liquid from bypassing the pump through the inner diameter. Figure 2.4 presents the construction and working principle of external gear pump.

In an internal gear pump, the pair of gears is meshed on their internal sides instead, where the inside gear is keyed to the motor shaft. The centres of the two gears are then not aligned, although they are parallel. This creates a variation of physical volume of the pumping chamber, allowing positive displacement action



**Fig. 2.4** External gear pump (*thin arrow for low pressure, thick arrow for high pressure*)

to take place. As the electric motor drives the pump, the liquid enters the pump and circulates along the pumping chamber. The displacement of the liquid from the larger chamber to the smaller chamber creates a liquid flow which effectively increases the pressure of the liquid.

Similar to other gear construction, gear pump, which typically uses spur gear, is not balanced. The lateral force created by the mesh of the gear creates a side force on the gears and shaft, thus reducing the pressure and speed at which the pump can be operated.

#### 2. Gerotor pump

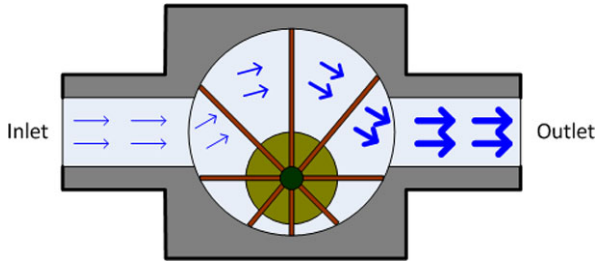
The construction of a gerotor pump is rather similar to the internal gear pump, except that it has several, instead of only one, pumping chambers. The number of the internal teeth is one less than that of the external teeth and equal to the number of pumping chambers. The idea of the design of gerotor pump is to combine the characteristics of external and internal gear pumps. The profile of the teeth is designed inwards, so they can also act as the seal.

#### 3. Screw pump

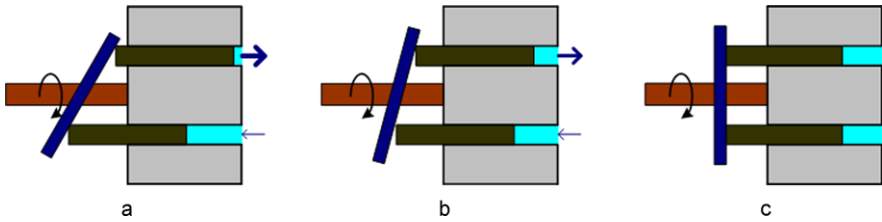
The pumping action is accomplished by a screw, which displaces the liquid axially through the pumping chamber. The helical profile of the screw causes the liquid to be displaced without generation of a lateral force, although axial force is present. This is one desirable feature of screw pump, apart from its noiseless operations.

#### 4. Vane pump

A vane pump comprises of vanes, rotor, and cam ring. The pumping action is accomplished by the vanes, which are installed in an eccentric rotor. The rotation of the rotor, driven by a primary power source, causes the vanes to slide radially, and thereby varying the volume of the pumping chamber. When the volume increases, the liquid enters the pumping chamber due to suction effect. When the volume decreases, the liquid inside the chamber is forced to a high pressure and ejected out of the pump.



**Fig. 2.5** Vane pump (*thin arrow for low pressure, thick arrow for high pressure*)



**Fig. 2.6** Piston pump

Due to its eccentric design, the performance of the pump can be significantly affected. To reduce this effect, a balancing mechanism is usually implemented to the pump. This includes the inlet and outlet port arrangement, intra-vane, and dual vanes.

A variable displacement vane pump employs an unbalanced design. This is achieved by adjusting the eccentricity between the cam ring and the rotor.

Figure 2.5 presents the construction and working principle of vane pump.

## 5. Piston pump

In a radial piston pump, the pistons are located around the pump shaft at right angles, *i.e.* along the pump's radius. Each piston is seated on a roller or a sliding shoe, while each roller is located on a common cam. The rotation of the cam, along with the pump shaft, will then reciprocate the pistons movement inside the bore cylinder. When the piston moves toward the centre (suction), the liquid from the low pressure chamber will be drawn into the cylinder. When the piston moves away from the centre (discharge), the liquid from the cylinder will be discharged into the high-pressure chamber. Figure 2.6 presents the construction and working principle of radial piston pump. As the shaft of the pump turns, the liquid flows into the pump through the low-pressure inlet. The inclined plate pushes the piston out, pressurising the liquid out of the pump through the high-pressure outlet. The amount of outlet pressure is adjustable via the angle of the inclined plate. Figure 2.6(a) provides maximum pressure with maximum angle (denoted with thick arrow), which can be reduced by flattening the angle as presented by Figure 2.6(b), with complete flat plate results in zero pressure build-up as in Figure 2.6(c).

In an axial piston pump, the pistons are fixed in parallel around the pump, each of them seated on a shoe that is attached to a common swash plate. The swash plate is installed at an inclined angle with respect to the shaft. With the rotation of the shaft, the swash plate will reciprocate the movement of the pistons. The reciprocation of the pistons inside the cylinder will alternately draw and discharge the liquid, creating a pumping action.

### 2.3.2.2 Boost Pump

In a large hydraulic drive, an additional pump may be installed to assist the main pump. This additional pump, which is called boost pump, is installed before the main pump (between reservoir and main pump) with the following responsibilities:

- to fill the circuit with oil in initial operation
- to replace oil lost due to internal leakage during operation

Boost pump is usually a small, fixed displacement pump, driven directly from the main pump. In many cases, the boost pump is housed within the same installation as the main pump.

### 2.3.2.3 Performance Indicators of the Pump

A key indicator of the performance of the hydraulic pump is measured by its efficiency, which is defined as follows:

$$\eta = \frac{P_{\text{fluid}}}{P_{\text{input}}}, \quad (2.8)$$

where  $P_{\text{fluid}}$  represents the output fluidic power, and  $P_{\text{input}}$  represents the input power to the pump, which is usually electrical power.

The flow rate of the pump, defined as the volume of the pumped liquid per unit time, is also an important indicator of the pump performance. Possible factors which may lower the pump efficiency include:

- mechanical friction within the pump
- internal leakage of the liquid in the pump
- friction between the liquid and the pump components

A pump performance can deteriorate over time. Improper operating conditions in a hydraulic drive may result in pump cavitation. Pump cavitation occurs when the local pressure of the pump falls below the vapor pressure of the liquid, causing the liquid to start vaporizing and creating bubbles. Cavitation can be caused by:

- inadequate suction pressure
- poorly designed inlet port
- incorrect pump selection

The effects of cavitation are far reaching. Bubbles which are formed in the low-pressure region can move to the high-pressure region, disintegrate in this region, yielding a counter force in this region as a consequence, which can lead to severe erosion of the pump.

### 2.3.3 Hydraulic Motor

The hydraulic motor will convert the hydraulic energy from the hydraulic liquid back into mechanical energy in the form of shaft rotation, hence producing torque and speed. Various types of hydraulic motor are available, such as radial piston, axial piston, gear, and vane motor. Depending on the design, the hydraulic motor has an ability to rotate in both the clockwise and counterclockwise directions.

The operation principle of hydraulic motor is exactly the reverse of a positive displacement pump. Hydraulic liquid enters the high-pressure chamber through the inlet port and pushes the energy converter component (which can be vane, piston, *etc.*, depending on the type of the pump), which in turn rotates the motor shaft. The hydraulic liquid will then leave the motor from the outlet port with reduced pressure.

Like hydraulic pumps, fixed and variable motors are available, allowing adjustment of speed and torque according to the load condition.

The construction of a hydraulic motor determines the performance of the motor. Table 2.2 shows the different motor designs, their characteristics and benefits.

#### 2.3.3.1 Types of Hydraulic Motors

Common types of hydraulic motors include the gear motor, the gerotor motor, the vane motor, and the piston motor.

##### 1. Gear motor

The construction of gear motor is very similar to a gear pump. A pair of gears is meshed onto each other, with one gear keyed to the output shaft. High-pressure liquid enters the motor and circulates around the outside of the gear teeth, since the inside is blocked by the mesh of the gear teeth. The circulation of the liquid from the high-pressure port to the low-pressure port around the outside diameter of both gears rotates the gear and, in turn, the shaft keyed to it. The favourable features of a gear pump is its high efficiency of up to 90%, speed range of up to 20,000rpm, power of up to 4kW; all these accomplished within a small size.

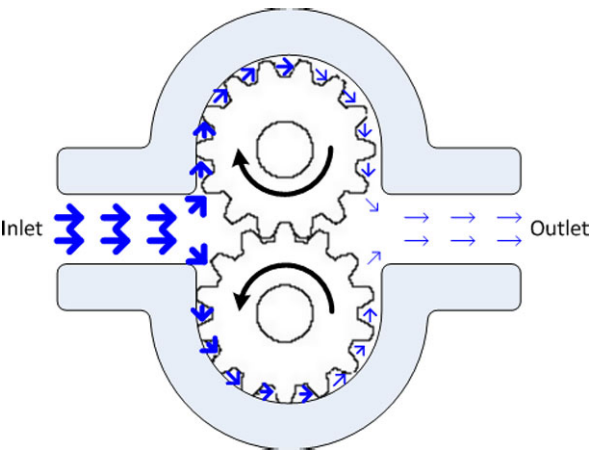
Figure 2.7 presents the construction and working principle of gear motor.

##### 2. Gerotor motor

Gerotor motor operates in the exactly reversed way of a gerotor pump. The liquid enters the motor and moves into the chamber between the inner and outer gears. The high pressure of the liquid impels the gear and causes the motor to rotate, while at the same time displaces the liquid to a low-pressure chamber.

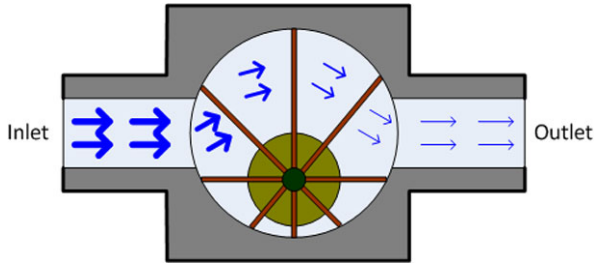
**Table 2.2** Motor designs, characteristics, and benefits

| Design                                    | Characteristics                                   | Benefits                                                                |
|-------------------------------------------|---------------------------------------------------|-------------------------------------------------------------------------|
| Cam design                                | Multiple stroke, large displacement               | High torque per weight (inertia) ratio                                  |
| Even number of pistons                    | Main bearing unloaded from radial piston forces   | Long service life of bearing                                            |
| Optimal cam geometry                      | Constant torque, no ripple, no pressure pulsation | High torque, no contamination entering housing                          |
| Cam roller, solid, balanced               | Reduced motor diameter                            | Long service life                                                       |
| Guide plate                               | Pistons unloaded from side forces, no stick slip  | Limited piston bore wear                                                |
| Side guide roller bearing                 | No stick slip                                     | High mechanical efficiency                                              |
| Oil distributing plate                    | Low volumetric loss                               | High volumetric efficiency, good low-speed performance, low noise level |
| Piston ring                               | Low volumetric loss                               | Improve volumetric efficiency                                           |
| Stationary motor housing with torque arm  | Compact design                                    | Motor bed plate eliminated                                              |
| Rotating cylinder block with hollow shaft | Compact design, no key ways                       | Ease in mounting                                                        |
| Through-hole in centre shaft              | Air venting                                       | Simplify mounting, possibility for cable through the motor              |



**Fig. 2.7** Gear motor (*thin arrow for low pressure, thick arrow for high pressure*)

Contacts between teeth of inner and outer gears provide the seal between adjacent chambers. The displacement of the motor is determined by the space of the chamber.



**Fig. 2.8** Vane motor (*thin arrow for low pressure, thick arrow for high pressure*)

### 3. Vane motor

The difference between the construction of a vane pump and a vane motor is the presence of a spring in vane motor to maintain the contact between the vanes and the cam ring. The liquid that enters the motor provides a high pressure and hence exerts a high force, against the vane. This causes rotation of the shaft, which is attached to the vanes. Figure 2.8 presents the construction and working principle of vane motor.

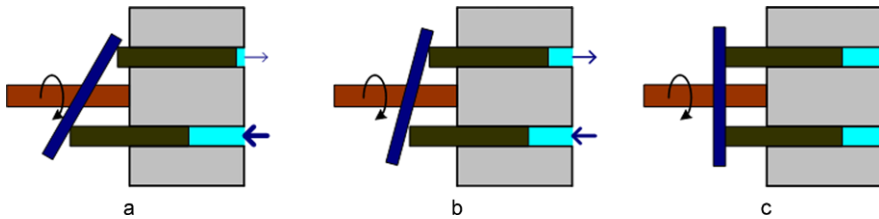
### 4. Piston motor

In a radial piston motor, the pistons are arrayed in a radial construction, each of which is pressed against a cam roller. All cam rollers push against a cam ring that is keyed on the motor shaft. Piston ring is installed on every piston to prevent leakage. When the liquid, at high pressure, enters the piston bore, force is generated in the contact between the cam roller and cam ring along the tangential direction with respect to the shaft. This force produces torque and therefore rotates the shaft. While the role of the piston is to convert hydraulic energy into mechanical energy and the cam ring is to produce rotation, the role of the cam roller is to help absorbing the lateral force reaction against the piston, thereby increasing its efficiency. A torque arm is usually installed to anchor the motor within a static frame in order to prevent undesirable motor body rotation.

Radial piston motor is usually used in heavy duty applications, *e.g.* crane hoisting, rolling mills, and railroad transportation. This is mainly because of its capability to sustain high radial and axial loads with short housing and length. Figure 2.9 presents the construction and working principle of piston motor, which is essentially the reverse of piston pump. As the high-pressure liquid flows into the motor, it pushes the piston, which in turns hits the inclined plate; thereby rotating the shaft. The liquid then flows out of the motor through low-pressure outlet. The output torque of the motor is adjustable via the angle of the inclined plate; high torque in Figure 2.9(a) with steep angle, moderate torque in Figure 2.9(b) with less angle, and no-torque in Figure 2.9(c) with flat angle.

In an axial piston motor, as the name suggests, pistons are arrayed axially, each of which is pressed against a roller. All rollers push against a swash plate, instead of a cam ring, which is installed with an inclination angle with respect to the shaft. When the high-pressure liquid enters the piston bore, a tangential force is generated in the contact between the roller and the swash plate, which





**Fig. 2.9** Piston motor

will produce a torque and a shaft rotation. Adjustment of swash plate inclination angle allows a variation of the rotation speed; thus this kind of motor is also known as a variable hydraulic motor.

In a large hydraulic motor, which is usually required to handle a high load, double banks of pistons and their subsequent components are installed to yield a larger torque. The rotation, however, remains unchanged.

The distribution of liquid to the right piston is important to ensure proper operation of the motor. This is accomplished via valve plates installed in the inlet port, equipped with port timing. Also, in a double direction motor, a right-left connection is provided in the inlet port to allow the motor to operate in clockwise and counterclockwise directions.

Piston motor can also be used as a pump if the mechanical energy is applied to the output shaft; this device is commonly called the pump-motor. This is a flexibility the piston motor construction has to offer.

### 2.3.3.2 Performance Indicators of Hydraulic Motors

The performance of a hydraulic motor can be measured by indicators in terms of its torque, speed, power, and efficiency. Efficiency is a measure of how much fluid power can be converted into usable mechanical power of the shaft, as follows:

$$\eta = \frac{P_{\text{output}}}{P_{\text{fluid}}}, \quad (2.9)$$

where  $P_{\text{output}}$  represents shaft output power, and  $P_{\text{fluid}}$  represents fluid input power.

### 2.3.4 Hydraulic Piston/Cylinder

Hydraulic piston converts hydraulic energy back into mechanical energy in the form of linear motion and force. It is basically a piston contained in a cylinder, which can have one or two protruding rods out of it. While hydraulic piston is mainly for loading purpose, it can also be applied as a cushioning device as in a suspension system. The selection of a hydraulic piston is based on considerations such as the purpose of application, construction, technical requirements (force, duty cycle, action), and environmental conditions.

### **2.3.4.1 Loading Piston**

The force exerted by a hydraulic piston is proportional to the liquid pressure and the cylinder's cross section area. Therefore, a piston with rods at both ends exerts the same force in both directions, while a piston with one rod exerts a larger force in one direction due to the difference in area.

Based on the activation approach, a hydraulic piston can be classified as either a single acting or a double acting piston.

A single acting hydraulic piston is activated by the hydraulic liquid from one side only. On the filling side, a channel is installed to allow oil to flow into the cylinder. When the liquid is directed to flow into the cylinder, it will push the piston by virtue of its pressure, and the load will be moved accordingly. The returning action is accomplished by external force, such as spring or load gravity. Alternatively, a drain valve can be installed to empty the liquid and thereby returns the load.

A double acting hydraulic piston has channels on both sides of the cylinder. These channels allow the liquid to flow into or out of the cylinder to generate motion. Depending on the direction to which the liquid is flowing, the piston will move either in forward or backward direction. A double acting piston can have one or two rods protruding out of the cylinder.

### **2.3.4.2 Cushioning Cylinder**

A variation in the application of hydraulic piston is cushioning cylinder. As its name suggests, it prevents or reduces shock to the load by decelerating a moving load. A typical application of cushioning cylinder is a shock absorber.

The working principle of cushioning device is to slow down the piston movement before it contacts the end of the cylinder. It uses a taper or stepped rod that enters a sleeve mounted in one end of the cylinder. Through this design, the pressure applied to the piston increases, thereby reducing its velocity.

### **2.3.4.3 Sealing**

Sealing is a very important issue to address in a hydraulic drive, especially in a hydraulic piston, because of its movable component (the rod) that extends from the pressure chamber. Since the rod is movable, there is a gap between the rod and the cylinder to allow motion. However, the gap must be as small as possible to prevent leakage. Another common problem relating to sealing lies in the seal itself, when it expands due to the repetitive movement of the rod.

### **2.3.4.4 Performance Indicators of Hydraulic Cylinder**

The performance of a hydraulic cylinder can be measured by its capability to generate force, which is dependent on the pressure of the liquid and the pressure area of

the cylinder as follows:

$$F = pA. \quad (2.10)$$

The velocity  $v$  at which the load is moved is also an important feature and formulated as follows:

$$v = \frac{f}{A}. \quad (2.11)$$

The stroke of the cylinder determines the total movement distance, and it is also an indicator of the performance of a cylinder.

### 2.3.5 Control Valves

Control valve is a device which is used to hydraulically regulate certain parameters, such as pressure and flow. Based on the nature of control, control valves can be classified into servo valves and proportional valves; the former referring to closed-loop control valves, while the latter referring to open-loop control valves. Based on their functions, they can be classified into a directional control valve (DCV), a flow control valve, or a pressure control valve.

#### 2.3.5.1 Evolution of Control Valves

The first electrically operated control valve, which will later bring on the servo valve and proportional valve, was developed after World War II. This valve used a linear spool slide unit controlled by a linear motor, and it was used in aeronautics. Hydraulic pilot control was later introduced to the valve assembly via a jet flapper and jet pipe amplifier. A few years after this invention, mechanical feedback of the spool position was incorporated, yielding the servo valve. The servo valve has gained popularity mainly because of the precision and the power balancing features which it enables. From the early 1960s, there was an increasing application of servo valve in the industries; a noteworthy example was in injection molding applications.

However, that servo valves had significant drawbacks: very sensitive to contamination and costly. These issues became even more significant when a large volumetric flow and rapid control are required. These issues led to the revolutionary design and the conception of the proportional valve.

The control of proportional valve was done electrically by either direct control of the spool (with magnet or motor) or by hydraulic pilot control. The proportional valve soon gained popularity and wide acceptance because of its large flow rate and its robustness to contamination. Over the time, the proportional valve continued to evolve with much effort generated towards the simplification of its control equipment. It became possible to have a robust proportional control valve under servo control. This control valve is sometimes called the servo proportional valve.

### 2.3.5.2 Fundamentals of Control Valves

The key component of a control valve is a linear spool slide, whose role is to block or unblock the flow of liquid with a sliding motion. In a more advanced design, it can also regulate the flow of the liquid. In general, this component is termed *throttle*. One full sliding motion is called one stroke, which ranges from 0.4 to 10.0mm. The ratio of spool diameter to the stroke is from 8:1 to 15:1.

As a control device, the control valve has to achieve high precision in its operations and minimize the amount of leakage occurring. The effects of leakage are:

- reduced positioning accuracy
- reduced power delivery and hence efficiency
- introduction of higher lateral and frictional force

Therefore, a control valve requires high accuracy in its manufacturing. The allowable clearance between the spool and the housing is typically up to 1:2000 or equal to a nominal separation of not more than  $2\mu\text{m}$ . The material used for the valve is also special (e.g. hardened spheroidal iron) to ensure that it has a high wear resistance. The roughness of the spool and cylinder bore is typically up to  $0.4\mu\text{m}$ . O-rings are used to further prevent leakage in the control valve and are usually installed on the connection holes.

The connection holes of control valve are assigned with special terminology. They are usually termed P for pressure supply (pump), T for drain (tank), A, B, and so on for actuators, and X-outlet and Y-inlet for pilot control. The size and position of the connection holes are also mostly standard to promote interoperability of equipment from different manufacturers.

The pressure drop across the valve is an important factor to consider in the design and selection of control valves. Pressure drop induces thermal rise (typically  $5^\circ\text{C}$  per 100bar) which in turn reduces efficiency and power delivery. Typically, 75% of the pressure losses occur at the variable throttle points near the maximum stroke of the valve. Pressure drops are caused by:

- friction between the hydraulic liquid and the valve wall
- redirection of the flow inside the valve

Pressure drop is a nonlinear phenomenon (mainly saturation), and this poses a big challenge in control design, especially when high precision is a significant factor. A typical remedy of this problem is to limit the operations of the valve in the nonsaturated operation range by means of a mechanical structure.

Another cause of power reduction is due to the flow resistance force, which is in turn due to the longitudinal flow of the liquid across the valve. Since the flow induces pressure, a force will be generated across the cross-sectional area of the spool, resisting the flow.

The control of the valve's spool is accomplished electrically. Several mechanisms can be used, such as plunger coil, linear motor, torque motor, or proportional magnet. This mechanism converts electrical signal into electromagnetic force that is able to put the spool in motion. Hydraulic pilot control, however, can also be used to amplify and transmit the electromagnetic force into spool motion.

The operational principle of the mechanisms, which is based on the electromagnetic principle, can be briefly described as follows. When a current is applied through the armature which is contained in a magnetic field, a force is generated. Depending to the mechanical structure, this force may be transmitted directly or indirectly to the spool, resulting in a motion. The control is accomplished by adjustment of the current's amplitude and interval. The development of electromagnetic converters contributes to the advance in valve performance. Examples of these contributions are:

- new materials for magnet, *e.g.* samarium–cobalt and neodymium–iron–boron, which have larger specific energy
- low-power plunger, with smaller size and elimination of magnetic hysteresis
- combination with hydraulic amplifier to provide larger torque/force to the spool
- combination of magnetic and nonmagnetic materials to direct and to concentrate magnetic flux within the air gap

The spool configuration affects the flow characteristics significantly. Spool can be configured to have an open-centre or a close-centre configuration. An open-centre spool has both control ports open to return when the spool is centred, and it is typically used with fixed pumps. A close-centre spool, on the other hand, is typically used with variable pumps to form a constant pressure hydraulic circuit.

In the presence of large flow resistance force which cannot be overcome satisfactorily by electromagnetic force, a hydraulic amplifier can be applied. Hydraulic amplifier generates a hydraulic force that is typically up to 10 times larger than flow resistance force. Hydraulic amplifier is included in a hydraulic pilot control installation together with the electromagnetic converter to form an integrated pilot control. An example of hydraulic amplifier is a four-edge amplifier, which corresponds to the main stage of the flow control valve.

### 2.3.5.3 Proportional Control Valve

Proportional control valve can be controlled continuously during its operation via an electrical signal, which is activated through manual controllers (usually located in the control station), as it is controlled in an open-loop manner. This valve can direct and meter the flow of the liquid to actuators.

A proportional control valve comprises of a spool as the main regulating component, housed inside a valve bore. Valve bore forms valve cavity, connected to several channels linked to actuators, pump, and reservoir (tank). The control of the valve is executed by controlling the spool electrically with various electromagnetic converters.

Despite the open-loop control configuration, a feedback signal is provided from the spool to balance the action of the electromagnetic converter so that it can maintain the valve position according to the signal from the manual controller. Hydraulic amplifier may be installed to assist controlling of proportional control valve.

There are several types of common proportional control valves: jet-flapper, sliding spool pilot stage, jet-pipe, and jet-deflector valve. These are elaborated as follows.

### 1. Jet-flapper valve

In a jet-flapper amplifier, two fixed and two variable throttles are arranged in a Wheatstone full-bridge; the fixed throttles are located at the upstream, and the variable throttles are located at the downstream. The flapper is arranged between the variable throttles, with its normal position in the centre. Two jets are directed towards the variable throttles. A flow channel, which houses the spool to be controlled, is connected to both fixed and variable throttles. The hydraulic liquid flow generates pressure drop at the throttle points.

If the flapper is located at the centre, equal pressure drop occurs so that no force is exerted on the control spool. If the flapper is displaced, for example, towards the left jet, the cross section of the left outlet reduces while the right outlet increases. The pressure in the left branch will then increase, while that of the right branch will decrease. This pressure difference will exert a force on the spool, pushing it to the right. If the flapper is displaced to the opposite direction, an opposite effect will occur.

The movement of the flapper is controlled by an electromagnetic converter, *e.g.* a torque motor. The armature of the converter is designed such that it has a fast dynamic response bandwidth and bidirectional control ability. A returning spring may be added to provide an even faster returning dynamic.

When the spool is in motion, a balancing flow flows from one branch of the bridge to the other branch. If the flapper happens to close a jet completely, the flow of this branch can be diverted and used for the positioning velocity. An additional throttle can be installed between the variable throttles and the drain line to stabilize incoming flow from the jet. The balancing flow is proportional to the flapper position.

If the actuators are blocked, no balancing flow will occur; a differential pressure will build up, instead, leading to leakage and power loss.

The jet-flapper valve is mainly used in a high performance hydraulic system.

### 2. Sliding spool pilot stage valve

This is a variation of a jet-flapper valve, except that the flow is across two meter-in and two meter-out control edges, connected to the controlling spool. The control of the valve is performed by the opening and closing of the meter-in and meter-out control edges.

This valve is commonly used in a modest performance hydraulic system.

### 3. Jet-pipe valve

In a jet-pipe amplifier, a jet-pipe with hydraulic liquid is integrated into the control element. A fluid jet flows from the pipe through a jet against two receiving holes, which are located close to each other.

A connecting pipe from each of the hole leads to both ends of the controlling spool, housed in a slide unit. In the neutral position, the jet-pipe is situated at the centre, and the liquid is therefore distributed equally to both holes, creating equal pressure on the right and left of the spool. If the jet-pipe is displaced towards, for example, the left hole, more flow will be directed to this hole, creating a pressure difference on the spool and in turn moves to spool to the right. The opposite effect will occur when the jet-pipe moves towards the opposite direction. The velocity of the movement can be regulated by the displacement of the jet-pipe.

Due to its construction, leakage will occur in this valve, mainly at the cross section area of the holes, inducing a power loss.

#### 4. Jet-deflector valve

This is a variation of jet-pipe valve, whereby its jet is installed and fixed opposite to the two receiving holes. The control is provided by a thin jet-deflector plate, located between the jet and the holes, perpendicular to the jet flow. The jet-deflector plate is attached to the electromagnetic converter to perform the controlling action.

In the neutral position, the jet-deflector plate is situated at the centre, and the liquid is therefore distributed equally to both holes, creating equal pressure on the right and left of the spool. Displacement of the jet-deflector plate towards the left will direct more flow to the left hole, creating a pressure difference on the spool and in turn moves to spool to the right. The opposite effect will occur when the jet-deflector plate moves along the opposite direction.

In short, the advantages of using a proportional control valve are as follows:

- accurate control of flow and direction
- installation of control valve can be near the actuators to simplify piping and plumbing
- reduction of fluid leakage
- several options of control available, *e.g.* with radio control

The disadvantages of using proportional control valve are as follows:

- less precise positioning as it uses open-loop control
- larger installation envelope

Proportional control valve is designed for a small pressure drop and therefore is suitable for a power delivery application. Typically, the pressure drop is up to 10% of the rated pressure, or equal to a nominal pressure drop of 10bar, with a flow dead zone of up to 30% of the spool stroke. Therefore, nonlinearity is a significant issue in the control of proportional control valve, especially when this valve is modified to operate in a closed-loop manner.

Closed-loop control can be implemented in a proportional control valve by replacing the manual controller with an electrically activated device. This is applied, for example, in a hydrostatic transmission, where manual controller is replaced by a potentiometer.

Proportional control valves are now commonly applied in the industries associated with material handling, construction equipment, and steel mill.

#### 2.3.5.4 Servo Control Valve

A servo control valve produces continuous controlled output via feedback control loop, as it implements a closed-loop control system. The reference signal is compared to the actual output and is used to generate control signal, resulting in a precise positioning of the valve according to the reference signal. The positioning of

the valve is accomplished by pilot flow, while the main flow of the liquid is carried out by the main ports. To increase its flow rate, the servo valve may be staged, which will provide a higher pressure to shift the spool. Because of its more complex control system, servo control valve is more expensive than proportional control valve.

The pressure drop of servo control valve can be large, reaching up to 30% of the rated pressure or equal to a nominal pressure of 70bar. The flow dead zone, however, is rather negligible. It is therefore very suitable for a precision metering application, where the effects of nonlinearity must be low.

Servo control valve can be used to measure various variables, such as position, velocity, pressure, or torque. The purpose of the valve determines the sensors to be used and also the controller structure. It is often required for a hydraulic drive, via its servo control valve, to satisfy the requirements relating to a number of variables simultaneously. These requirements will further increase the number of sensors needed, and complicate the controller structure.

With the advance in closed-loop control technology, many options are now available to simplify the structure of the valve's controller without sacrificing the performance. State observers, for example, can be implemented to reduce the number of sensors in an operation. The idea is to obtain a limited number of sensor signals of certain variables and then to estimate the other variables via computation.

### 2.3.5.5 Classification of Control Valves Based on Functions

Control valves can also be classified according to the function it performs in the overall system.

#### 1. Directional control valve (DCV)

As the name suggests, DCV serves as the direction controller of the liquid flow to the actuators, which can be motors or pistons. It can therefore control the direction of the actuators—whether the motor rotates in clockwise or counter-clockwise direction, or whether the piston extends or retracts but cannot control the speed or velocity of actuators.

In the context of DCV, the following terms are commonly used:

- *PORT*

This refers to the number of connection of a DCV to external devices. A DCV must have at least two ports; one to a pressure source (pump) and another one to an actuator. For a DCV with more than two ports, the ports may be connected to a reservoir from the drain or to other actuators.

- *POSITION*

This refers to the number of its possible position. It may theoretically be infinite if the sliding of the DCV is not restricted by its housing.

- *WAY*

This refers to the number of flow path through the valve.



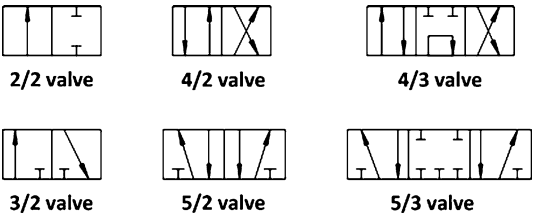


Fig. 2.10 Examples of how DCV is named

| Table 2.3 Comparison of hydraulic systems with an open-centre and a close-centre valve |                    |                    |
|----------------------------------------------------------------------------------------|--------------------|--------------------|
| Features                                                                               | Open-centre valve  | Close-centre valve |
| System idle time                                                                       | Long               | Short              |
| Typical power source                                                                   | Fixed pump         | Variable pump      |
| Time characteristic of applications                                                    | Time insignificant | Time critical      |

A DCV with  $m$  ports and  $n$  positions is called an  $m/n$  DCV, as exemplified in Figure 2.10.

Directing action can be accomplished through the sliding spool, ball, plate, etc. A DCV can be controlled in various manners; with respect to its control (automatically or manually), its mechanism (mechanically, electrically, or hydraulically), and its distance from the controller (remote or direct-acting). The manner through which a DCV is controlled is presented in the symbol of the DCV.

When a pilot control is used in a DCV, the pilot fluid can be isolated from the hydraulic circuit and therefore permitting the usage of other substance to control the DCV.

A combination of several DCVs with proximity switches can develop into a sequencing hydraulic circuit, which can run automatically to perform a periodic task. The normal position of a DCV is important to determine the nature of the system at rest, especially in an automation system. Considerations over normal position of the valve also include the configuration of open-centre and close-centre valve. An open-centre valve connects the pump and the reservoir at rest; while a close-centre valve does not. The comparison between hydraulic systems with open-centre and close-centre valve is presented in Table 2.3.

2. Flow control valve

A flow control valve is used to control the flow rate of the hydraulic liquid. By controlling the flow rate of the liquid, it can effectively control the speed or velocity of the actuator. It can therefore be used as a speed control device to complement a DCV in a hydraulic system.

The operational principle of a flow control valve is based on flow restriction which will alter the flow rate of the liquid. However, flow restriction may affect the temperature and pressure, which will require timely compensation to maintain the operating conditions. For modest applications, however, compensation may not be necessary. The flow rate of the liquid across a flow control valve

depends on the pressure difference, type of valve, and the characteristics of the hydraulic liquid.

With pressure compensation, the flow rate can be kept constant regardless of pressure changes in the system, which may occur due to the flow restriction itself. Similarly, with temperature compensation, the valve maintains the flow rate despite temperature changes, which also changes the viscosity of the hydraulic liquid.

The restriction of the liquid flow is conducted by a series of fixed or variable orifices. A fully open orifice allows the flow of the liquid at its rated flow rate, while a restricted orifice reduces the flow rate. Pressure drop is thus inevitable across a flow control valve.

A type of flow control valve, called deceleration valve, is used to alter the speed or velocity of the actuators at an intermediate position. This valve is typically manually operated but may be equipped with a proximity switch as a position indicator. An adjustable needle valve may also be employed to further control the flow rate.

### 3. Pressure control valve

A pressure control valve serves as the controller of the pressure of a hydraulic system, often to limit the pressure below which the system should operate. Pressure control valves include the compound pilot drained valve, pressure reducing valve, sequence valve, unloading valve, counterbalance valve, and the pilot-operated check valve.

A compound pilot drained valve is operated via a pilot control, resulting in a better pressure sensitivity. The main components are piston, poppet, and spring, which work together to open or close the discharge port when necessary.

A pressure reducing valve is employed to supply low-pressure liquid. This valve steps down the pressure by restricting the flow when the preset pressure is reached.

A sequence valve controls the order of operation that has to be performed by several actuators or circuits. This valve is connected to sensors (typically proximity sensors) and is activated to the respective sequencing position by the respective sensors.

An unloading valve is used to discharge the liquid from the pump when the pump is not in use. This action will reduce power loss more efficiently than using pressure relief valve. A pilot control is employed to control this valve.

A counterbalance valve is used to maintain the backward pressure in a vertically mounted hydraulic piston/cylinder. The application of pilot control in this valve will reduce energy consumption.

A pilot-operated check valve is used to position varying loads on a hydraulic piston/cylinder by locking the cylinder upon shifting of DCV.

#### 2.3.5.6 Performance Indicators of Control Valves

The performance of a control valve is measured with various indicators which determine the suitability of the valve to the overall application. Many of the parameters,

such as responsiveness, backlash, and hysteresis, are common in closed-loop control and will be described further in Chapter 5.

There are also indicators unique to hydraulic control valves, *e.g.* hydraulic overlap, which represents the linearity deviation of the liquid flow in the vicinity of zero crossing.

### 2.3.6 Sensors

Measurements are necessary in the closed-loop control system of a servo hydraulic drive to monitor the condition of the system, such as its pressure, flow rate, and temperature. Motion control of the actuators will also require other measurements of position, velocity, force, and torque.

#### 2.3.6.1 Pressure

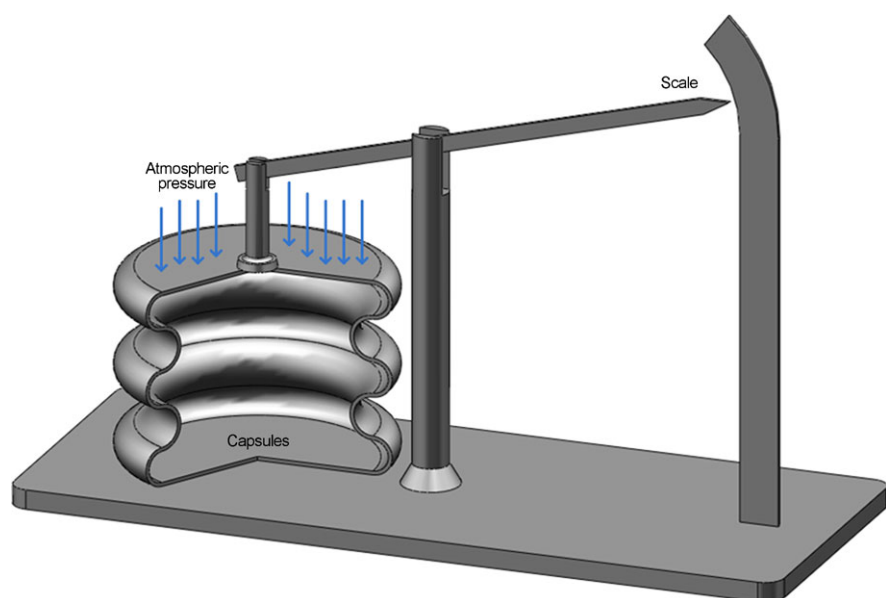
Pressure measurement is one of the most widely measured physical parameters. In fact, a vast number of technological breakthroughs would not have been possible without an accurate measurement of pressure. Two common pressure sensors widely used is the aneroid barometer and the bourdon tube.

1. Aneroid barometer

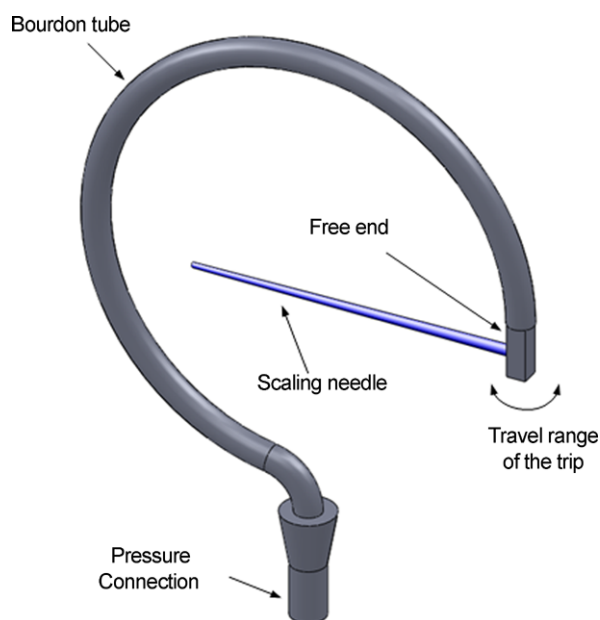
An aneroid barometer, as shown in Figure 2.11, is used for the measurement of the atmospheric pressure and consists of an evacuated metal capsule with flexible top and bottom faces. The shape of the capsules changes with variations in atmospheric pressure, and this deformation is usually amplified mechanically via a series of levers or gears. The pressure capsule can be fabricated in the form of bellows to provide further deflection. The measurement of deflection is done visually by a pointer connected to the levers aligned to an appropriate scale. To increase the effective stroke, more than one capsule can be connected together. This configuration of multiple capsules will have the same characteristics as a much larger single capsule, which makes it possible to construct low-pressure gauges and still maintain a reasonably small size.

2. Bourdon tube

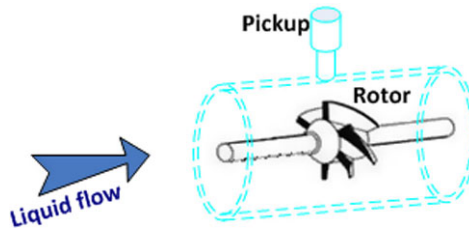
A bourdon tube operates on the same principle as an aneroid barometer, except that it uses a C-shaped or helical tube instead of an evacuated capsule or bellows arrangement, as shown in Figure 2.12. The tubes are closed at the one end and connected to the point of measurement at the other end, which is fixed in position. The Bourdon tube is made from a section of oval tube that has been formed into a specific shape. When pressure is applied to the tube, it tends to straighten. This movement at the end of the tube is used to move a pointer over a calibrated dial. The deflection of the Bourdon tube varies with the ratio of its major-to-minor cross-sectional axes, the tube length, the difference between the internal and external pressure, and its total tube angle.



**Fig. 2.11** Aneroid barometer sensing element



**Fig. 2.12** Bourdon tube sensing element



**Fig. 2.13** Turbine meter

Bourdon tubes are usually used in the gauge pressure sensing application; however, sensing of differential pressure is possible by connecting two tubes to one pointer, thereby causing the pointer to measure the pressure difference between the two tubes. Helical tubes are more compact and reliable than the more traditional C-shaped devices. Bourdon tubes are used throughout the industry and are available in a wide range of pressure specifications.

### 2.3.6.2 Flow

Flow is often measured indirectly through the measurement of volume. Common flow sensors include the turbine meter and the paddle wheel meter.

#### 1. Turbine meter

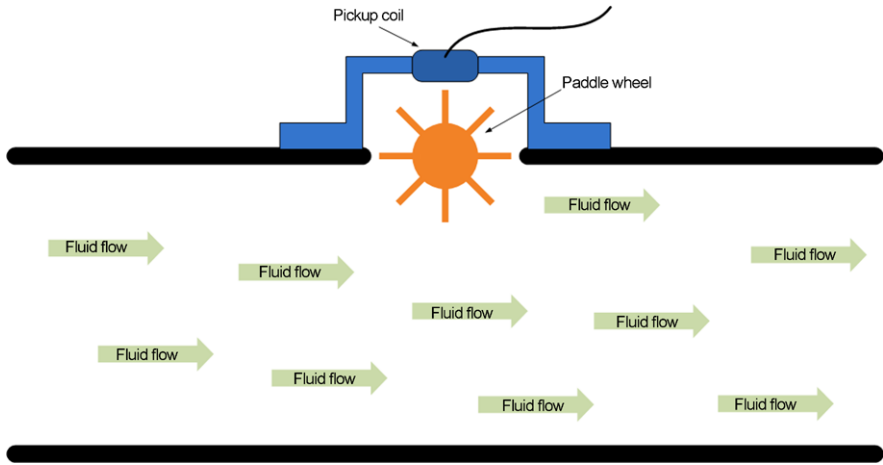
Invented by Reinhard Woltman in the 18th century, a turbine meter is an accurate and reliable method used to measure flow rate for both liquids and gases. Figure 2.13 shows a typical design of a turbine meter. As fluid flows through it, the freely spinning turbine blade assembly would start to rotate. The pickup senses the movement of the blades and generates pulses to the meter. The rotating speed of the turbine is directly proportional to the flow rate of the fluid, thus the volumetric flow rate can be determined. Alternatively, a tachometer can be attached to the turbine to determine the number of revolutions of the turbine directly.

The accuracy and sensitivity of the meter largely depend on the smoothness of the turbine rotations, which can be enhanced by reducing the friction between the blades and the shaft. Other factors affecting the accuracy include the nature of the fluid and the straightness of the fluid flow. There is a minimum flow rate needed for the turbine meter to function satisfactorily, and this is usually stated in the specification sheet. Turbine meters are expensive, but the measurements are highly accurate.

Turbine flow meters are commonly used in the food and beverages, chemical, petroleum, and water distribution industries.

#### 2. Paddle wheel meter

A paddle wheel meter uses a rotor whose axis of rotation is parallel to the direction of flow as shown in Figure 2.14. In most cases, a paddle wheel meter is



**Fig. 2.14** Paddle wheel meter

bidirectional with flat-bladed rotors. However, some types of paddle wheel meter have crooked rotors, which restrict their usage to measure forward fluid flow.

When the fluid flows pass the paddle wheel, the paddle wheel will start to rotate along the direction of the flow. This will in turn activate the magnetic pickup coil and, as each paddle wheel passes through the magnetic field, a pulse is generated. The frequency of the generated pulse is proportional to the flow rate through the meter.

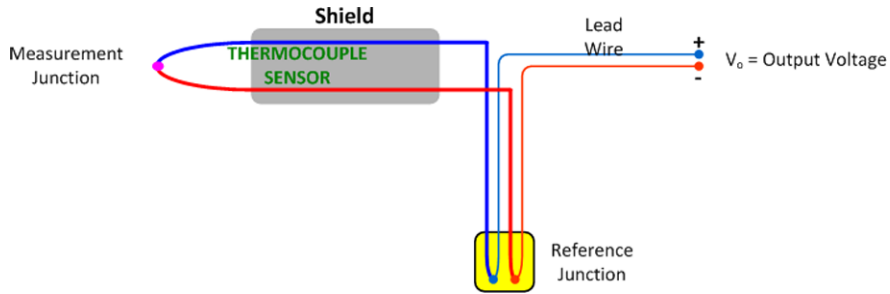
Paddle wheel flow meters are used in many applications including those found in the chemical industries, irrigation, air-conditioning, and refrigeration. Because paddle wheel flow meters are inexpensive and need little maintenance, they are used especially in applications where the cost to measure the variable is an important consideration.

### 2.3.6.3 Temperature

Temperature measurement and control are necessary in a hydraulic drive to maintain the viscosity of the hydraulic liquid. Two common temperature sensors in a hydraulic drive are the thermostat and the thermocouple.

#### 1. Bimetallic thermostat

A bimetallic thermostat is a device which can turn on or turn off a heating system to keep the hydraulic system at a range of desired temperature. The bimetallic strip is positioned so that when it is heated and bends, or when it is cooled and straightened, it will break or make an electric circuit. This effect is used to show if the temperature exceeds some threshold, or to control the heat produced by a heating system. The thermostat is thus only capable of on–off temperature measurement or control.



**Fig. 2.15** Thermocouple

## 2. Thermocouple

The thermocouple has two dissimilar metals joined together, forming a closed circuit. Figure 2.15 shows the construction of a thermocouple. One junction is held in a probe which is placed in the medium whose temperature is to be measured. The other junction is usually maintained at a fixed temperature. When the temperature at the two junctions differs, a resultant electromotive force (emf) is induced. Current will flow, and the direction and magnitude of the current flow depend on the temperature difference between the two junctions. This current can then be calibrated to give the required temperature measurement.

### 2.3.7 Auxiliary Equipment

Apart from the key components highlighted in the earlier sections, there is also auxiliary equipment in a hydraulic drive, whose role is to ensure safety, maintain pressure level, remove contaminants, and other additional functions.

#### 2.3.7.1 Pressure Relief Valve

A pressure relief valve is used to avoid excessive pressure in a flow. It is usually installed near the outlet port of the pump to protect the pump and the system against pressure overload.

Several mechanisms can be employed in the pressure relief valve. In a spring actuated ball valve, which is the typical type of pressure relief valve, a ball element is placed on a conic seat and is pressed by a spring. The spring acts so that it tends to close the valve, while the flow of the liquid is directed in the opposite direction to open the valve. When the force of the liquid, caused by its pressure, exceeds the limit sets by the spring force, the valve is opened, and the liquid flows out of the channel to the reservoir until the pressure of the system returns to normal. As long as the pressure is below the limit, the force from the liquid does not exceed the spring force, and the valve remains close.

In relation to its operating mechanism, these two measures of pressure characterize a pressure relief valve as follows:

- cracking pressure; the pressure above which the valve passes liquid through
- closing pressure; the pressure below which the valve does not pass liquid through after being opened

### 2.3.7.2 Check Valve

A check valve is used to ensure that the flow of the liquid is only along one direction, hence preventing unwanted direction of flow. In a typical type of check valve called ball check valve, a ball is seated on a taper channel and is pushed by a spring against the flow of the liquid. When the liquid flows in the correct direction, *i.e.* against the spring, the liquid pushes the spring and opens the gap around the ball, allowing the liquid to flow. When the flow is in the opposite (*i.e.* incorrect) direction, the spring will shut the gap, and hence blocking the flow. This valving action can also be accomplished by a flapper or a poppet.

### 2.3.7.3 Shuttle Valve

A shuttle valve is a double-check valve with a cross bleed, permitting reverse flow between several connections in the circuit. It is a hydraulic version of an OR logic. It has two input connections and one output connections, making it suitable to implement an OR logic function.

### 2.3.7.4 Filter

A filter is used to remove harmful contaminants, especially solids, from the hydraulic liquid. A filter is usually installed with a bypass check valve to facilitate filter replacement. Various types of filter are available to serve different purposes.

Solid particles are often produced by high mechanical or hydraulic stress, which causes wear. Solid particles traveling in a hydraulic system will further cause more wear and therefore more contamination. The existence of solid in the system will cause the following:

- reduced efficiency and energy consumption due to internal leakage and heat generation
- slow cycle time and poor response dynamics
- sticky valve
- shorter life of bearing

A filter comprises a filter element that is contained inside a strong shell. The filter element may be blocked and has to be replaced from time to time. This is indicated



by a differential pressure gage that is usually installed across the filter to serve as a clog indicator.

Common types of filter in a hydraulic drive are as follows:

- return line filter, installed in the return line prior to entering the reservoir
- boost filter, installed to filter the oil leaving boost pump, and therefore protects the main pump
- drain filter, to filter oil from the internal leakage of major components
- suction strainer, installed inside the reservoir to filter oil prior to reentering the system

### 2.3.7.5 Flow Divider

As its name suggests, a flow divider is used for dividing the flow of hydraulic liquid to desired components. A flow divider is employed when it is required to power several circuits with different flow simultaneously. The allocation of the flow is based on proportional or priority.

It is important to keep the flow divided evenly to prevent unwanted flow from a higher pressure discharge to a lower pressure discharge.

### 2.3.7.6 Accumulator

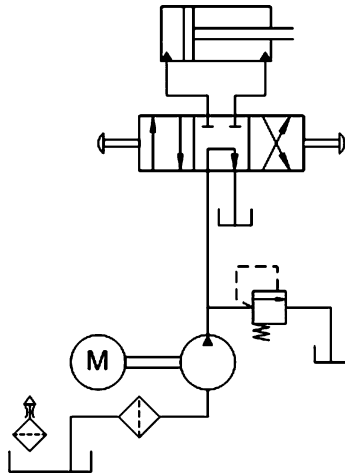
The main task of an accumulator is to keep certain amount of the hydraulic liquid under pressure and releases it to the system upon demand. Various types of accumulator are available, suited for specific applications, *e.g.* gas accumulator and spring accumulator.

The operational principle of a gas accumulator is based on Boyle's law. A compressed gas, usually nitrogen, is contained in a bladder against the liquid. Hydraulic pressure develops until a balance is achieved, hence keeping the pressure constant.

The operations of an accumulator can be divided into two stages:

1. When the pump in the system causes the liquid to enter the accumulator, the gas in the bladder compresses, and its pressure increases. The process of bladder compression stops when the pressures of the liquid and the gas are equal. At this stage, the bladder is not subject to abnormal mechanical stress, and due to its design, it compresses inwards.
2. When the system pressure falls, the stored liquid is returned to the system under pressure by the compressed gas, thereby increasing the system pressure closer to its normal level.

An accumulator can also be used to maintain system pressure, absorb hydraulic shock, cushion loads, dispense lubricants, and provide additional power source.



**Fig. 2.16** Constant flow system

## 2.4 Basic Hydraulic Circuits

A hydraulic circuit refers to a combination of hydraulic components, connected to one another, to form a complete hydraulic system. There are various classifications of hydraulic systems. Based on its hydraulic characteristic, hydraulic circuits can be classified into the constant flow, the constant pressure, and the constant power system.

Several key issues in the design of hydraulic circuits, applicable to each of these categories, are as follows:

- A filter/strainer is installed before the main pump, after the tank.
- Check valves are installed before hydraulic actuator to maintain the flow direction and prevent cavitations.

### 2.4.1 Constant Flow System

As the name suggests, in a constant flow system (Figure 2.16), the volumetric flow of the system is kept constant throughout the operation. This system is usually used when constant displacement or velocity is required in the actuator; the reason being is that the volumetric flow is directly proportional to displacement and velocity. Constant volumetric flow can be obtained from a fixed pump turning at a relatively stable speed. Since the speed of the pump is independent of the load, the input power is proportional to the pressure due to the load. Constant flow system is applied in, for example, a hydraulic press and conveyor.

Despite its constant volumetric flow, infrequent changes of the flow may still occur. For this purpose, a flow control valve can be employed.

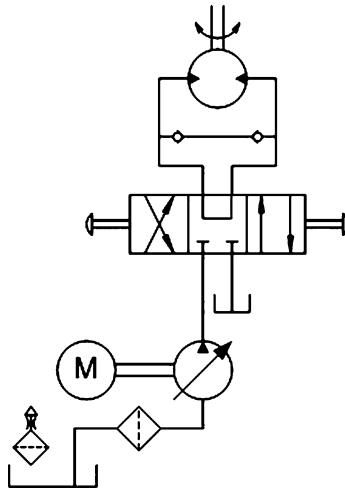


Fig. 2.17 Constant pressure system

### 2.4.2 Constant Pressure System

In a constant pressure system (Figure 2.17), the pressure of the system is kept constant throughout its operations. This system is usually used when constant force or torque is required in the actuator; the reason being is that the force is directly proportional to pressure. To allow the pressure to be kept constant, the volumetric flow from the pump has to be variable; thus a variable pump is usually employed in this system. A pressure-compensated variable pump is the typical pump used for a constant pressure system. This system is applied in, for example, unloading machine.

When the dynamic response becomes an important issue, a fixed pump can be used instead of a variable pump. The variation of the volumetric flow is then executed by a pressure relief valve.

### 2.4.3 Constant Power System

A constant power system (Figure 2.18) transmits constant power throughout the operations of the system, regardless of changes in the load. This requirement is achieved by a fixed displacement pump and a pressure relief valve, working in tandem with a variable displacement hydraulic motor. This arrangement provides constant power to the motor, while the motor adjusts its own displacement according to the requirement of the load. The constant power system is applied, for example, in a winch.

Constant power can also be achieved electrically by a constant power source (main drive), *e.g.* a storage battery providing a constant power. An increase in the load, for example, will increase the current and decrease the voltage, keeping the power constant.





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