4

Control valves

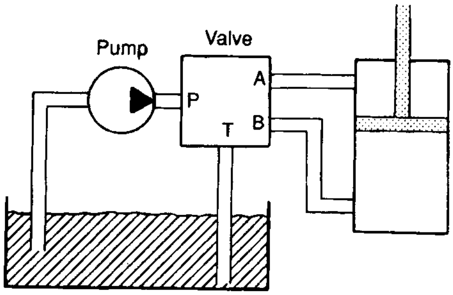
Pneumatic and hydraulic systems require control valves to direct and regulate the flow of fluid from compressor or pump to the various load devices. Although there are significant practical differences between pneumatic and hydraulic devices (mainly arising from differences in operating pressures and types of seals needed for gas or liquid) the operating principles and descriptions are very similar.

Although valves are used for many purposes, there are essentially only two types of valve. An infinite position valve can take up any position between open and closed and, consequently, can be used to modulate flow or pressure. Relief valves described in earlier chapters are simple infinite position valves.

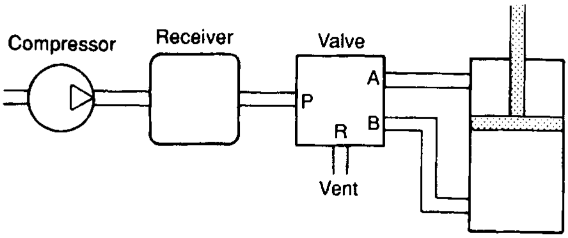
Most control valves, however, are only used to allow or block flow of fluid. Such valves are called finite position valves. An analogy between the two types of valve is the comparison between an electric light dimmer and a simple on/off switch. Connections to a valve are termed 'ports'. A simple on/off valve therefore has two ports. Most control valves, however, have four ports shown in hydraulic and pneumatic forms in Figure 4.1.

In both the load is connected to ports labelled A, B and the pressure supply (from pump or compressor) to port P. In the hydraulic valve, fluid is returned to the tank from port T. In the pneumatic valve return air is vented from port R.

Figure 4.2 shows internal operation of valves. To extend the ram, ports P and B are connected to deliver fluid and ports A and T connected to return fluid. To retract the ram, ports P and A are connected to deliver fluid and ports B and T to return fluid.



(a) Hydraulic system



(b) Pneumatic system

Figure 4.1 *Valves in a pneumatic and hydraulic system*

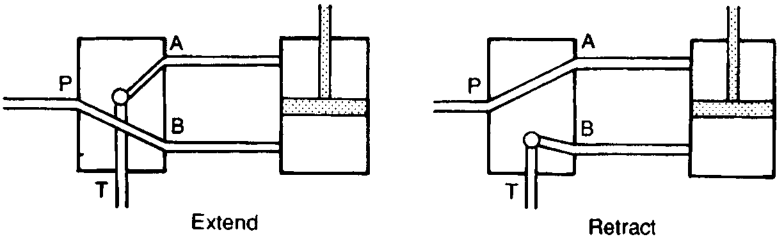


Figure 4.2 *Internal valve operation*

Another consideration is the number of control positions. Figure 4.3 shows two possible control schemes. In Figure 4.3a, the ram is controlled by a lever with two positions; extend or retract. This valve has two control positions (and the ram simply drives to one end or other of its stroke). The valve in Figure 4.3b has three positions; extend, off, retract. Not surprisingly the valve in Figure 4.3a is called a two position valve, while that in Figure 4.3b is a three position valve.

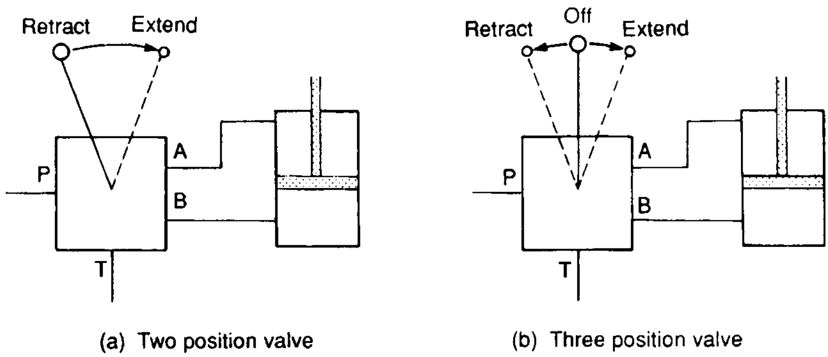


Figure 4.3 *Valve control positions*

Finite position valves are commonly described as a port/position valve where *port* is the number of ports and *position* is the number of positions. Figure 4.3a therefore illustrates a 4/2 valve, and Figure 4.3b shows a 4/3 valve. A simple block/allow valve is a 2/2 valve.

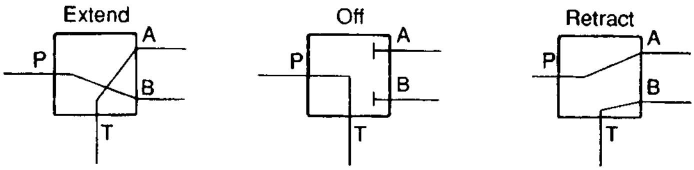


Figure 4.4 *Possible valve action for a 4/3 valve*

The numbers of ports and positions does not, however, completely describe the valve. We must also describe its action. Figure 4.4 shows one possible action for the 4/3 valve of Figure 4.3b. Extend and retract connections are similar, but in the off position ports P and T are connected–unloading the pump back to the tank without need of a separate loading valve, while leaving the ram locked in position. (This approach could, of course, only be used where the pump supplies one load). Other possible arrangements may block all four ports in the off position (to maintain pressure), or connect ports A, B and T (to leave the ram free in the off position). A complete valve description thus needs number of ports, number of positions *and* the control action.

Graphic symbols

Simple valve symbols have been used so far to describe control actions. From the discussions in the previous section it can be seen that control actions can easily become too complex for representation by sketches showing how a valve is constructed.

A set of graphic symbols has therefore evolved (similar, in principle, to symbols used on electrical circuit diagrams). These show component function without showing the physical construction of each device. A 3/2 spool valve and a 3/2 rotary valve with the same function have the same symbol; despite their totally different constructions.

Symbols are described in various national documents; DIN24300, BS2917, ISO1219 and the new ISO5599, CETOP RP3 plus the original American JIC and ANSI symbols. Differences between these are minor.

A valve is represented by a square for each of its switching positions. Figure 4.5a thus shows the symbol of a two position valve, and Figure 4.5b a three position valve. Valve positions can be represented by letters a, b, c and so on, with 0 being used for a central neutral position.

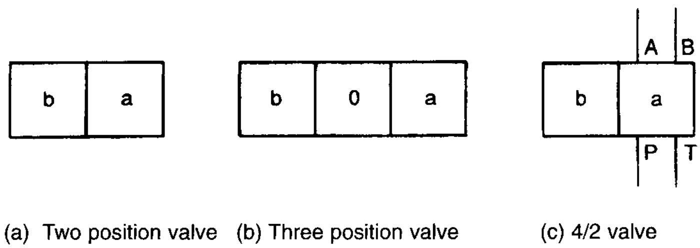


Figure 4.5 *Basis of graphic symbols*

Ports of a valve are shown on the outside of boxes in normal unoperated or initial position. Four ports have been added to the two position valve symbol shown in Figure 4.5c. Designations given to ports are normally:

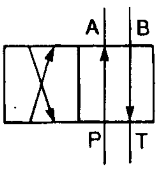
Port	Designation
Working lines	A, B, C and so on
Pressure (power) supply	P
Exhaust/Return	R, S, T and so on (T normally used for hydraulic systems, R and S for pneumatic systems)
Control (Pilot) Lines	Z, Y, X and so on

ISO 5599 proposes to replace these letters with numbers, a retrograde step in the author's opinion.

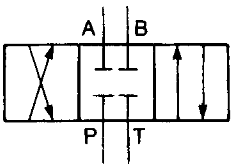
Arrow-headed lines represent direction of flow. In Figure 4.6a, for example fluid is delivered from port P to port A and returned from port B to port T when the valve is in its normal state a. In state b, flow is reversed. This valve symbol corresponds to the valve represented in Figures 4.2 and 4.3a.

Shut off positions are represented by **T**, as shown by the central position of the valve in Figure 4.6b, and internal flow paths can be represented as shown in Figure 4.6c. This latter valve, incidentally, vents the load in the off position.

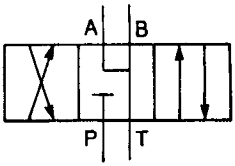
In pneumatic systems, lines commonly vent to atmosphere directly at the valve, as shown by port R in Figure 4.6d.



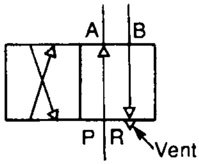
(a) 4/2 valve



(b) 4/3 valve centre off (load isolated)



(c) 4/3 valve, load free in centre

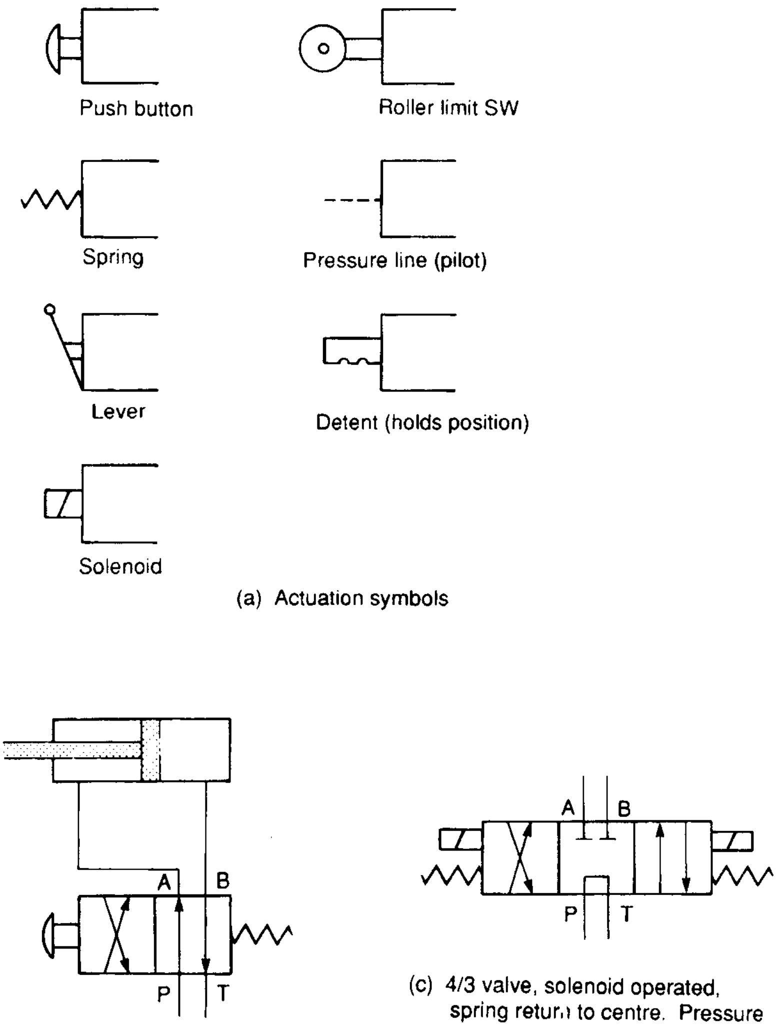


(d) Pneumatic valve with vent (pneumatic valves often represented with unshaded arrowheads)

Figure 4.6 *Valve symbols*

Figure 4.7a shows symbols for the various ways in which valves can be operated. Figure 4.7b thus represents a 4/2 valve operated by a pushbutton. With the pushbutton depressed the ram extends. With the pushbutton released, the spring pushes the valve to position a and the ram retracts.

Actuation symbols can be combined. Figure 4.7c represents a solenoid-operated 4/3 valve, with spring return to centre.



(a) Actuation symbols

(b) Pushbutton extend, spring retract when pushbutton released

(c) 4/3 valve, solenoid operated, spring return to centre. Pressure line unloads to tank and load locked in centre position

Figure 4.7 *Complete valve symbols*

Infinite position valve symbols are shown in Figure 4.8. A basic valve is represented by a single square as shown in Figure 4.8a, with the valve being shown in a normal, or non-operated, position. Control is shown by normal actuation symbols: in Figure 4.8b, for example, the spring pushes the valve right decreasing flow, and pilot pressure pushes the valve left increasing flow. This represents a pressure relief valve which would be connected into a hydraulic system as shown in Figure 4.8c.

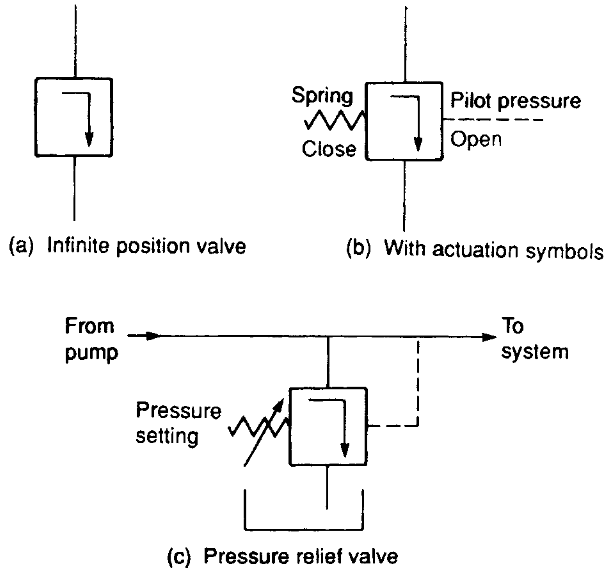


Figure 4.8 *Infinite position valve symbols*

Types of control valve

There are essentially three types of control valve; poppet valves spool valves and rotary valves.

Poppet valves

In a poppet valve, simple discs, cones or balls are used in conjunction with simple valve seats to control flow. Figure 4.9 shows the construction and symbol of a simple 2/2 normally-closed valve, where depression of the pushbutton lifts the ball off its seat and

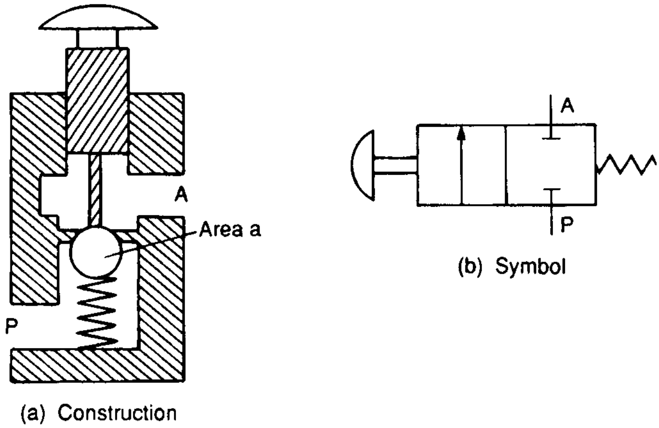


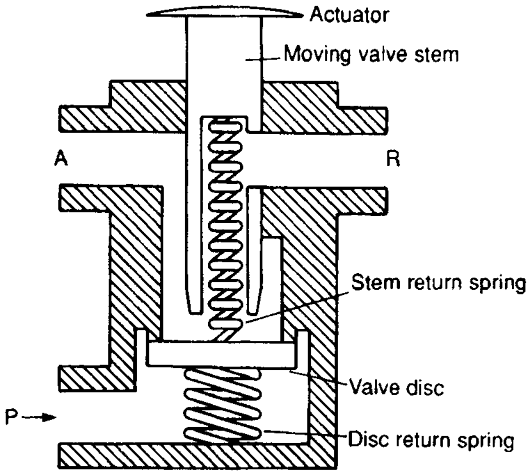
Figure 4.9 *Simple 2/2 poppet valve*

allows fluid to flow from port P to port A. When the button is released, spring and fluid pressure force the ball up again closing the valve.

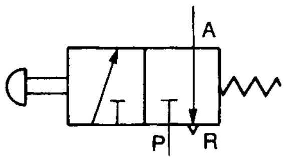
Figure 4.10 shows the construction and symbol of a disc seal 3/2 poppet. With the pushbutton released, ports A and R are linked via the hollow pushbutton stem. If the pushbutton is pressed, port R is first sealed, then the valve disc pushed down to open the valve and connect ports P and A. As before, spring and fluid pressure from port P closes the valve.

The valve construction and symbol shown in Figure 4.11 is a poppet changeover 4/2 valve using two stems and disc valves. With the pushbutton released, ports A and R are linked via the hollow left-hand stem and ports P and B linked via the normally-open right hand disc valve. When the pushbutton is pressed, the link between ports A and R is first closed, then the link between P and B closed. The link between A and P is next opened, and finally the link between B and R opened. When the pushbutton is released, air and spring pressure puts the valve back to its original state.

Poppet valves are simple, cheap and robust, but it is generally simpler to manufacture valves more complicated than those shown in Figure 4.11 by using spool valves. Further, a major disadvantage of poppet valves is the force needed to operate them. In the poppet valve of Figure 4.10, for example, the force required on the push-button to operate the valve is $P \times a$ newtons. Large capacity valves need large valve areas, leading to large operating force. The high pressure in hydraulic systems thus tends to prevent use of simple



(a) Construction



(b) Symbol

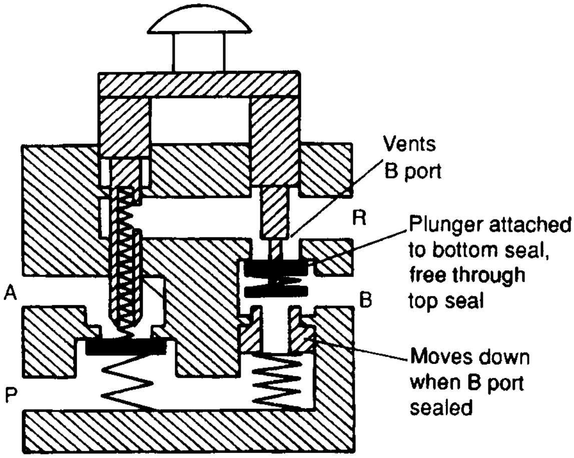
Figure 4.10 *A 3/2 poppet valve*

poppet valves and they are, therefore, mainly found in low pressure pneumatic systems.

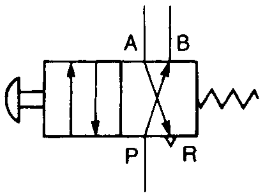
Spool valves

Spool (or slide) valves are constructed with a spool moving horizontally within the valve body, as shown for the 4/2 valve in Figure 4.12. Raised areas called 'lands' block or open ports to give the required operation.

The operation of a spool valve is generally balanced. In the valve construction in Figure 4.12b, for example, pressure is applied to opposing faces D and E and low tank pressure to faces F and G. There is no net force on the spool from system pressure, allowing the spool to be easily moved.

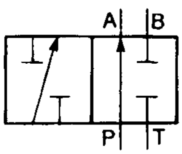


(a) Construction

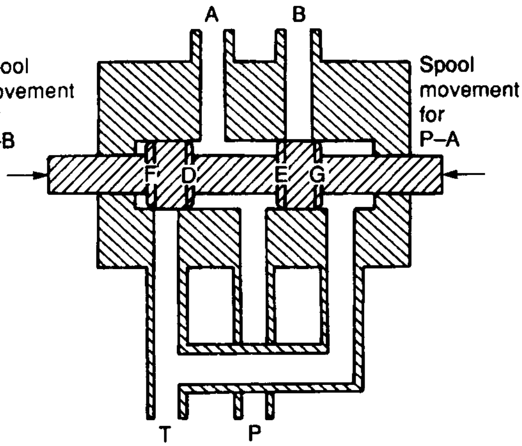


(b) Symbol

Figure 4.11 *A 4/2 poppet valve*

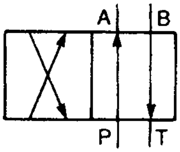


(a) Symbol

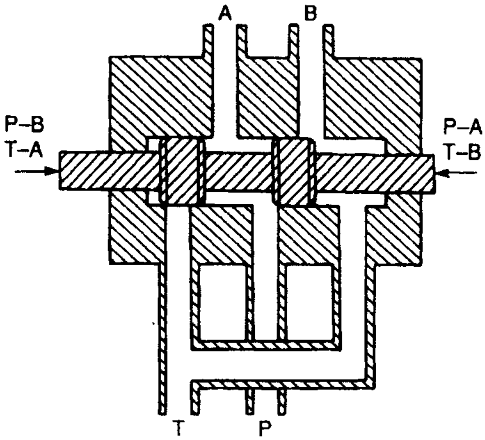


(b) Construction

Figure 4.12 *Two-way spool valve*



(a) Symbol



(b) Construction

Figure 4.13 *Four-way spool valve*

Figure 4.13 is a changeover 4/2 spool valve. Comparison of the valves shown in Figures 4.12 and 4.13 shows they have the same body construction, the only difference being the size and position of lands on the spool. This is a major cost-saving advantage of spool valves; different operations can be achieved with a common body and different spools. This obviously reduces manufacturing costs.

Figure 4.14 shows various forms of three position changeover valves; note, again, these use one body with different functions achieved by different land patterns.

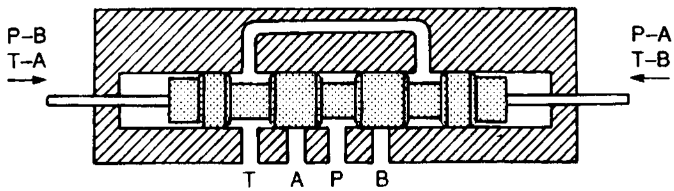
Spool valves are operated by shifting the spool. This can be achieved by button, lever or striker, or remotely with a solenoid. Self-centring can easily be provided if springs are mounted at the end of the spool shaft.

Solenoid-operated valves commonly work at 24 V DC or 110 V AC. Each has its own advantages and disadvantages. A DC power supply has to be provided for 24 V DC solenoids, which, in large systems, is substantial and costly. Operating current of a 24 V solenoid is higher than a 110 V solenoid's. Care must be taken with plant cabling to avoid voltage drops on return legs if a common single line return is used.

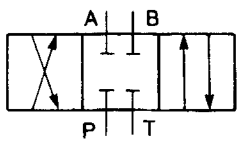
Current through a DC solenoid is set by the winding resistance. Current in an AC solenoid, on the other hand, is set by the inductance of the windings, and this is usually designed to give a high inrush current followed by low holding current. This is achieved by using the core of the solenoid (linked to the spool) to raise the coil inductance when the spool has moved. One side effect of this is that a jammed spool results in a permanent high current which can damage the coil or the device driving it. Each and every AC solenoid should be protected by an individual fuse. DC solenoids do not suffer from this characteristic. A burned out DC solenoid coil is almost unknown.

Whatever form of solenoid is used it is very useful when fault finding to have local electrical indication built into the solenoid plug top. This allows a fault to be quickly identified as either an electrical or hydraulic problem. Fault finding is discussed further in Chapter 8.

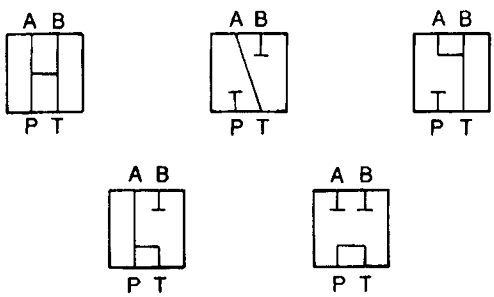
A solenoid can exert a pull or push of about 5 to 10 kg. This is adequate for most pneumatic spool valves, but is too low for direct operation of large capacity hydraulic valves. Here pilot operation must be used, a topic discussed later.



(a) Construction of centre off valve



(b) Symbol



(c) Common centre position connections

Figure 4.14 *Three position four-way valves*

Rotary valves

Rotary valves consist of a rotating spool which aligns with holes in the valve casing to give the required operation. Figure 4.15 shows the construction and symbol of a typical valve with centre off action.

Rotary valves are compact, simple and have low operating forces. They are, however, low pressure devices and are consequently mainly used for hand operation in pneumatic systems.

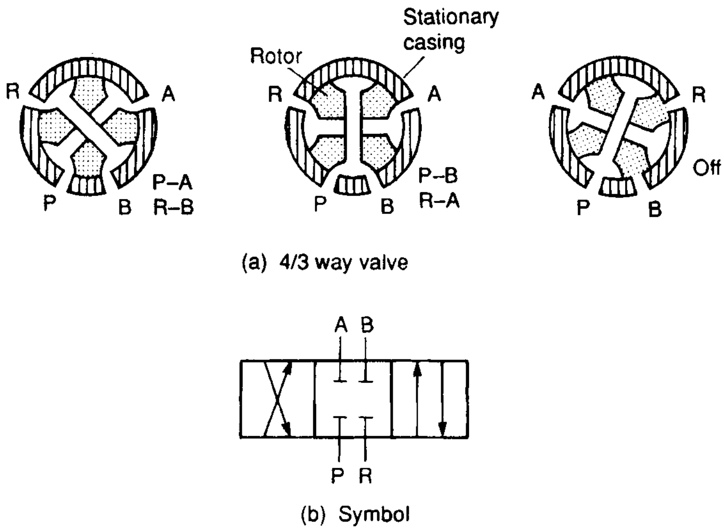


Figure 4.15 *Rotary valve*

Pilot-operated valves

With large capacity pneumatic valves (particularly poppet valves) and most hydraulic valves, the operating force required to move the valve can be large. If the required force is too large for a solenoid or manual operation, a two-stage process called pilot operation is used.

The principle is shown in Figure 4.16. Valve 1 is the main operating valve used to move a ram. The operating force required to move the valve, however, is too large for direct operation by a solenoid, so a second smaller valve 2, known as the pilot valve, has been added to allow the main valve to be operated

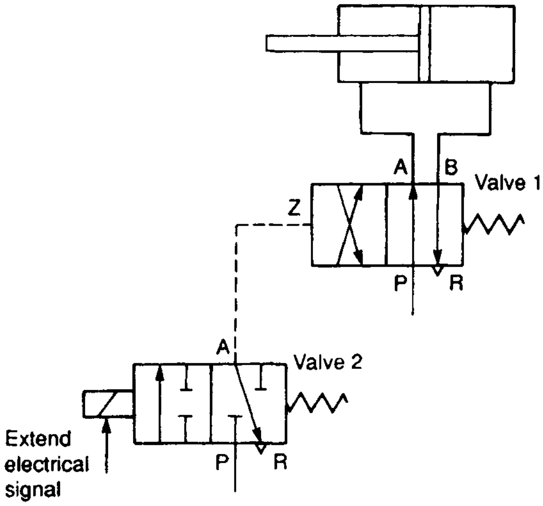


Figure 4.16 *Pilot-operated valve*

by system pressure. Pilot pressure lines are normally shown dotted in circuit diagrams, and pilot ports on main valves are denoted Z, Y, X and so on.

In Figure 4 16, pilot port Z is depressurised with the solenoid de-energised, and the ram is retracted. When the solenoid is energised valve 2 changes over, pressurising Z; causing valve 1 to energise and the ram to extend.

Although pilot operation can be achieved with separate valves it is more usual to use a pilot/main valve assembly manufactured as a complete ready made unit. Figure 4.17 shows the operation of a pilot-operated 3/2 pneumatic valve. The solenoid operates the small pilot valve directly. Because this valve has a small area, a low operating force is required. The pilot valve applies line pressure to the top of the control valve causing it to move down, closing the exhaust port. When it contacts the main valve disc there are two forces acting on the valve stem. The pilot valve applies a downwards force of P × D, where P is the line pressure and D is the area of the control valve. Line pressure also applies an upwards force P × E to the stem, where E is the area of the main valve. The area of the control valve, D, is greater than area of the main valve E, so the downwards force is the larger and the valve opens.

When the solenoid de-energises, the space above the control valve is vented. Line and spring pressure on the main valve causes the valve stem to rise again, venting port A.

A hydraulic 4/2 pilot-operated spool valve is shown in Figure 4.18. The ends of the pilot spool in most hydraulic pilot-operated valves are visible from outside the valve. This is useful from a maintenance viewpoint as it allows the operation of a valve to be checked. In extreme cases the valve can be checked by pushing the pilot spool directly with a suitably sized rod (welding rod is ideal!). Care must be taken to check solenoid states on dual solenoid valves before attempting manual operation. Overriding an energised AC solenoid creates a large current which may damage the coil, (or blow the fuse if the solenoid has correctly installed protection).

Check valves

Check valves only allow flow in one direction and, as such, are similar in operation to electronic diodes. The simplest construction is the ball and seat arrangement of the valve in Figure 4.19a, commonly used in pneumatic systems. The right angle construction in Figure 4.19b is better suited to the higher pressures of a hydraulic

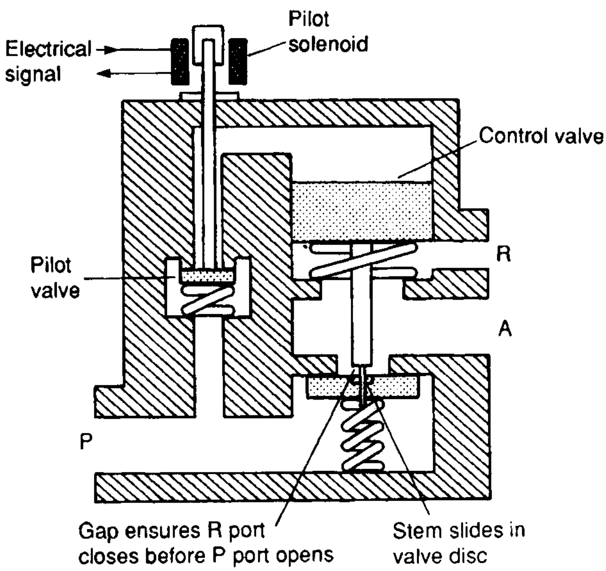
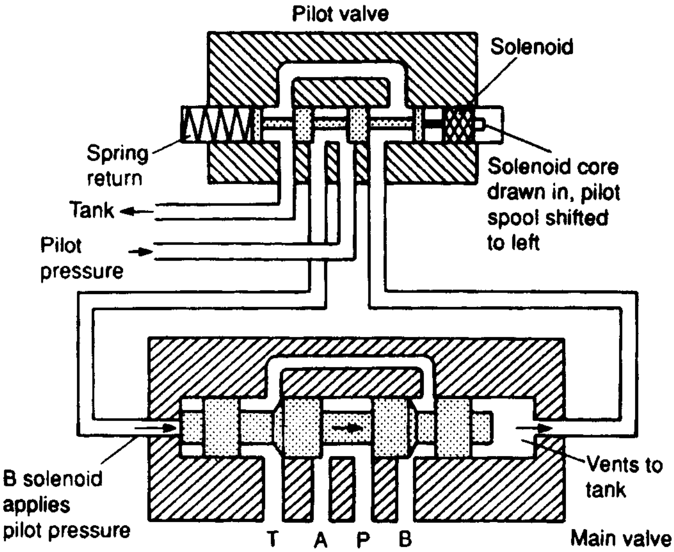
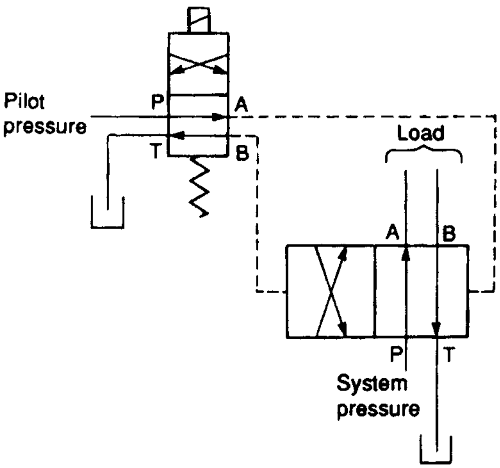


Figure 4.17 *Construction of a pilot-operated 3/2 valve*



(a) Construction: power applied to solenoid has moved pilot spool to left. This applies pilot pressure to left hand end of main spool, shifting spool to right and connecting P & B ports



(b) Symbol

Figure 4.18 *Pilot-operated valve*

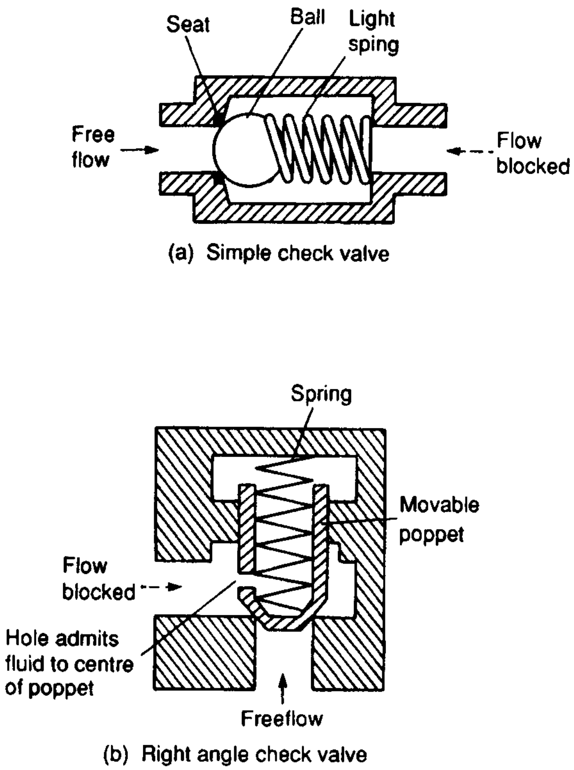


Figure 4.19 *Check valves*

system. Free flow direction is normally marked with an arrow on the valve casing.

A check valve is represented by the graphic symbols in Figure 4.20. The symbol in Figure 4.20a is rather complex and the simpler symbol in Figure 4.20b is more commonly used.

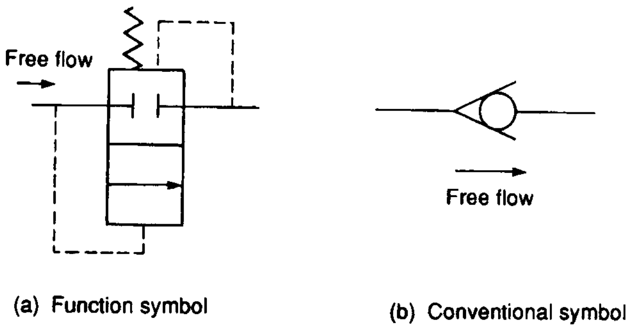


Figure 4.20 *Check valve symbols*

Figure 4.21 illustrates several common applications of check valves. Figure 4.21a shows a combination pump, used where an application requires large volume and low pressure, or low volume and high pressure. A typical case is a clamp required to engage quickly (high volume and low pressure) then grip (minimal volume but high pressure). Pump 1 is the high volume and low pressure pump, and pump 2 the high pressure pump. In high volume mode both pumps deliver to the system, pump 1 delivering through the check valve V_3. When high pressure is required, line pressure at X rises operating unloading valve V_1 via pilot port Z taking pump 1 off load. Pump 2 delivers the required pressure set by relief valve V_2, with the check valve preventing fluid leaking back to pump 1 and V_1.

Figure 4.21b shows a hydraulic circuit with a pressure storage device called an accumulator (described in a later chapter). Here a check valve allows the pump to unload via the pressure regulating valve, while still maintaining system pressure from the accumulator.

A spring-operated check valve requires a small pressure to open (called the cracking pressure) and acts to some extent like a low pressure relief valve. This characteristic can be used to advantage. In Figure 4.21c pilot pressure is derived before a check valve, and in Figure 4.21d a check valve is used to protect a blocked filter by diverting flow around the filter when pressure rises. A check valve is also included in the tank return to prevent fluid being sucked out of the tank when the pump is turned off.

Pilot-operated check valves

The cylinder in the system in Figure 4.22 should, theoretically, hold position when the control valve is in its centre, off, position. In practice, the cylinder will tend to creep because of leakage in the control valve.

Check valves have excellent sealage in the closed position, but a simple check valve cannot be used in the system in Figure 4.22 because flow is required in both directions. A pilot-operated check is similar to a basic check valve but can be held open permanently by application of an external pilot pressure signal.

There are two basic forms of pilot-operated check valves, shown in Figure 4.23. They operate in a similar manner to basic check valves, but with pilot pressure directly opening the valves. In the 4C valve shown in Figure 4.23a, inlet pressure assists the pilot. The

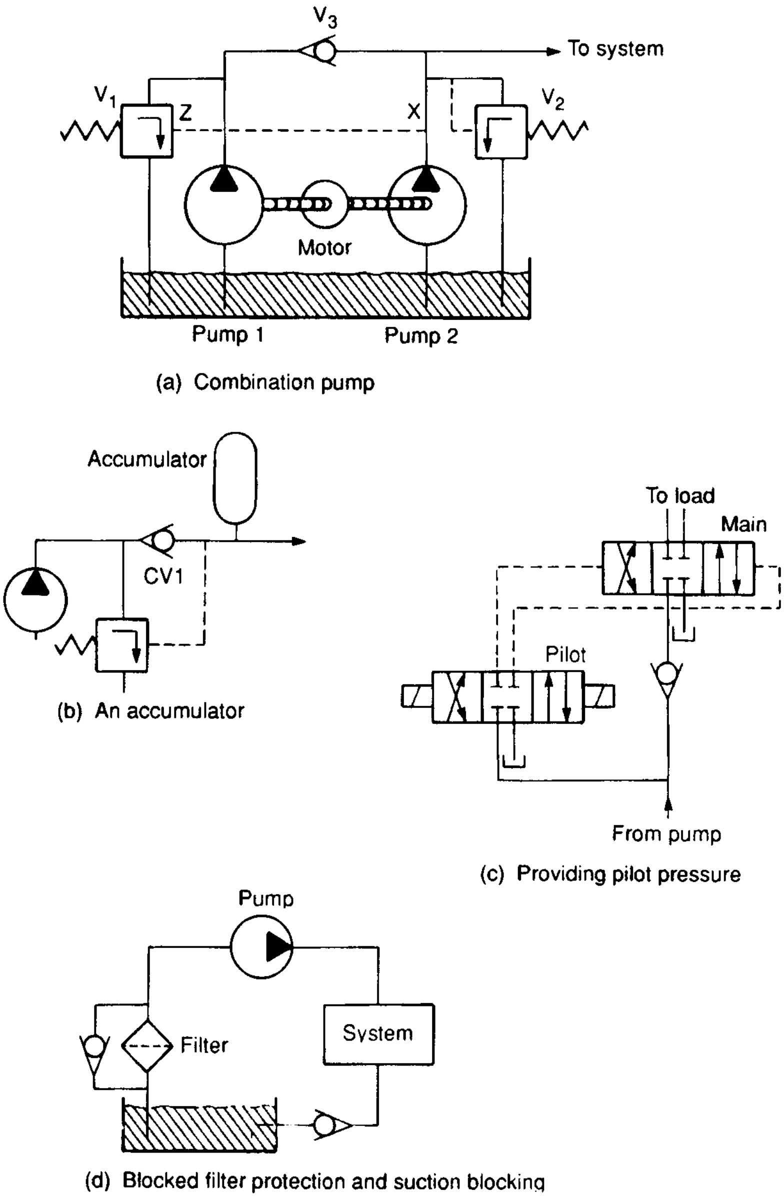


Figure 4.21 *Check valve applications*

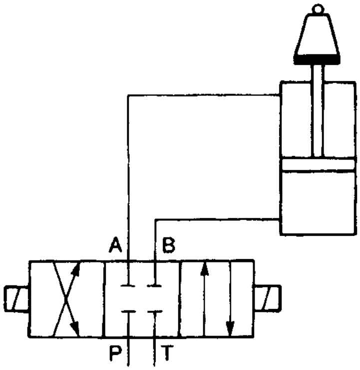


Figure 4.22 *System requiring a check valve. In the off position the load 'creeps'*

symbol of a pilot-operated check valve is shown in Figure 4.23c.

The cylinder application of Figure 4.22 is redrawn with pilot-operated check valves in Figure 4.23d. The pilot lines are connected to the pressure line feeding the other side of the cylinder. For any cylinder movement, one check valve is held open by flow (operating as a normal check valve) and the other is held open by pilot pressure. For no required movement, both check valves are closed and the cylinder is locked in position.

Restriction check valves

The speed of a hydraulic or pneumatic actuator can be controlled by adjusting the rate at which a fluid is admitted to, or allowed out from, a device. This topic is discussed in more detail in Chapter 5 but a speed control is often required to be direction-sensitive and this requires the inclusion of a check valve.

A restriction check valve (often called a throttle relief valve in pneumatics) allows full flow in one direction and a reduced flow in the other direction. Figure 4.24a shows a simple hydraulic valve and Figure 4.24b a pneumatic valve. In both, a needle valve sets restricted flow to the required valve. The symbol of a restriction check valve is shown in Figure 4.24c.

Figure 4.24d shows a typical application in which the cylinder extends at full speed until a limit switch makes, then extend further at low speed. Retraction is at full speed.

A restriction check valve V_2 is fitted in one leg of the cylinder. With the cylinder retracted, limit-operated valve V_3 is open allowing free flow of fluid from the cylinder as it extends. When the striker plate on the cylinder ram hits the limit, valve V_3 closes and flow out of the cylinder is now restricted by the needle valve setting of valve V_2. In the reverse direction, the check valve on valve V_2 opens giving full speed of retraction.

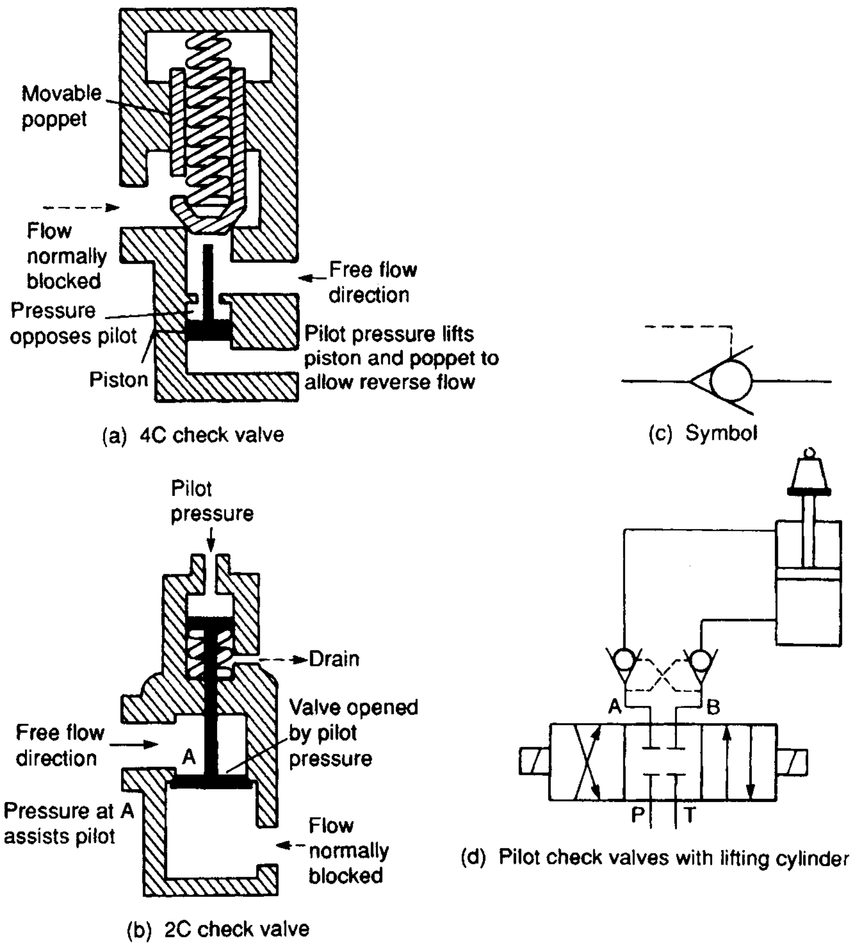


Figure 4.23 *Pilot-operated check valves*

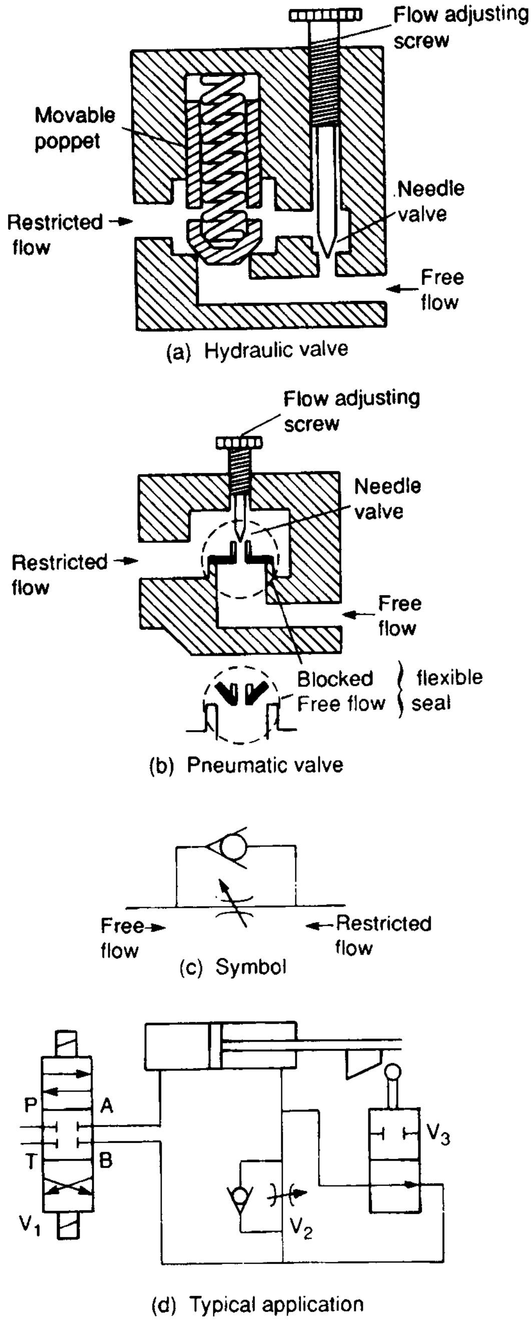


Figure 4.24 *Restriction check valve*

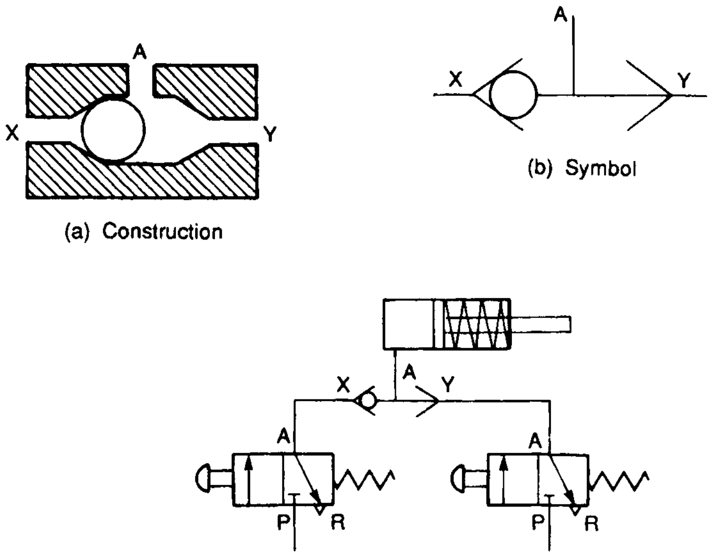
Shuttle and fast exhaust valves

A shuttle valve, also known as a double check valve, allows pressure in a line to be obtained from alternative sources. It is primarily a pneumatic device and is rarely found in hydraulic circuits.

Construction is very simple and consists of a ball inside a cylinder, as shown in Figure 4.25a. If pressure is applied to port X, the ball is blown to the right blocking port Y and linking ports X and A. Similarly, pressure to port Y alone connects ports Y and A and blocks port X. The symbol of a shuttle valve is given in Figure 4.25b.

A typical application is given in Figure 4.25c, where a spring return cylinder is operated from either of two manual stations. Isolation between the two stations is provided by the shuttle valve. Note a simple T-connection cannot be used as each valve has its A port vented to the exhaust port.

A fast exhaust valve (Figure 4.26) is used to vent cylinders quickly. It is primarily used with spring return (single-acting) pneumatic cylinders. The device shown in Figure 4.26a consists of a movable disc which allows port A to be connected to



(a) Construction

(b) Symbol

(c) Typical application

Figure 4.25 *Pneumatic shuttle valve*

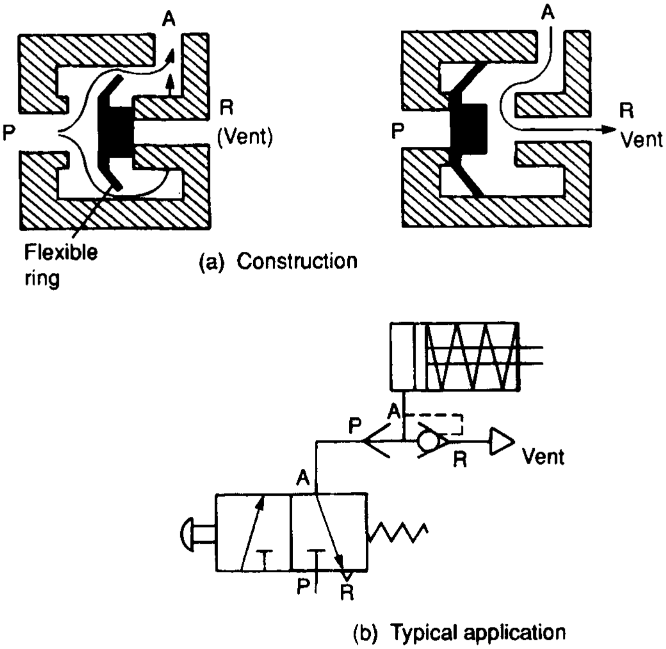


Figure 4.26 *Fast exhaust valve*

pressure port P or large exhaust port R. It acts like, and has the same symbol as, a shuttle valve. A typical application is shown in Figure 4.26b.

Fast exhaust valves are usually mounted local to, or directly onto, cylinders and speed up response by avoiding any delay from return pipes and control valves. They also permit simpler control valves to be used.

Sequence valves

The sequence valve is a close relative of the pressure relief valve and is used where a set of operations are to be controlled in a pressure related sequence. Figure 4.27 shows a typical example where a workpiece is pushed into position by cylinder 1 and clamped by cylinder 2.

Sequence valve V_2 is connected to the extend line of cylinder 1. When this cylinder is moving the workpiece, the line pressure is low, but rises once the workpiece hits the end stop. The sequence valve opens once its inlet pressure rises above a preset level.

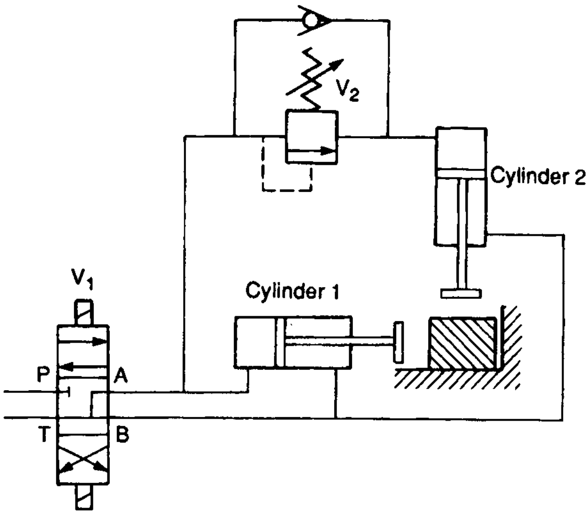


Figure 4.27 *Sequence valve*

Cylinder 2 then operates to clamp the workpiece. A check valve across V_2 allows both cylinders to retract together.

Time delay valves

Pneumatic time delay valves (Figure 4.28) are used to delay operations where time-based sequences are required. Figure 4.28a shows construction of a typical valve. This is similar in construction to a 3/2 way pilot-operated valve, but the space above the main valve is comparatively large and pilot air is only allowed in via a flow-reducing needle valve. There is thus a time delay between application of pilot pressure to port Z and the valve operation, as shown by the timing diagram in Figure 4.28b. The time delay is adjusted by the needle valve setting.

The built-in check valve causes the reservoir space above the valve to vent quickly when pressure at Z is removed to give no delay off.

The valve shown in Figure 4.28 is a normally-closed delay-on valve. Many other time delay valves (delay-off, delay on/off, normally-open) can be obtained. All use the basic principle of the air reservoir and needle valve.

The symbol of a normally-dosed time delay valve is shown in Figure 4.28c.

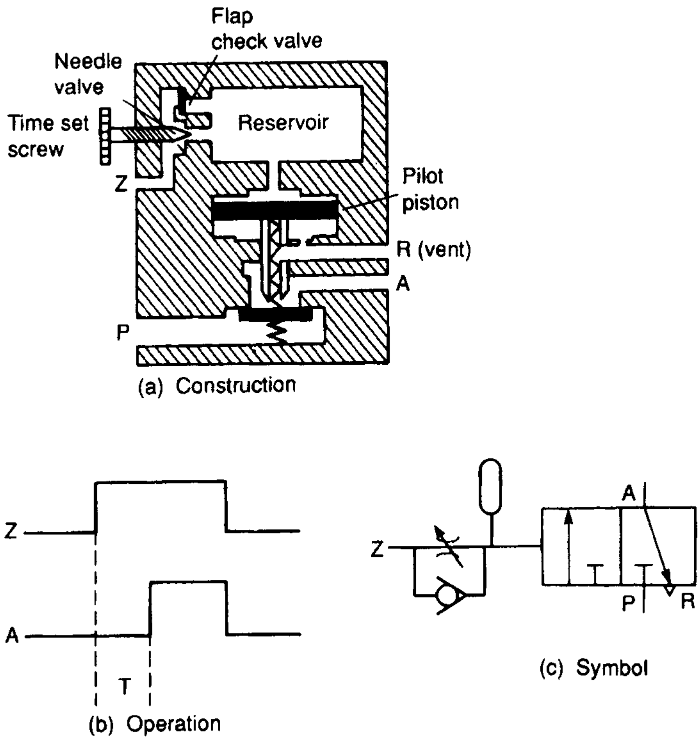


Figure 4.28 *Pneumatic time delay valve*

Proportional Valves

The solenoid valves described so far act, to some extent, like an electrical switch, i.e. they can be On or Off. In many applications it is required to remotely control speed, pressure or force via an electrical signal. This function is provided by proportional valves.

A typical two position solenoid is only required to move the spool between 0 and 100% stroke against the restoring force of a spring. To ensure predictable movement between the end positions the solenoid must also increase its force as the spool moves to ensure the solenoid force is larger than the increasing opposing spring force at all positions.

A proportional valve has a different design requirement. The spool position can be set anywhere between 0% and 100% stroke by varying the solenoid current. To give a predictable response the solenoid must produce a force which is dependent solely on the

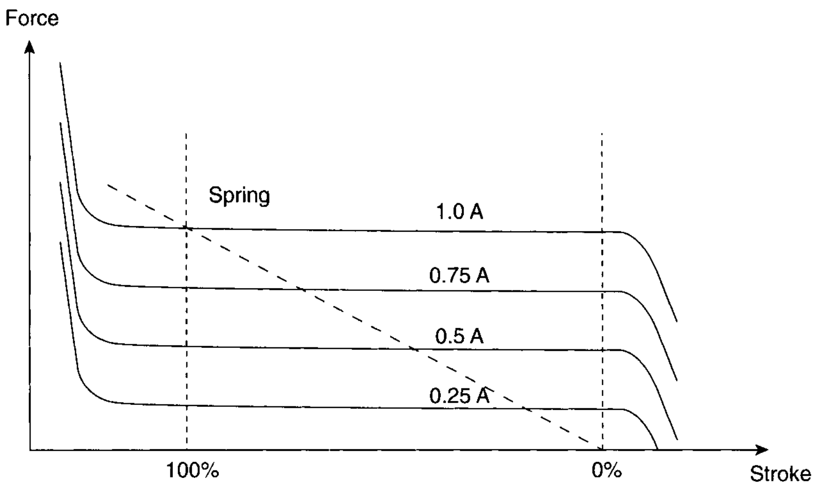


Figure 4.29 *The relationship between coil current force and stroke for a proportional valve solenoid. Note the flat part of the curve and the linear relationship between current and force*

current and not on the spool position, i.e. the force for a given current must be constant over the full stroke range. Furthermore, the force must be proportional to the current.

Figure 4.29 shows a typical response. The force from the solenoid is opposed by the force from a restoring spring, and the spool will move to a position where the two forces are equal. With a current of 0.75 A, for example, the spool will move to 75% of its stroke.

The spool movement in a proportional valve is small; a few mm stroke is typical. The valves are therefore very vulnerable to stiction, and this is reduced by using a 'wet' design which immerses the solenoid and its core in hydraulic fluid.

A proportional valve should produce a fluid flow which is proportional to the spool displacement. The spools therefore use four triangular metering notches in the spool lands as shown on Figure 4.30. As the spool is moved to the right, port A will progressively link to the tank and port B to the pressure line.

The symbol for this valve is also shown. Proportional valves are drawn with parallel lines on the connection sides of the valve block on circuit diagrams.

Figure 4.30 gives equal flow rates to both A and B ports. Cylinders have different areas on the full bore and annulus sides

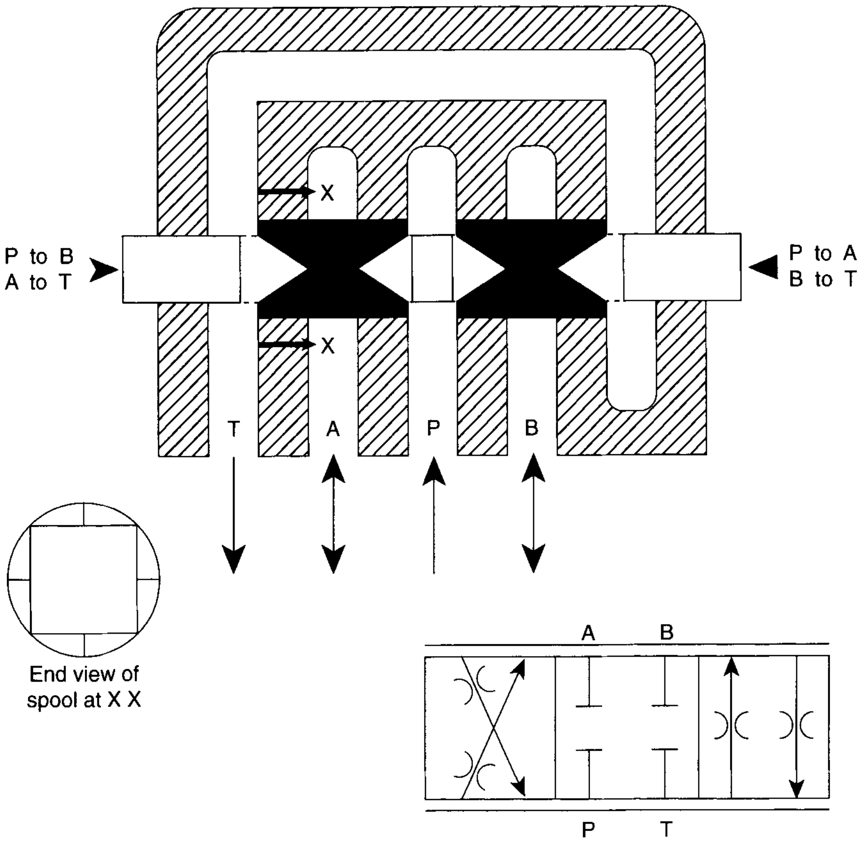


Figure 4.30 *Construction and symbol for a proportional valve. When used with a cylinder with 2:1 full bore to annulus area ratio, half the V cutouts will be provided on one of the P lands*

(see Figure 5.4). To achieve equal speeds in both directions, the notches on the lands must have different areas. With a 2:1 cylinder ratio, half the number of notches are used on one side.

Figure 4.31 shows the construction and symbol for a restricted centre position valve. Here the extended notches provide a restricted (typically 3%) flow to tank from the A and B ports when the valve is in the centre position.

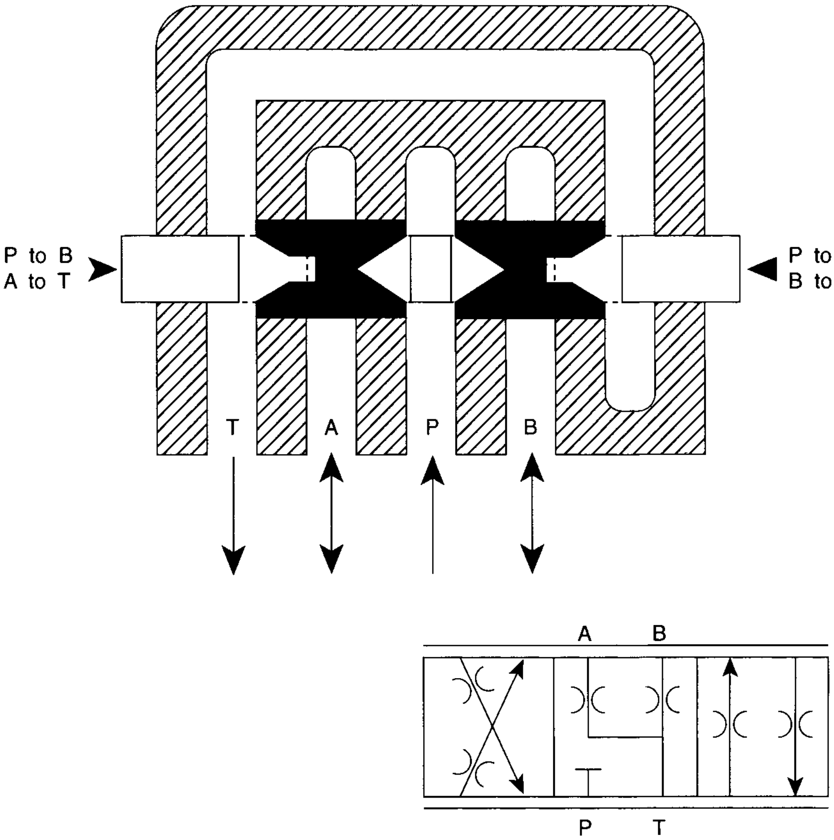


Figure 4.31 *Construction and symbol for a proportional valve with A and B ports linked to tank in the null position*

So far we have assumed the spool position is determined by the balance between the force from the solenoid and the restoring force from a spring. Whilst this will work for simple applications, factors such as hydraulic pressure on the spool and spring ageing mean the repeatability is poor. Direct solenoid/spring balance is also not feasible with a pilot/main spool valve. What is really required is some method of position control of the spool.

To achieve this, the spool position must be measured. Most valves use a device called a Linear Variable Differential

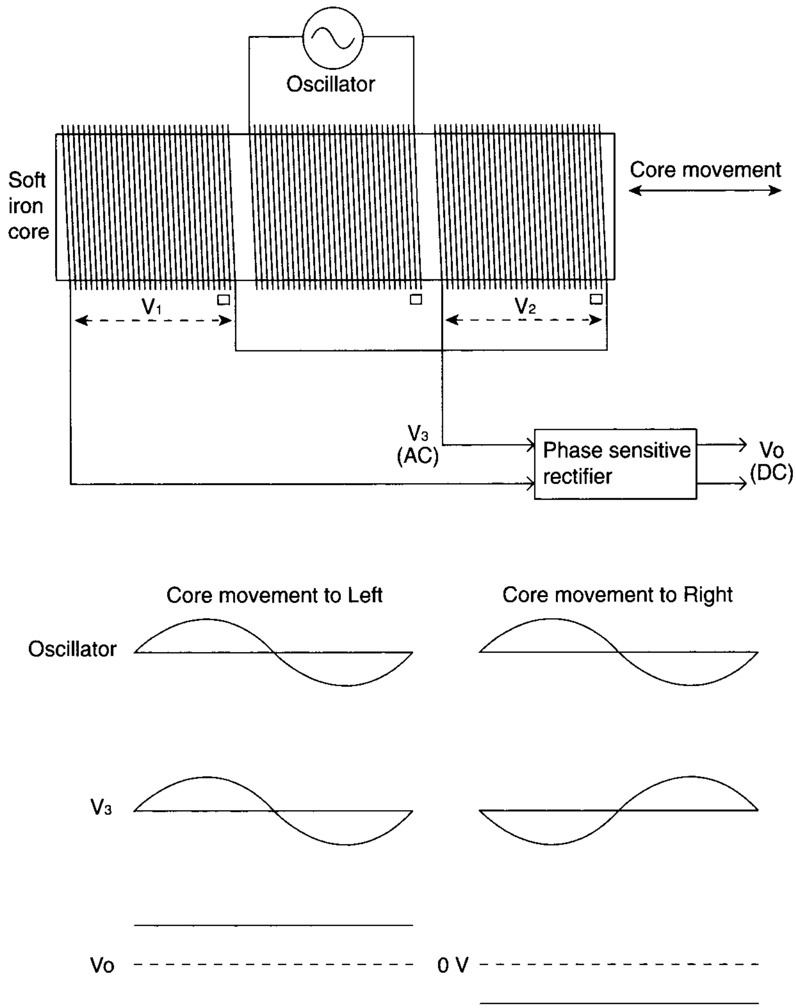


Figure 4.32 *The use of an LVDT to give position control of the valve spool. The LVDT can be connected to the pilot or main spool. (a) The circuit arrangement of the LVDT and phase sensitive rectifier. (b) Output signals for core displacement to left and right*

Transformer (or LVDT) shown on Figure 4.32a. The LVDT consists of a soft iron core whose position is to be measured surrounded by three electrical windings. A high frequency (typically a few kHz) AC signal is applied to the centre winding which induces voltages into the other two windings. When the core is central, V_1 and V_2 are equal but opposite in phase giving zero volts at V_3.

If the core moves away from the central position, to the left say, V_2 will decrease, but V_1 will remain unchanged. V_3 (which is the difference between V_1 and V_2) thus increases and is in phase with the driving oscillator signal as shown on Figure 4.32b. If the core moves to the right V_3 will also increase, but will now be anti-phase to the driving signal. The amplitude of V_3 is proportional to the distance the core moves, and the phase depends on the direction. V_3 is connected to a phase sensitive rectifier to give a bi-polar DC output signal V_0 proportional to the core displacement.

A position control system can now be achieved as Figure 4.33. The demanded and actual spool positions can be compared by a position controller, and the solenoid current increased or decreased automatically until the position error is zero. In a pilot/main valve the position feedback will be taken from the main spool

The spool position is determined by the solenoid current. A typical solenoid will operate over a range of about 0 to 1 amp. Power dissipation in the current controller is V × I watts where V is the volts drop and I the current. Maximum dissipation occurs at half current (0.5 A) which, with a typical 24 V supply, gives 12 watts. This implies substantial, bulky (and hence expensive), power transistors.

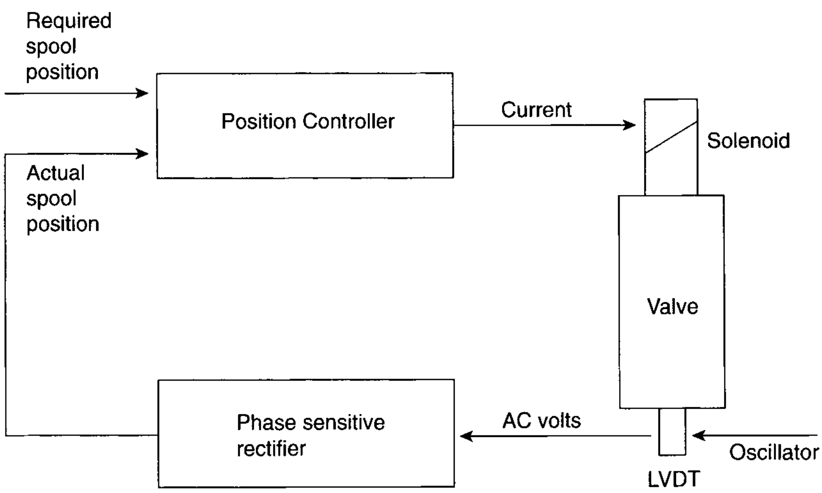


Figure 4.33 *Position of the spool in a proportional valve with an LVDT and a phase sensitive rectifier. In many systems the oscillator, LVDT and phase sensitive rectifier are now included in the valve itself*

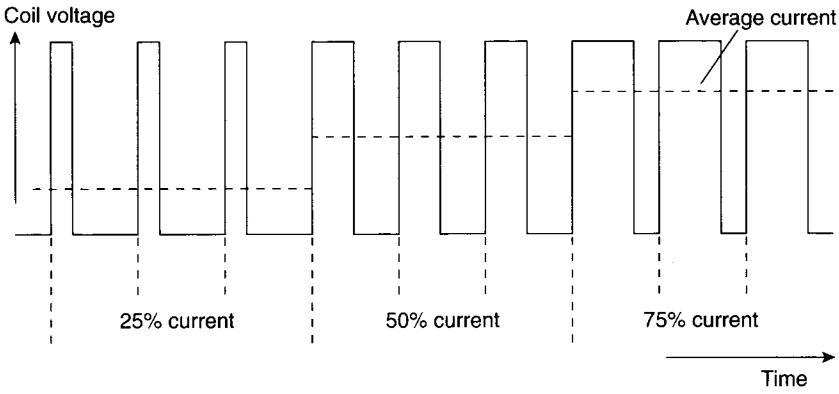


Figure 4.34 *Pulse Width Modulation (PWM) used to control solenoid current with minimal power dissipation in the output transistors*

Current control is usually performed with Pulse Width Modulation (PWM) shown in Figure 4.34. Here the current is turned rapidly On and Off with the On/Off ratio determining the mean current. The control circuit is either turned fully on (low voltage drop, high current but low dissipation) or fully off (high voltage drop, zero current, again low dissipation). Because the dissipation is low, smaller and cheaper transistors can be used.

Proportional valves operate with small forces from the solenoid and rely on small deflections of the spool. They are hence rather vulnerable to stiction which causes the valve to ignore small changes in demanded spool position. The effect is made worse if the valve spool is held in a fixed period for a period of time, allowing the spool to settle. Dirt in the oil also encourages stiction as small dirt particles will increase the probability of the spool sticking.

A high frequency (typically a few kHz), signal is therefore added to the command signal as Figure 4.35. This is too fast for the valve to follow, but the small movement prevents the spool from staying in a fixed position. This action, called Dither, is normally factory set on the electronic control card described below.

It is not possible for a proportional valve to totally shut off flow in the centre, null, position unless the spool is manufactured with a small deadband as Figure 4.36. The result is a non-linear response

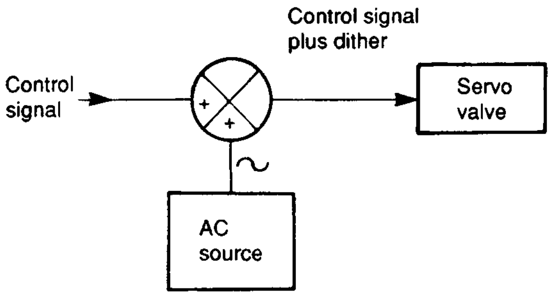


Figure 4.35 *Using dither to reduce stiction. The dither frequency and amplitude are normally a factory preset on the electronic control card*

between demanded spool position and the resultant flow. In many cases this is of no concern, but if full reversing control is required the deadband may be a problem.

Most electronic control cards thus include a deadband compensation. This adds an adjustable offset to the reference signal in each direction effectively allowing the width of the deadband region to be controlled.

Sudden changes of speed imply large accelerations which in turn imply large forces since $F = ma$ where F is the force, m is the mass

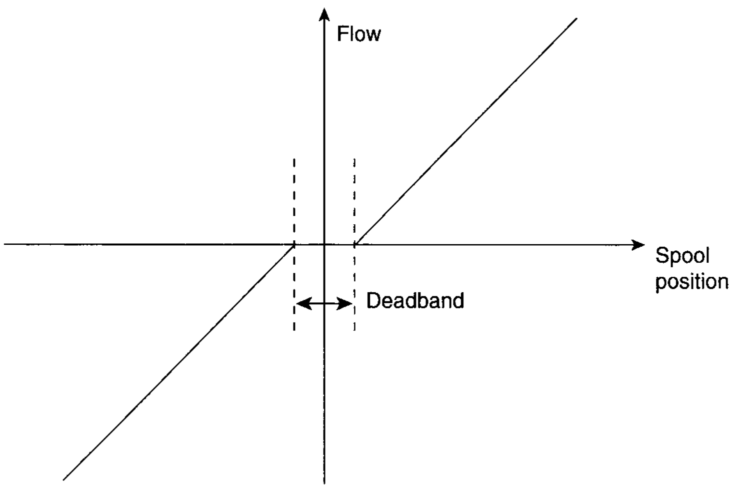


Figure 4.36 *To prevent flow in the null (centre) position most proportional valves have a small deadband as shown. This can be offset by a Deadband adjustment on the controlling card*

and a the acceleration. At best, sudden speed changes will result in noise from the system. More probably, however, the step forces will result in eventual damage and failure of piping, pumps and actuators. Most proportional valve control circuits therefore include methods by which the acceleration and deceleration can be controlled as shown on Figure 4.37a and b. Here four ramp rates, two for acceleration and two for deceleration, soften the impact of the stepped demanded input signal. These ramp rates can be pre-set, usually by trim potentiometers on the electronic control card described below.

Figure 4.37 allows independent adjustment of acceleration and deceleration in all four quadrants (A,B,C and D). In simpler, (and hence cheaper), arrangements there may be two adjustable ramp rates for acceleration and deceleration (i.e. A and D are equal and B and C are equal), or two ramp rates according to slope sign (i.e. A and C are equal and B and D are equal). In the simplest case there is only a single adjustable ramp rate (i.e. A, B, C and D are all equal).

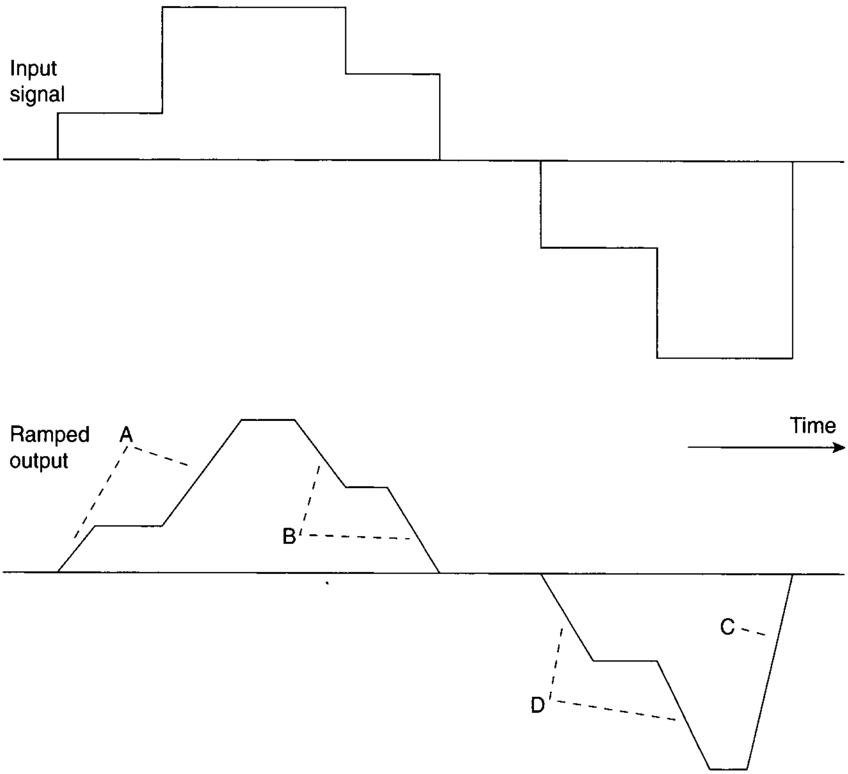
A proportional valve must be used with some form of electronic control. Usually this is provided by a single card per valve. Cards can be mounted onto a back plate or, more usually, in a 19 inch rack. Figure 4.38 shows a typical card schematic.

Electronic cards for proportional valves usually run on a single 24 volt power supply, and require a current of around 1 to 2 amps; not insignificant when several cards are being used on the same project. The tolerance on the supply volts is usually quite wide, typically 20 to 30 V is quoted. Diode D1 on the card protects against inadvertent supply reversal.

An on board power supply produces the multiple supply rails needed by the card circuit; +15 V, +10 V, –10 V and –15 V are common, with 5 V on microprocessor based cards. The +10 V and –10 V supplies are brought out to card terminal as supplies for a manually adjusted control potentiometer.

The Enable input allows current to pass to the valve solenoids. To enable the card, this must be connected to +24 V. This input can be used for safety critical functions such as emergency stops, overtravel limits, safety gates etc.

The valve reference can come in many forms; the card illustrated uses three. First is a voltage signal with a range from +10 V (solenoid A fully open) to –10 V (solenoid B fully open). This signal range is normally used with a manual control potentiometer. The second signal accepts the standard instrumentation signal of 4–20 mA to cover the same valve range. Current signals are less



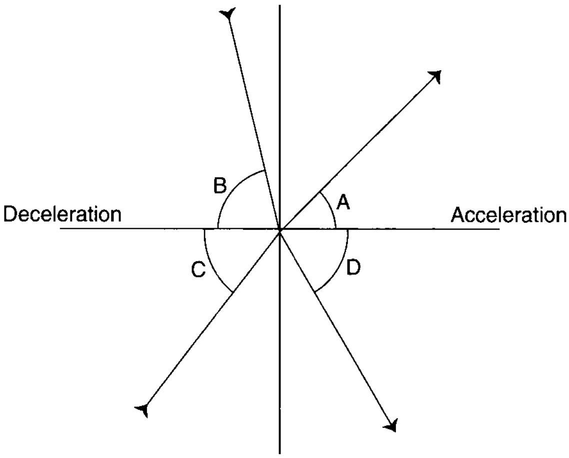


Figure 4.37 *Ramped response. Four quadrant operation is shown, single ramp rate and two quadrant operation are more common. (a) Effect of applying ramps with four quadrant feature. (b) Definition of the four quadrants*

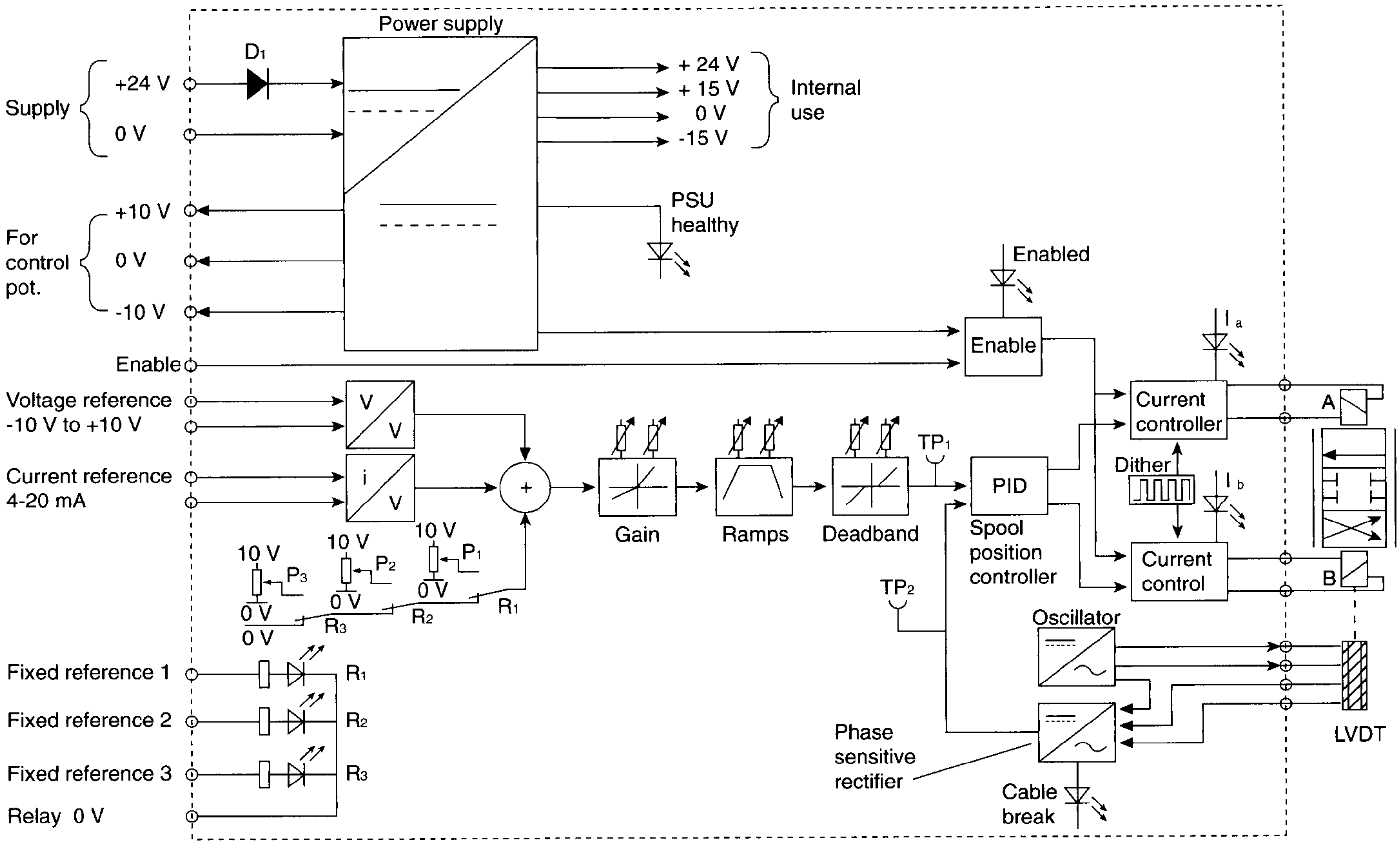


Figure 4.38 *Block Diagram of a typical electronic card for a proportional valve. In many systems the oscillator, LVDT and phase sensitive rectifier are all included in the valve itself*

prone to interference on long cable runs from the source to the card if a valve is being remotely controlled by a PLC or computer. The final reference comes from three fixed settings on potentiometers P1 to P3 mounted on the card itself. These are selected by digital signals which energize relays R1 to R3. The resulting reference is the *sum* of all three. In practice only one will be used, the others being zero. On some cards the source is selected by small switches on the card.

The resulting reference is then adjusted for gain, ramp rate (two quadrants shown on this example, single and four quadrants are also common) and deadband. The result is a required spool position which can be monitored with a voltmeter on TP1.

This setpoint is compared with the actual spool position, also available for monitoring on TP2, and the error used by a three term (proportional integral and derivative, PID) controller to adjust the current to solenoids A and B. Dither is added to the current signals to reduce stiction.

The spool position is monitored by an LVDT, fed from an oscillator on the card. The signal from the LVDT is turned into a DC signal by a phase sensitive rectifier and fed back to the PID spool position controller.

Extensive monitoring and diagnostic facilities are built into the card. The desired and actual spool positions are a crucial test point as these show if the valve is responding to the reference signal. This provides a natural break point for diagnostics, as it shows if the reference is being received.

Another useful test points are LEDs I_a and I_b. These glow with an intensity which is proportional to the solenoid current. If the valve sticks, for example, one LED will shine brightly as the PID controller sends full current to try to move the valve and reduce the error between TP1 and TP2.

Other LED's show the correct operation of the power supply, the state of the Enable signal, the selected fixed speed (if used) and a cable break fault from the LVDT.

Figure 4.38 is based on conventional electronic amplifiers. Increasingly microprocessors are being used, and although the operation is identical in function, it is performed by software. Serial communications, (RS232, RS485 or Fieldbus standards such as Profibus), is becoming common for adjusting the reference and reading the valve status. The settings of gains, ramp rates, fixed references etc. can be set remotely and easily changes by a computer or PLC control system.

With microprocessor based cards, stepper motors are often used to position the spool via a screw thread. This removes the need to balance a solenoid force against a spring force and combines the spool positioning actuator and feedback in the same device.

As electronics becomes smaller there is also a tendency to move the PID controller, current controllers and LVDT circuit into the valve head itself, i.e. everything to the right of TP1. Here the card simply provides a spool reference and a 24 V supply to the valve.

The valves described so far are directional valves, allowing flow to be controlled to and from a load. A proportional valve can also be used to control pressure. The principle is shown on Figure 4.39.

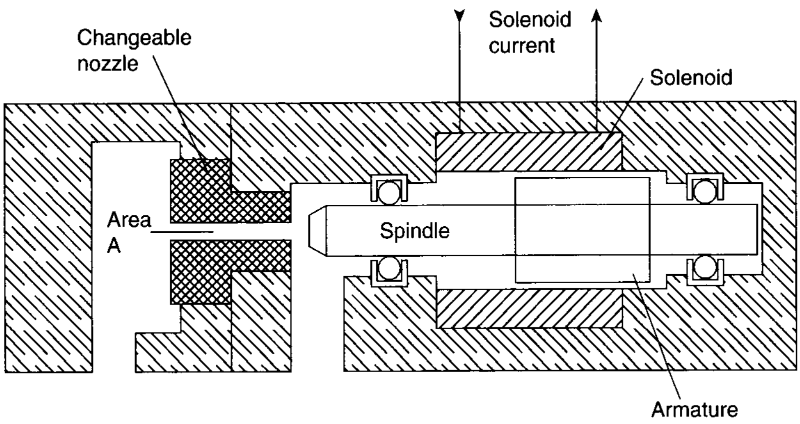


Figure 4.39 *Proportional pressure control valve. The pressure is given by the force produced by the solenoid divided by the area*

The solenoid spindle is aligned with a nozzle connected to the pressure line. For oil to pass from the pressure line back to tank, the force resulting from the fluid pressure must exceed the solenoid force. The relief valve will thus pass fluid back to the tank if the pressure force exceeds the solenoid force, and the pressure will be maintained at

$$\text{Pressure} = \frac{\text{solenoid force}}{\text{nozzle area}}$$

The solenoid force is directly proportional to the solenoid current, so the pressure is also directly proportional to the current. The range of the relief valve is set by the nozzle area, and manufacturers supply nozzle inserts with different areas.

The circuit of Figure 4.39 can only handle a small fluid flow, so a practical valve will incorporate a proportional valve pilot stage linked to a main stage in a similar manner to the manually set spring operated relief valve of Figure 2.6b.

Servo valves

Servo valves are a close relative of the proportional valve and are based on an electrical torque motor which produces a small deflection proportional to the electrical current through its coil. They commonly use feedback between the main and pilot spools to give precise control. A typical device is shown on Figure 4.40. This consists of a small pilot spool connected directly to the torque motor. The pilot spool moves within a sliding sleeve, mechanically linked to the main spool.

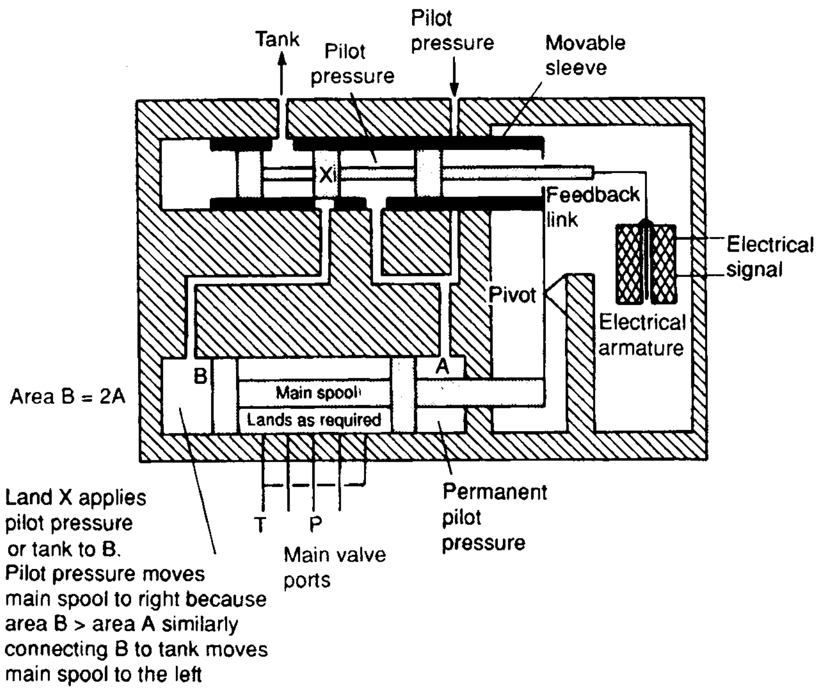


Figure 4.40 *Two-stage servo valve*

The right-hand end of the main spool is permanently connected to the pilot pressure line, but because of the linkage rod its area is reduced to an annulus of area A. Pressure at the left-hand end of the spool is controlled by the pilot valve. There is no area restriction at this end, and the valve is designed such that the spool has an area of 2A.

If the same pressure P is applied to both ends, the spool experiences a left force of $P \times A$ and a right force of $2P \times A$ causing a net force of $P \times A$ to the right, resulting in a shift of the spool to the right.

If a pressure of P is applied to the right-hand end and 0.5P is applied to the left-hand end, equal and opposite forces of $P \times A$ result and the valve spool is stationary.

With a pressure of P on the right-hand end and a pressure less than 0.5P on the left-hand end, net force is to the left and the valve spool moves in that direction.

The pilot valve can thus move the main spool in either direction, in a controlled manner, by varying pressure at left-hand end of the main spool from zero to full pilot pressure.

The mechanical linkage between main spool and pilot sleeve controls the flow of fluid between pilot valve and main valve, and hence controls pressure at the left-hand end of the main spool. Suppose the electrical control signal causes the pilot spool to shift left. This increases the pressure causing the main valve to shift right which in turn pushes the sleeve left. The main valve stops moving when the hole in the pilot sleeve exactly aligns with the land on the pilot spool. A change in electrical signal moving the pilot spool to the right reduces pressure at the left-hand end of the main spool by bleeding fluid back to the tank. This causes the main spool to move left until, again, pilot sleeve and pilot lands are aligned. The main valve spool thus follows the pilot spool with equal, but opposite movements.

Figure 4.41 illustrates the construction of a different type of servo valve, called a jet pipe servo. Pilot pressure is applied to a jet pipe which, with a 50% control signal, directs an equal flow into two pilot lines. A change of control signal diverts the jet flow giving unequal flows and hence unequal pressures at ends of the main spool. The main spool is linked mechanically to the jet pipe, causing it to move to counteract the applied electrical signal. Spool movement ceases when the jet pipe is again centrally located over the two pilot pipes. This occurs when the main valve spool movement exactly balances the electrical control signal.

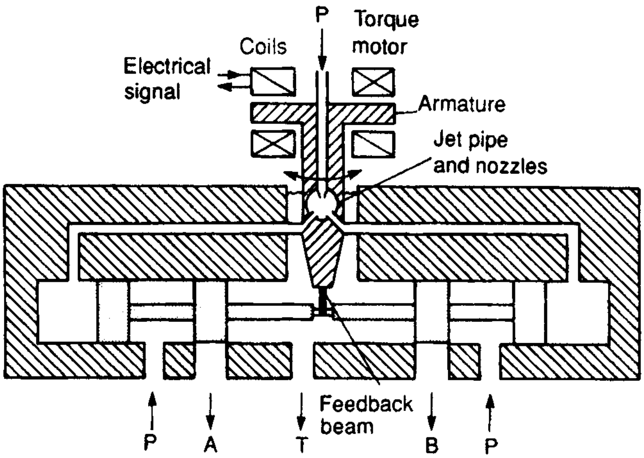


Figure 4.41 *Jet pipe servo valve*

The servo valve in Figure 4.42 is called a flapper servo and is really the inverse of the jet pipe servo. Here, pilot pressure is applied to both ends of the main spool and linked by orifices to small jets playing to a flapper which can be moved by the electrical control signal. Pressure at each end of the main spool (and hence spool movement) is determined by the flow out of each jet which, in turn, is determined by flapper position and electrical control signal.

Servo valves are generally used as part of an external control loop in a feedback control system. The principle of a feedback

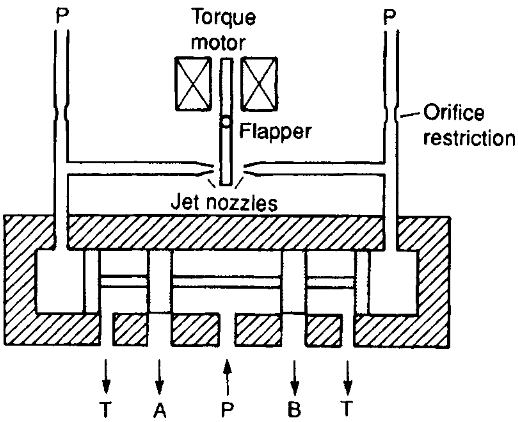


Figure 4.42 *Flapper jet servo valve*

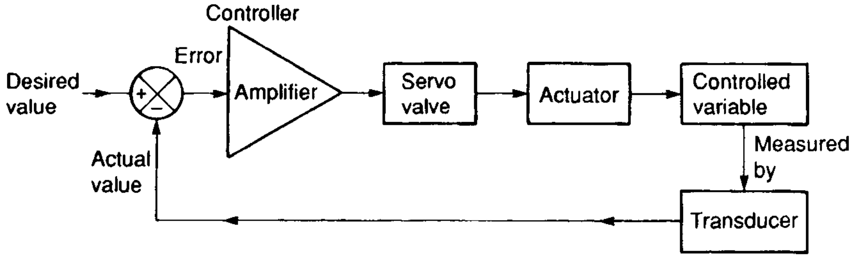


Figure 4.43 *A feedback control system*

control system is shown in Figure 4.43 where some plant variable (velocity or position, for example) is to be controlled. The plant variable is measured by a suitable transducer, and electronically compared with the desired value to give an error signal. This is amplified and used as the control signal for the servo valve.

It can be appreciated that, with small movements of the pilot spool (in Figure 4.40) and the fine jets (in Figures 4.41 and 4.42), servo valves are particularly vulnerable to dirt. Cleanliness is important in *all* aspects of pneumatics and hydraulics, but is overwhelmingly important with servo valves. A filtration level of 10 μm is normally recommended (compared with a normal filtration of 25 μm for finite position valve systems).

Servo valves which are stationary for the majority of time can stick in position due to build-up of scum around the spool. This is known, aptly, as stiction. A side effect of stiction can be a deadband where a large change of control signal is needed before the valve responds at all.

Figure 4.44 shows a purely mechanical servo used as a mechanical booster to allow a large load to be moved with minimal effort. The pilot valve body is connected to the load, and directs fluid to the fixed main cylinder. The cylinder, and hence the load, moves until pilot spool and cylinder are again aligned. Variations on the system in Figure 4.44 are used for power steering in motor cars.

Modular valves and manifolds

Valves are normally mounted onto a valve skid with piping at the rear, or underneath, to allow quick changes to be made for maintenance purposes. Piping can, however, be dispensed with almost totally by mounting valves onto a manifold block- with intercon-

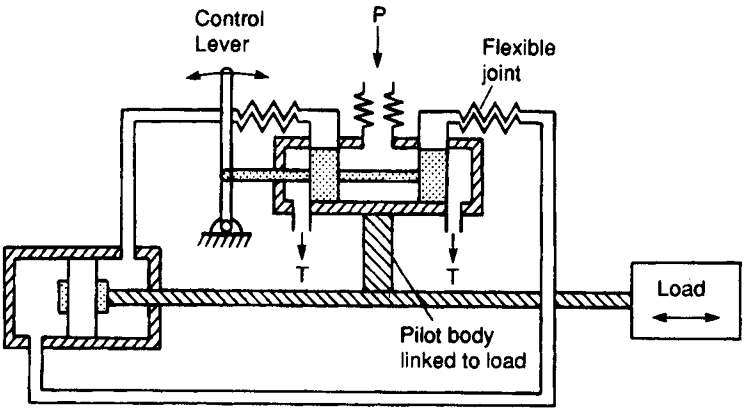


Figure 4.44 *Power assistance using mechanical servo valve*

nections formed by drilled passages in a solid block or by cut-outs on a plate-formed manifold.

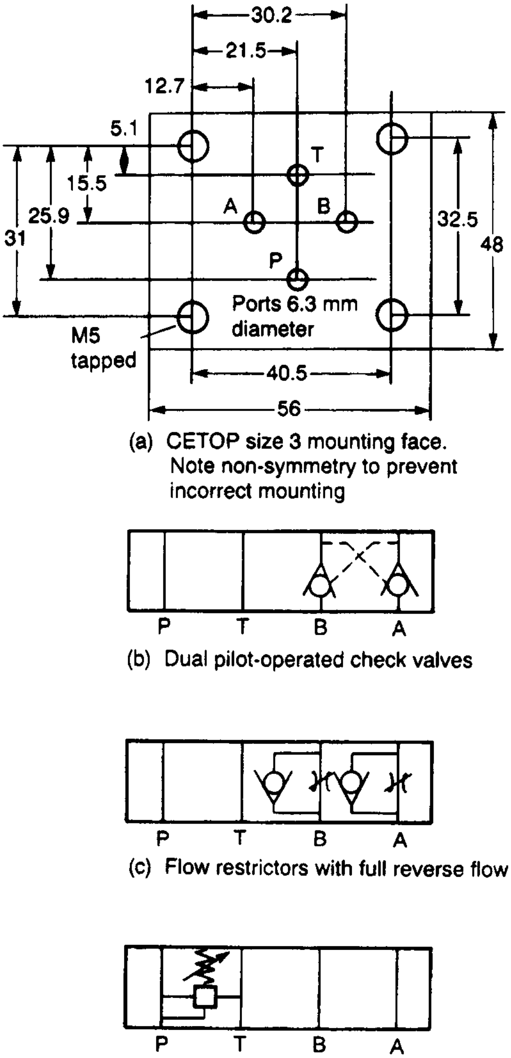
Modular valve assemblies allow piping to be reduced still further. These follow standards laid down by the *Comité European des Transmission Oleophydrauliques et Pneumatiques* and are consequently known as *CETOP* modular valves.

Modular valves consist of a base plate, shown in Figure 4.45a, and a wide variety of modules which may be stacked up on top. Figures 4.45b to d show some modules available. At the top of the stack a spool valve or crossover plate is fitted. Quite complicated assemblies can be built up with minimal piping and the ease of a child's building block model.

Cartridge logic valves

These are simple two position Open/Shut valves using a poppet and seat. Figure 4.46 shows the construction and symbol for a normally open (pilot to close) valve. A normally closed (pilot to open) valve can be constructed as Figure 4.47.

Because a cartridge valve is a two position valve, four valves are needed to provide directional control. Figure 4.48 shows a typical circuit for moving a cylinder. Note these are operated in pairs by a solenoid operated two position valve; 2 and 4 cause the cylinder to extend and 1 and 3 cause the cylinder to retract. As drawn the cylinder will drive to a fully extended or fully retracted position. If the cylinder was required to hold an intermediate position the single



(a) CETOP size 3 mounting face. Note non-symmetry to prevent incorrect mounting

(b) Dual pilot-operated check valves

(c) Flow restrictors with full reverse flow

(d) Pressure relief valve

Figure 4.45 *CETOP modular valves. Examples shown are only a small proportion of those available*

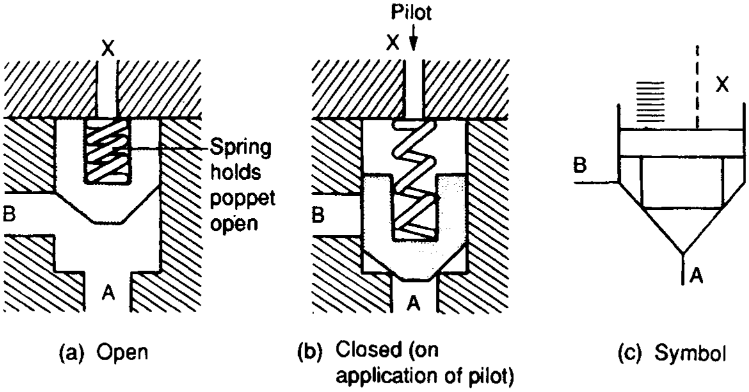


Figure 4.46 *Cartridge logic valve*

two position solenoid valve would be replaced by a three position centre blocked valve with one solenoid for extend and one for retract.

At first sight this may be thought over complex compared with the equivalent spool valve circuit, but cartridge valves have some

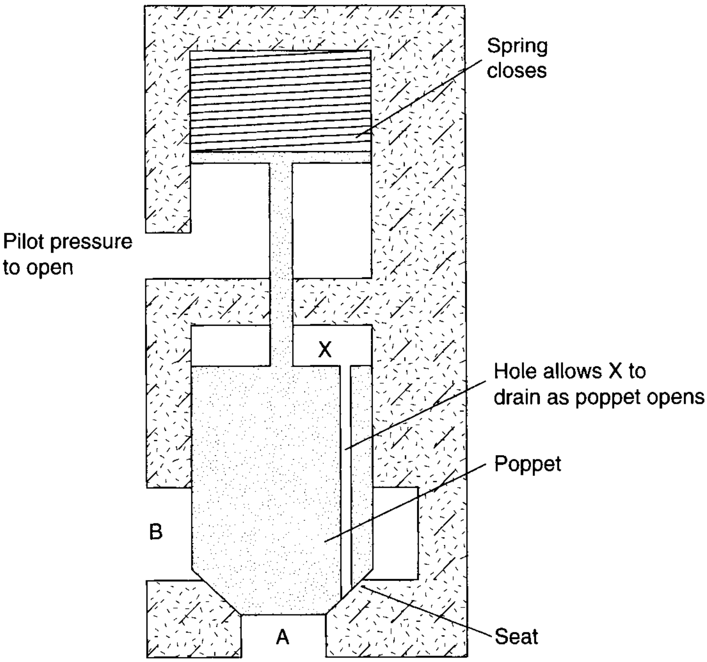


Figure 4.47 *Normally closed, pilot to open, cartridge valve*

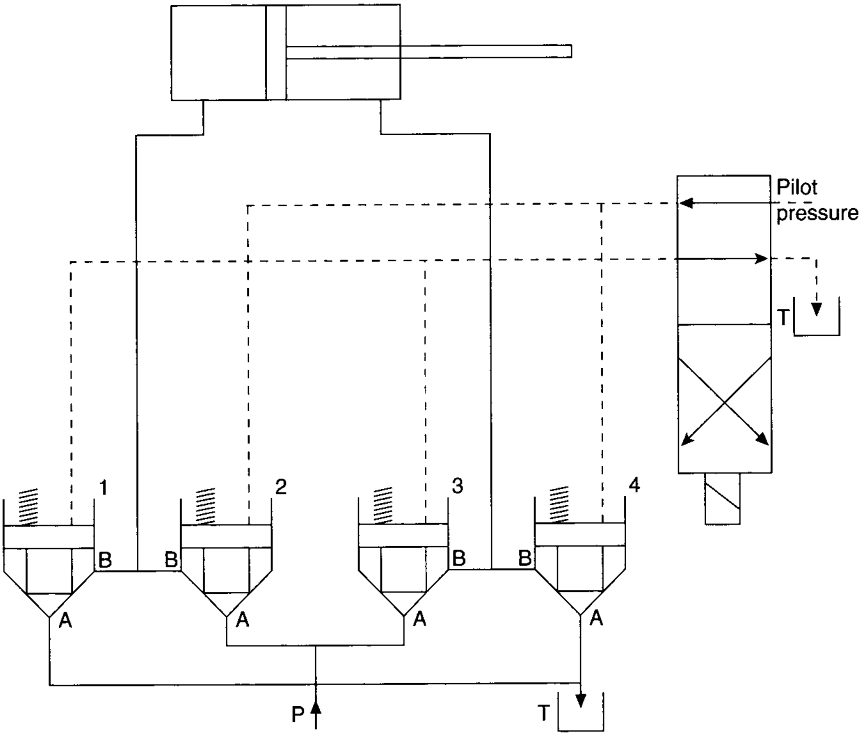


Figure 4.48 *Direction control using four cartridge valves. As shown the cyclinder will fully extend or fully retract. If two solenoid valves are used, one for open, one for close, the cylinder can hold position*

distinct advantages. Because of their construction they have very low leakage and can handle higher flows than spool valves of a similar size. They are also modular and are connected by screwing into a pre-drilled manifold. This provides high reliability and easy fault diagnosis and replacement. They are commonly used on mobile plant and with water based fluids where leakage can be a problem.