5 Pneumatic and hydraulic actuation systems

5.1 Actuation systems

Actuation systems are the elements of control systems which are responsible for transforming the output of a microprocessor or control system into a controlling action on a machine or device. Thus, for example, we might have an electrical output from the controller which has to be transformed into a linear motion to move a load. Another example might be where an electrical output from the controller has to be transformed into an action which controls the amount of liquid passing along a pipe.

In this chapter pneumatic and hydraulic actuation systems are discussed. In Chapter 6 mechanical actuator systems are discussed and in Chapter 7 electrical actuation systems. For a more detailed consideration of pneumatic and hydraulic systems the reader is referred to more specialist books such as *Pneumatic and Hydraulic Systems* by W. Bolton (Butterworth-Heinemann 1997), *Power Pneumatics* by M.J. Pinches and B.J. Callear (Prentice-Hall 1996), *Pneumatic Control for Industrial Automation* by P. Rohner and G. Smith (Wiley 1987, 1990) or *Industrial Hydraulic Control* by P. Rohner (Wiley 1984, 1986, 1988, 1995).

5.2 Pneumatic and hydraulic systems

Pneumatic signals are often used to control final control elements, even when the control system is otherwise electrical. This is because such signals can be used to actuate large valves and other high power control devices and so move significant loads. The main drawback with pneumatic systems is, however, the compressibility of air. Hydraulic signals can be used for even higher power control devices but are more expensive than pneumatic systems and there are hazards associated with oil leaks which do not occur with air leaks.

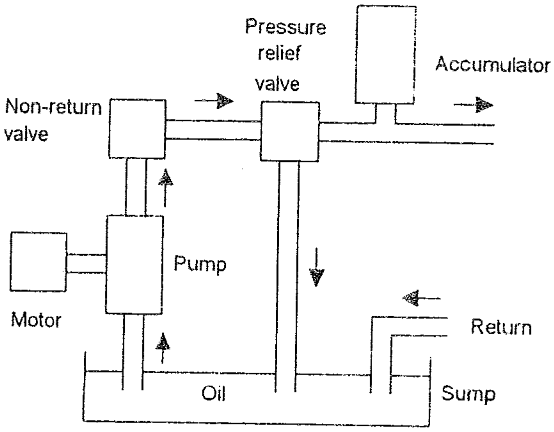

Fig. 5.1 Hydraulic power supply

5.2.1 Power supplies

With a hydraulic system, pressurised oil is provided by a pump driven by an electric motor. The pump pumps oil from a sump through a non-return valve and an accumulator to the system, from which it returns to the sump. Figure 5.1 illustrates the arrangement. A pressure relief valve is included, this being to release the pressure if it rises above a safe level, the non-return valve is to prevent the oil being back driven to the pump and the accumulator is to smooth out any short-term fluctuations in the output oil pressure. Essentially the accumulator is just a container in which the oil is held under pressure against an external force. Figure 5.2 showing the most commonly used form which is gas pressurised and involves gas within a bladder in the chamber containing the hydraulic fluid, an older type involved a spring-loaded piston. If the oil pressure rises then the bladder contracts, increases the volume the oil can occupy and so reduces the pressure. If the oil pressure falls, the bladder expands to reduce the volume occupied by the oil and so increases its pressure.

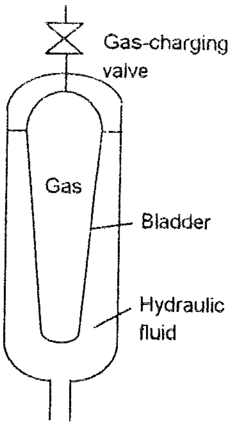

Fig. 5.2 Accumulator

With a pneumatic power supply (Fig. 5.3) an electric motor drives an air compressor. The air inlet to the compressor is likely to be filtered and via a silencer to reduce the noise level. A pressure relief valve provides protection against the pressure in the system rising above a safe level. Since the air compressor increases the temperature of the air there is likely to be a cooling system and to remove contamination and water from the air a filter with water trap. An air receiver increases the volume of air in the system and smoothes out any short-term pressure fluctuations.

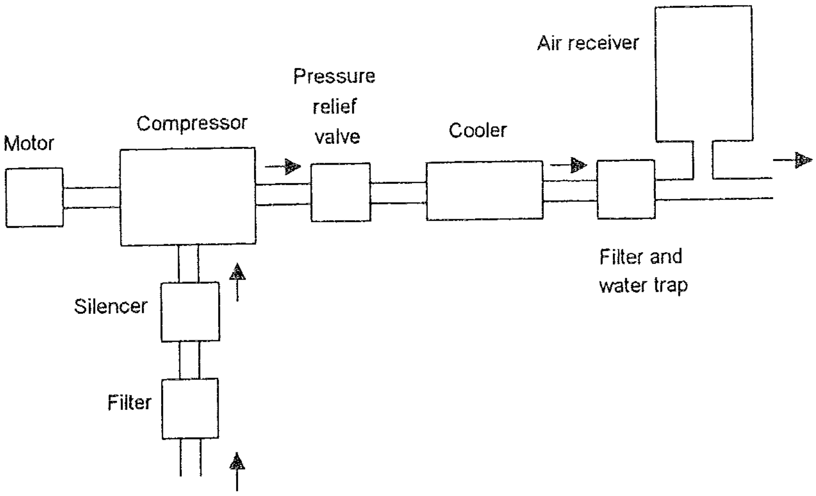

Fig. 5.3 Pneumatic power supply

5.3 Directional control valves

Pneumatic and hydraulic systems use directional control valves to direct the flow of fluid through a system. They are not intended to vary the rate of flow of fluid but are either completely open or completely closed, i.e. on/off devices. Such on/off valves are widely used to develop sequenced control systems (see later in this chapter). They might be activated to switch the fluid flow direction by means of mechanical, electrical or fluid pressure signals.

A common type of directional control valve is the *spool valve*. A spool moves horizontally within the valve body to control the flow. Figure 5.4 shows a particular form. In (a) the air supply is connected to port 1 and port 3 is closed. Thus the device connected to port 2 can be pressurised. When the spool is moved to the left (Fig. 5.4(b)) the air supply is cut off and port 2 is connected to port 3. Port 3 is a vent to the atmosphere and so the air pressure in the system attached to port 2 is vented. Thus the movement of the spool has allowed the air to firstly flow into the system and then be reversed and flow out of the system. *Rotary spool valves* have a rotating spool which, when it rotates, opens and closes ports in a similar way.

Another common form of directional control valve is the *poppet valve*. Figure 5.5 shows one form. This valve is normally in the closed condition, there being no connection between port 1 to which the pressure supply is connected and port 2 to which the system is connected. In poppet valves, balls, discs or cones are used in conjunction with valve seats to control the flow. In the figure a ball is shown. When the push-button is depressed, the ball is pushed out of its seat and flow occurs as a result of port 1 being connected to port 2. When the button is released, the spring forces the ball back up against its seat and so closes off the flow.

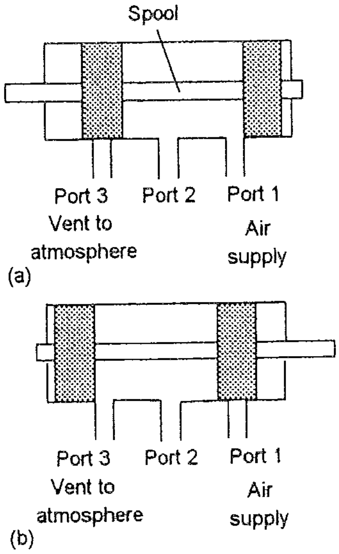

Fig. 5.4 Spool valve

5.3.1 Valve symbols

The symbol used for control valves consists of a square for each of its switching positions. Thus for the poppet valve shown in Figure 5.5, there are two positions: one with the button not pressed and one with it pressed. Thus a two-position valve will have two squares, a three-position valve three squares. Arrow-headed lines (Fig. 5.6(a)) are used to indicate the directions of flow in each of the positions, with blocked-off lines closed flow lines (Fig. 5.6(b)). The initial position of the valve has the connections (Fig. 5.6(c)) to the ports shown; in Fig. 5.6(c) the valve has four ports. Ports are labelled by a number or a letter according to their function. The ports are labelled 1 (or P) for pressure supply, 3 (or T) for hydraulic return port, 3 or 5 (or R or S) for pneumatic exhaust ports, and 2 or 5 (or B or A) for output ports.

Figure 5.7 shows examples of some of the symbols which are used to indicate the various ways the valves can be actuated. More than one of these symbols might be used with the valve symbol.

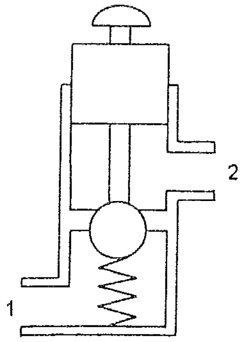

Fig. 5.5 Poppet valve

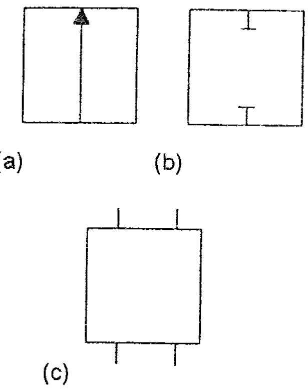

Fig. 5.6 (a) Flow path, (b) flow shut-off, (c) initial connections

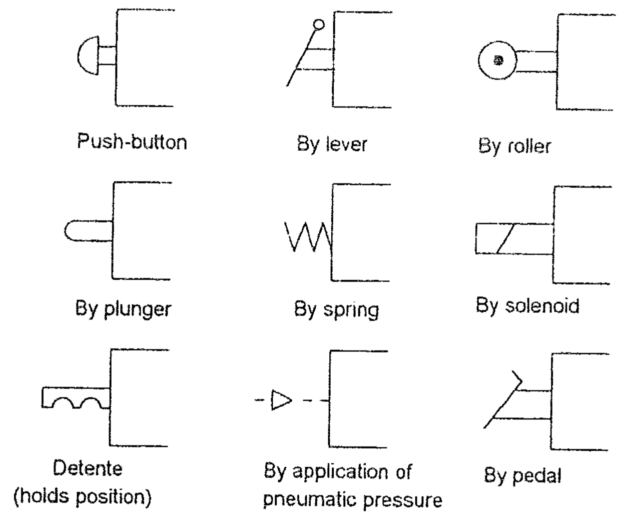

Fig. 5.7 Valve actuation symbols

As an illustration of how these various symbols can be combined to describe how a valve operates, Figure 5.8 shows the symbol for the 2 port 2 position poppet valve of Figure 5.6. Note that a 2 port 2 position valve would be described as a 2/2 valve, the first number indicating the number of ports and the second number the number of positions.

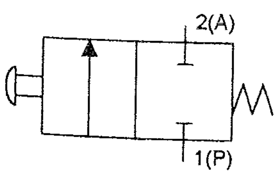

Fig. 5.8 2/2 valve

As a further illustration, Figure 5.9 shows a solenoid operated spool valve and Figure 5.10 its symbol. The valve is actuated by a current passing through a solenoid and returned to its original position by a spring.

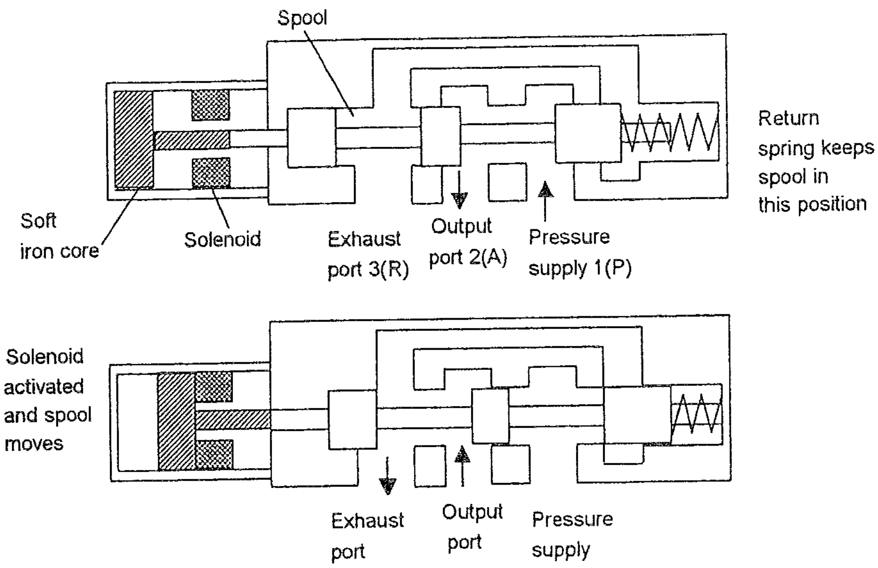

Fig. 5.9 Single-solenoid valve

Figure 5.11 shows the symbol for a 4/2 valve. The connections are shown for the initial state, i.e. 1(P) is connected to 2(A) and 3(R) closed. When the solenoid is activated it gives the state indicated by the symbols used in the square to which it is attached, i.e. we now have 1(P) closed and 2(A) connected to 3(R). When the current through the solenoid ceases, the spring pushes the valve back to its initial position. The spring movement gives the state indicated by the symbols used in the square to which it is attached.

Figure 5.12 shows a simple example of an application of valves in a pneumatic lift system. Two push-button 2/2 valves are used. When the button on the up valve is pressed, the load is lifted. When the button on the down valve is pressed, the load is lowered. Note that with pneumatic systems an open arrow is used to indicate a vent to the atmosphere.

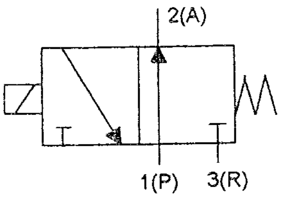

Fig. 5.10 3/2 valve

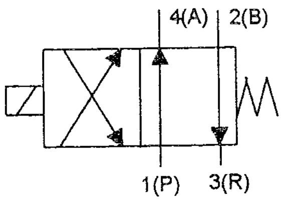

Fig. 5.11 4/2 valve

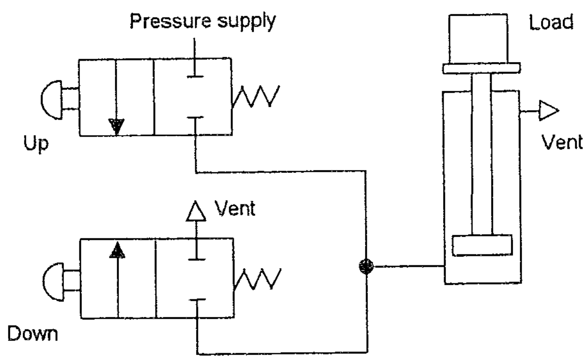

Fig. 5.12 Lift system

5.3.2 Pilot-operated valves

The force required to move the ball or shuttle in a valve can often be too large for manual or solenoid operation. To overcome this problem a *pilot-operated system* is used where one valve is used to control a second valve. Figure 5.13 illustrates this. The pilot valve is small capacity and can be operated manually or by a solenoid. It is used to allow the main valve to be operated by the system pressure. The pilot pressure line is indicated by dashes. The pilot and main valves can be operated by two separate valves but they are often combined in a single housing.

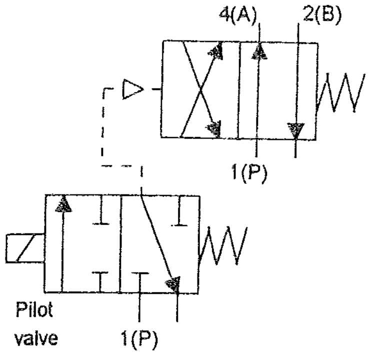

Fig. 5.13 Pilot-operated system

5.3.3 Directional valves

Figure 5.14 shows a simple *directional valve* and its symbol. Free flow can only occur in one direction through the valve, that which results in the ball being pressed against the spring. Flow in the other direction is blocked by the spring forcing the ball against its seat.

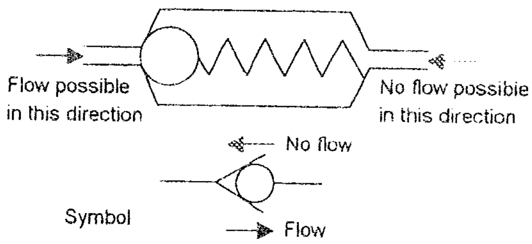

Fig. 5.14 Directional valve

5.4 Pressure control valves

There are three main types of pressure control valves:

1 *Pressure regulating valves*
These are used to control the operating pressure in a circuit and maintain it at a constant value.

2 *Pressure limiting valves*
These are used as safety devices to limit the pressure in a circuit to below some safe value. The valve opens and vents to the atmosphere, or back to the sump, if the pressure rises above the set safe value.

3 *Pressure sequence valves*
These valves are used to sense the pressure of an external line and give a signal when it reaches some preset value.

5.4.1 Pressure limiting valve

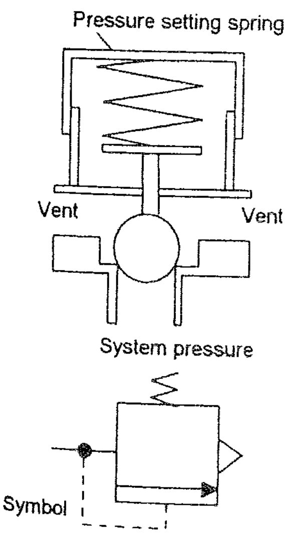

Fig. 5.15 Pressure limiting valve

Figure 5.15 shows a *pressure limiting/relief valve* which has one orifice which is normally closed. When the inlet pressure overcomes the force exerted by the spring, the valve opens and vents to the atmosphere, or back to the sump. This can be used as a pressure relief valve to safeguard a system against excessive pressures.

5.4.2 Pressure sequence valve

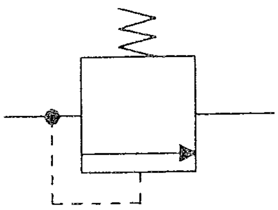

Fig. 5.16 Pressure sequence valve

With the pressure limiting valve of Figure 5.15, the limiting pressure is set by the pressure at the inlet to the valve. We can adapt such a valve to give a sequence valve. This can be used to allow flow to occur to some part of the system when the pressure has risen to the required level. For example, in an automatic machine we might require some operation to start when the clamping pressure applied to a workpiece is at some particular value. Figure 5.16 shows the symbol for a sequence valve, the valve switching on when the inlet pressure reaches a particular value and allowing the pressure to be applied to the system that follows.

Figure 5.17 shows a system where such a sequential valve is used. When the 4/3 valve first operates, the pressure is applied to cylinder 1 and its ram moves to the right. While this is happening the pressure is too low to operate the sequence valve and so no pressure is applied to cylinder 2. When the ram of cylinder 1 reaches the end stop, then the pressure in the system rises and, at an appropriate level, triggers the sequence valve to open and so apply pressure to cylinder 2 to start its ram in motion.

5.5 Cylinders

The *hydraulic* or *pneumatic cylinder* is an example of a linear actuator. The principles and form are the same for both hydraulic and pneumatic versions, differences being purely a matter of size as a consequence of the higher pressures used with hydraulics. The cylinder consists of a cylindrical tube along which a piston/ ram can slide.

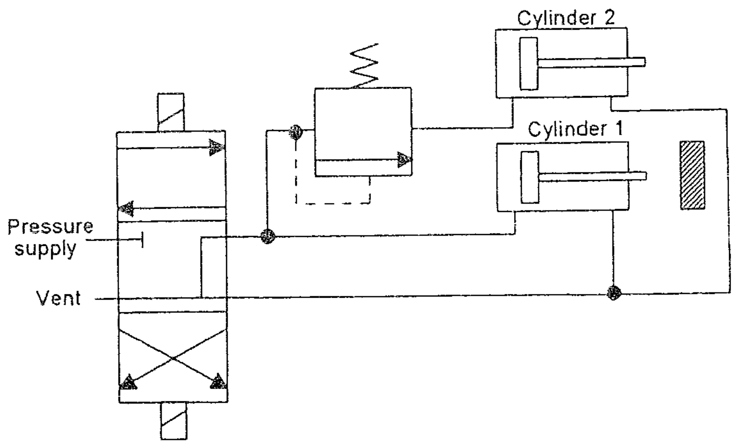

Fig. 5.17 Sequential system

The term *single acting* is used when the control pressure is applied to just one side of the piston, a spring often being used to provide the opposition to the movement of the piston. For the single-acting cylinder shown in Figure 5.18, when a current passes through the solenoid, the valve switches position and pressure is applied to move the piston along the cylinder. When the current through the solenoid ceases, the valve reverts to its initial position and the air is vented from the cylinder. As a consequence the spring returns the piston back along the cylinder.

The term *double acting* is used when the control pressures are applied to each side of the piston. A difference in pressure between the two sides then results in motion of the piston, the piston being able to move in either direction along the cylinder as a result of high pressure signals. For the double-acting cylinder shown in Figure 5.19, current through one solenoid causes the piston to move in one direction with current through the other solenoid reversing the direction of motion.

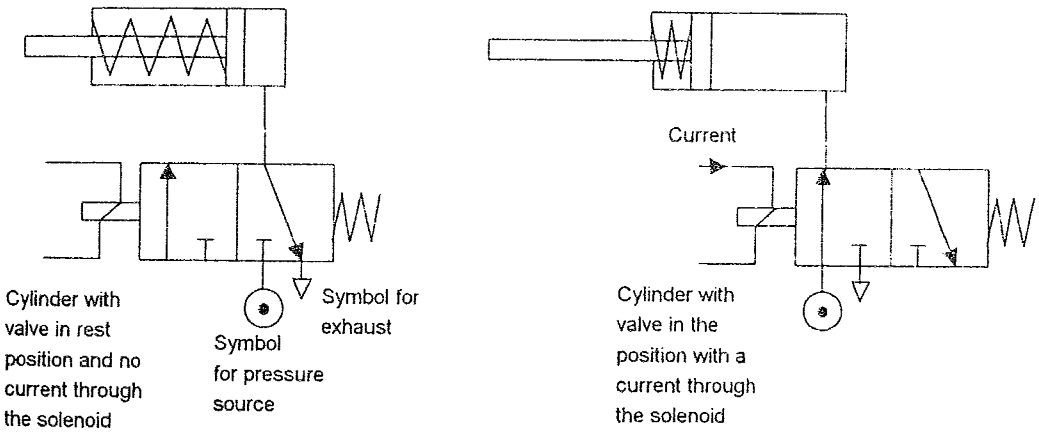

Fig. 5.18 Control of a single-acting cylinder

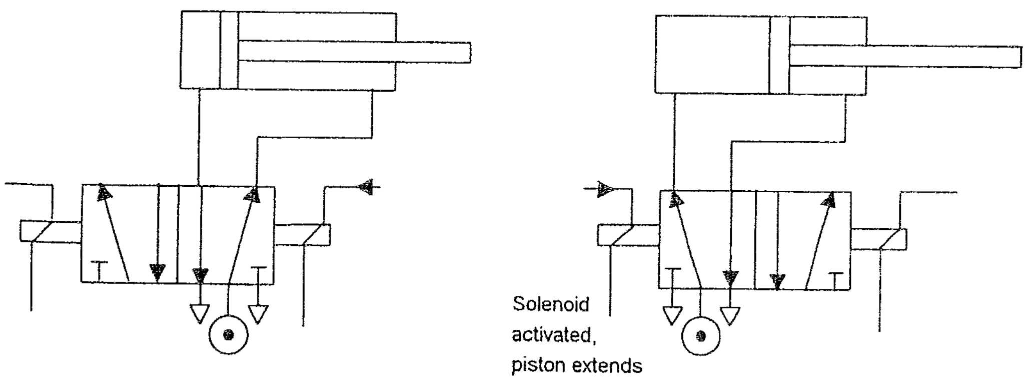

Fig. 5.19 Control of a double-acting cylinder

The choice of cylinder is determined by the force required to move the load and the speed required. Hydraulic cylinders are capable of much larger forces than pneumatic cylinders. However, pneumatic cylinders are capable of greater speeds. The force produced by a cylinder is equal to the cross-sectional area of the cylinder multiplied by the working pressure, i.e. the pressure difference between the two sides of the piston, in the cylinder. A cylinder for use with a working pneumatic pressure of 500 kPa and having a diameter of 50 mm will thus give a force of 982 N. A hydraulic cylinder with the same diameter and a working pressure of 15 000 kPa will give a force of 29.5 kN.

If the flow rate of hydraulic liquid into a cylinder is a volume of Q per second, then the volume swept out by the piston in a time of 1 s must be Q. But for a piston of cross-sectional area A this is a movement through a distance of v in 1 s, where we have $Q = Av$. Thus the speed v of a hydraulic cylinder is equal to the flow rate of liquid Q through the cylinder divided by the cross-sectional area A of the cylinder. Thus for a hydraulic cylinder of diameter 50 mm and a hydraulic fluid flow of 7.5×10^{-3} m^3/s the speed is 3.8 m/s. The speed of a pneumatic cylinder cannot be calculated in this way since its speed depends on the rate at which air can be vented ahead of the advancing piston. A valve to adjust this can be used to regulate the speed.

To illustrate the above consider the problem of a hydraulic cylinder to be used to move a work piece in a manufacturing operation through a distance of 250 mm in 15 s. If a force of 50 kN is required to move the work piece, what is the required working pressure and hydraulic liquid flow rate if a cylinder with a piston diameter of 150 mm is available? The cross-sectional area of the piston is $\frac{1}{4}\pi \times 0.150^2 = 0.0177$ m^2. The force produced by the cylinder is equal to the product of the cross-sectional area of the cylinder and the working pressure. Thus the working pressure is $50 \times 10^3/0.0177 = 2.8$ MPa. The speed of a hydraulic cylinder is equal to the flow rate of liquid through the cylinder divided by the cross-sectional area of the cylinder. Thus the required flow rate is $(0.250/15) \times 0.0177 = 2.95 \times 10^{-4}$ m^3/s.

5.5.1 Cylinder sequencing

Many control systems employ pneumatic or hydraulic cylinders as the actuating elements and require a sequence of extensions and retractions of the cylinders to occur. For example, we might have two cylinders A and B and require that when the start button is pressed, the piston of cylinder A extends and then, when it is fully extended, the piston of cylinder B extends. When this has happened and both are extended we might need the piston of cylinder A to retract, and when it is fully retracted we might then have the piston of B retract. In discussions of sequential control with cylinders it is common practice to give each cylinder a reference letter A, B, C, D, etc., and to indicate the state of each cylinder by using a + sign if it is extended or a – sign if retracted. Thus the above required sequence of operations is A+, B+, A–, B–. Figure 5.20 shows a circuit that could be used to generate this sequence.

The sequence of operations is:

1 Initially both the cylinders have retracted pistons. Start push-button on valve 1 is pressed. This applies pressure to valve 2, as initially limit switch b– is activated, hence valve 3 is switched to apply pressure to cylinder A for extension.
2 Cylinder A extends, releasing limit switch a–. When cylinder A is fully extended, limit switch a+ operates. This switches valve 5 and causes pressure to be applied to valve 6 to switch it and so apply pressure to cylinder B to cause its piston to extend.
3 Cylinder B extends, releasing limit switch b–. When cylinder B is fully extended, limit switch b+ operates. This switches valve 4 and causes pressure to be applied to valve 3 and so applies pressure to cylinder A to start its piston retracting.
4 Cylinder A retracts, releasing limit switch a+. When cylinder A is fully retracted, limit switch a– operates. This switches valve 7 and causes pressure to be applied to valve 5 and so applies pressure to cylinder B to start its piston retracting.

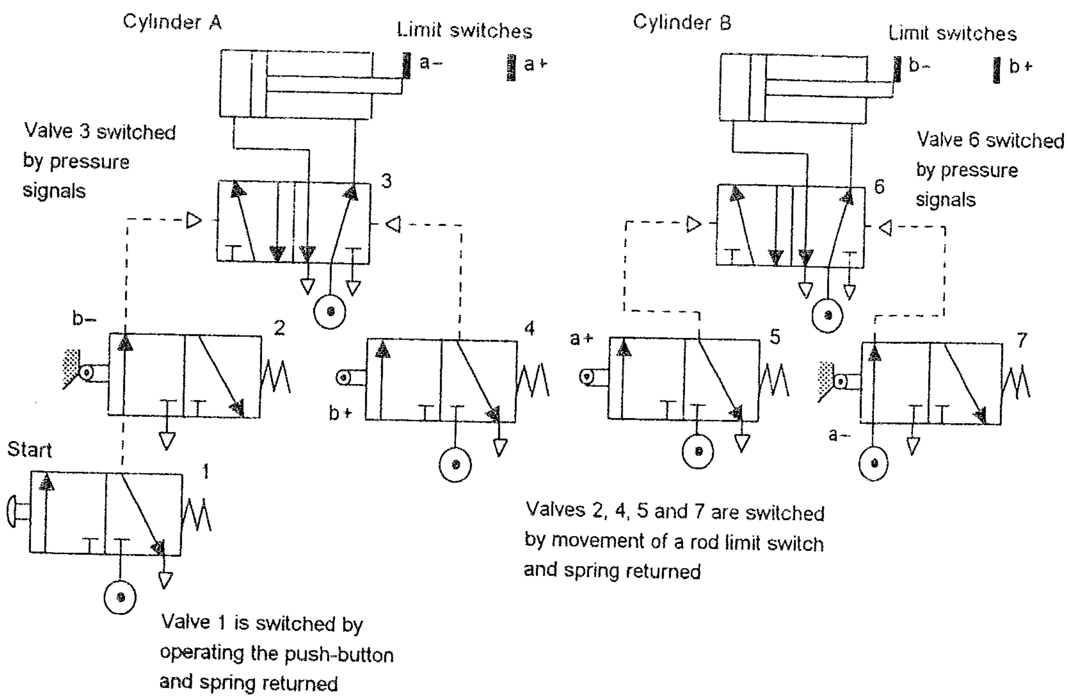

Fig. 5.20 Two-actuator sequential operation

5 Cylinder B retracts, releasing limit switch b+. When cylinder B is fully retracted, limit switch b– operates to complete the cycle.

The cycle can be started again by pushing the start button. If we wanted the system to run continuously then the last movement in the sequence would have to trigger the first movement.

An alternative way of realising the above sequence involves the air supply being switched on and off to valves in groups and is termed *cascade control*. This avoids a problem that can occur with circuits, formed in the way shown in Figure 5.20, of air becoming trapped in the pressure line to control a valve and so preventing the valve from switching. With cascade control, the sequence of operations is divided into groups with no cylinder letter appearing more than once in each group. Thus for the sequence A+, B+, B–, A– we can have the groups A+, B+ and A–, B–. A valve is then used to switch the air supply between the two groups, i.e. air to the group A+B+ and then the air switched to the group with A–B–. A start/stop valve is included in the line that selects the first group, and if the sequence is to be continuously repeated, the last operation has to supply a signal to start the sequence over again. The first function in each group is initiated by that group supply being switched on; further actions within the group are controlled by switch-operated valves, and the last valve operation initiates the next group to be selected. Figure 5.21 shows the pneumatic circuit.

5.6 Process control valves

Process control valves are used to control the rate of fluid flow and are used where, perhaps, the rate of flow of a liquid into a tank has to be controlled. The basis of such valves is an actuator being used to move a plug into the flow pipe and so alter the cross-section of the pipe through which the fluid can flow.

A common form of pneumatic actuator used with process control valves is the *diaphragm actuator*. Essentially it consists of a diaphragm with the input pressure signal from the controller on one side and atmospheric pressure on the other, this difference in pressure being termed the *gauge pressure*. The diaphragm is made of rubber which is sandwiched in its centre between two circular steel discs. The effect of changes in the input pressure is thus to move the central part of the diaphragm, as illustrated in Figure 5.22. This movement is communicated to the final control element by a shaft which is attached to the diaphragm.

The force F acting on the shaft is the force that is acting on the diaphragm and is thus the gauge pressure P multiplied by the diaphragm area A. A restoring force is provided by a spring. Thus if the shaft moves through a distance x, and assuming the compression of the spring is proportional to the force, i.e. $F = kx$ with k being a constant, then $kx = PA$ and thus the displacement of the shaft is proportional to the gauge pressure.

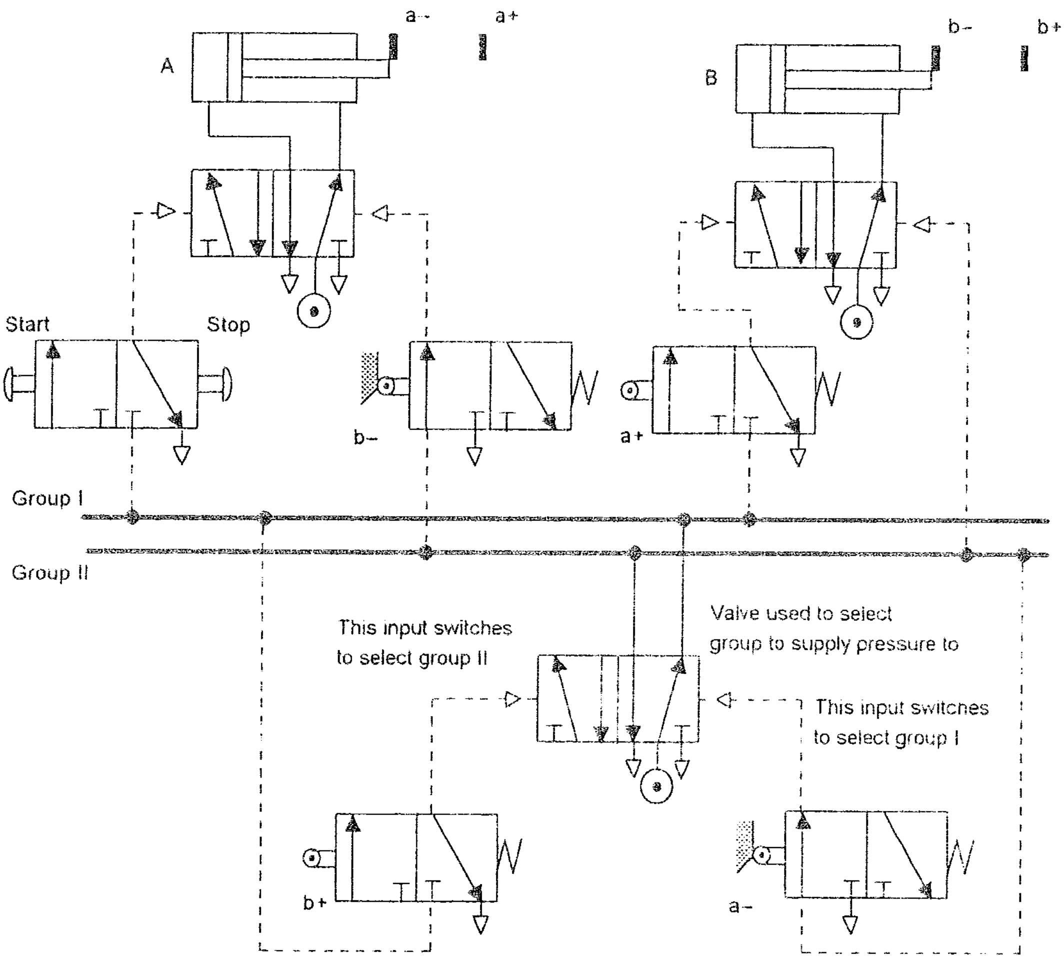

Fig. 5.21 Cascade control used to give A+, B+, B−, A−

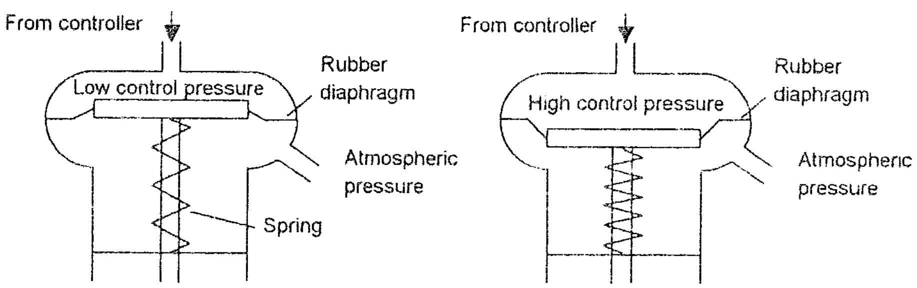

Fig. 5.22 Pneumatic diaphragm actuator