MECHATRONICS

ELECTRONIC CONTROL SYSTEMS IN MECHANICAL AND ELECTRICAL ENGINEERING

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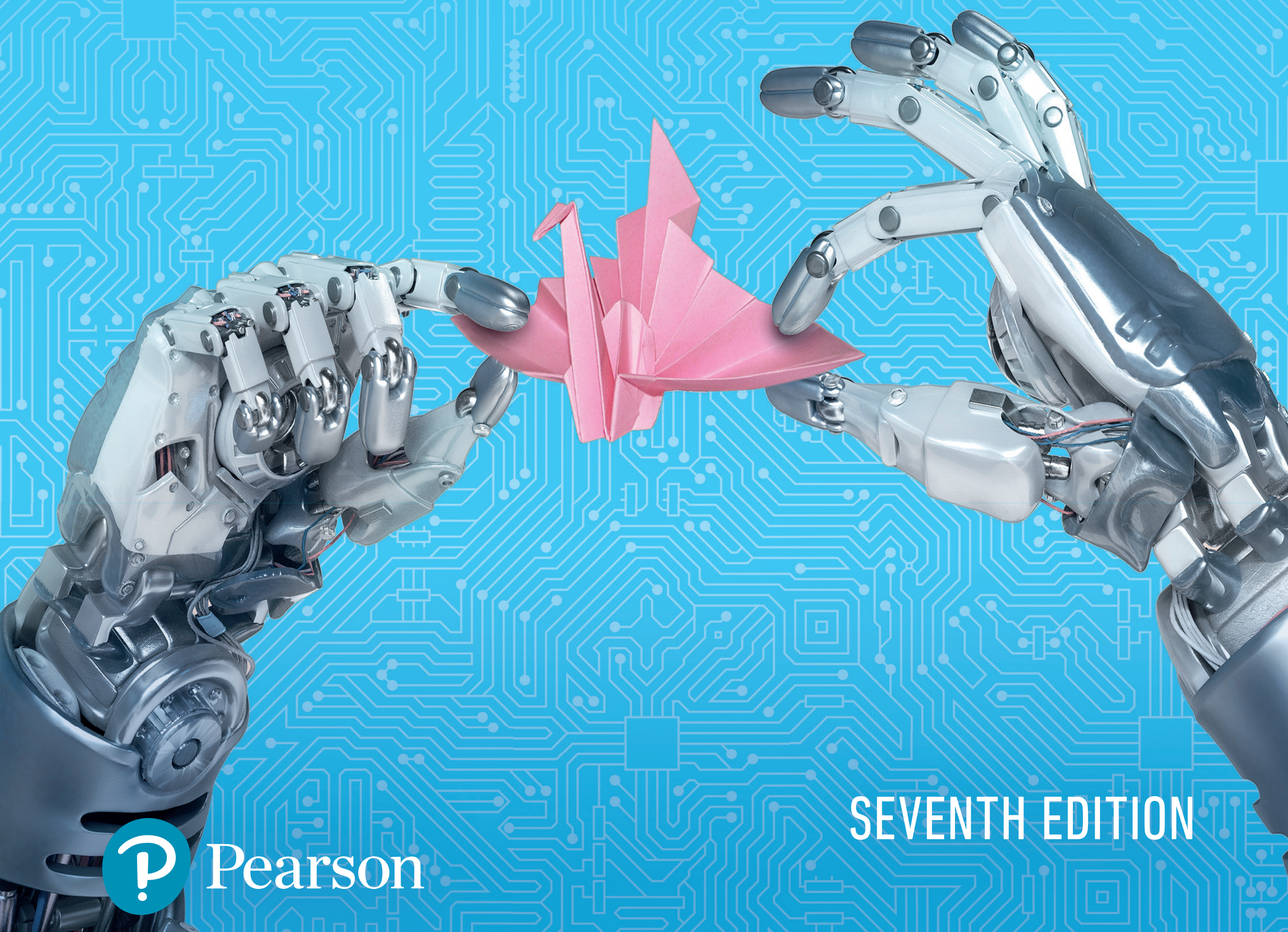

SEVENTH EDITION

Pearson

MECHATRONICS

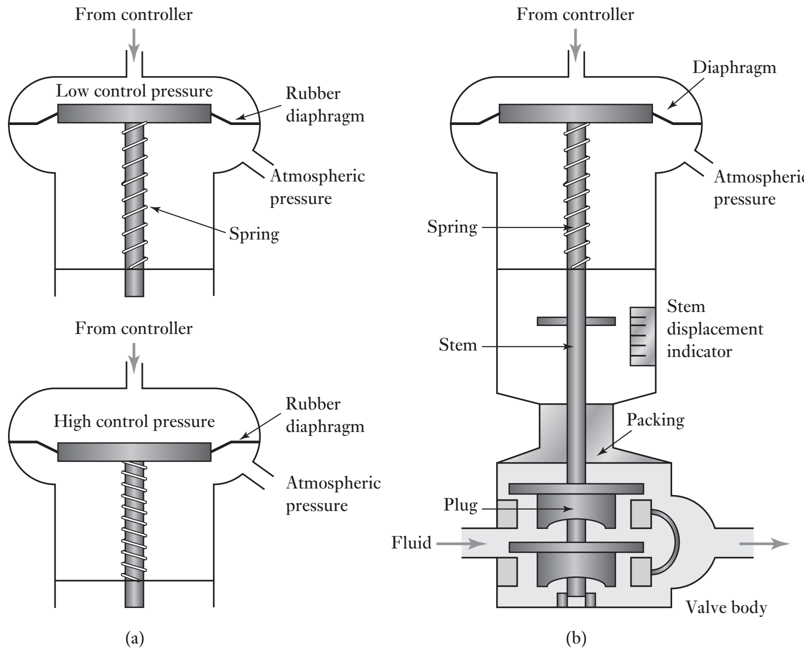

Figure 7.25 (a) Pneumatic diaphragm actuator, (b) control valve.

and so consequently the valve stem. The result of this is a movement of the inner valve plug within the valve body. The plug restricts the fluid flow and so its position determines the flow rate.

There are many forms of valve body and plug. Figure 7.26 shows some forms of valve bodies. The term **single-seated** is used for a valve where there is just one path for the fluid through the valve and so just one plug is needed to control the flow. The term **double-seated** is used for a valve where the fluid on entering the valve splits into two streams, as in Figure 7.26, with each stream passing through an orifice controlled by a plug. There are thus two plugs with such a valve.

A single-seated valve has the advantage that it can be closed more tightly than a double-seated one, but the disadvantage that the force on the plug due to the flow is much higher and so the diaphragm in the actuator has to exert considerably higher forces on the stem. This can result in problems in accurately positioning the plug. Double-seated valves thus have an advantage here. The form of the body also determines whether an increasing air pressure will result in the valve opening or closing.

The shape of the plug determines the relationship between the stem movement and the effect on the flow rate. Figure 7.27(a) shows three commonly used types and Figure 7.27(b) how the percentage by which the volumetric rate of flow is related to the percentage displacement of the valve stem.

With the **quick-opening** type a large change in flow rate occurs for a small movement of the valve stem. Such a plug is used where on/off control of flow rate is required.

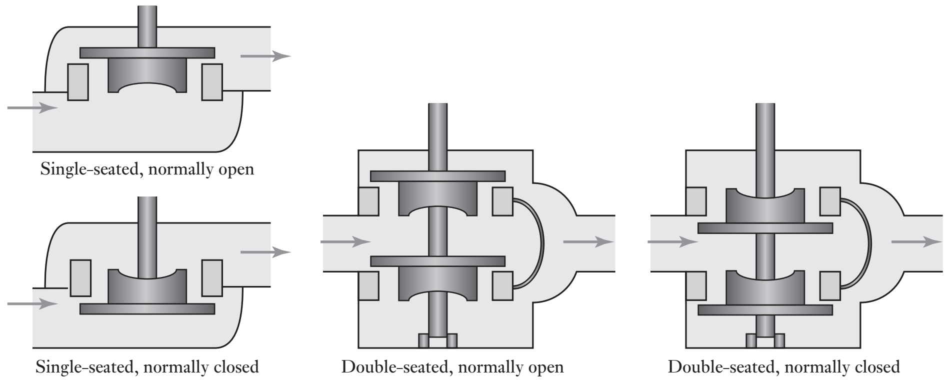

Figure 7.26 Valve bodies.

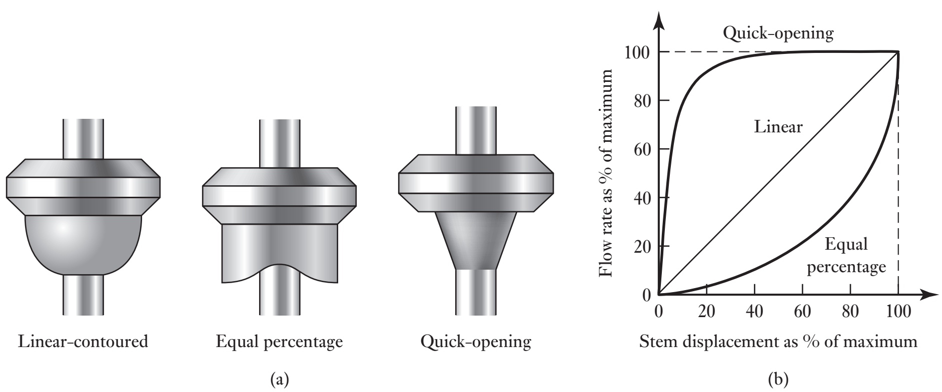

Figure 7.27 (a) Plug shapes, (b) flow characteristics.

With the **linear-contoured** type, the change in flow rate is proportional to the change in displacement of the valve stem, i.e.

$$\text{change in flow rate} = k(\text{change in stem displacement})$$

where k is a constant. If Q is the flow rate at a valve stem displacement S and Q_{max} is the maximum flow rate at the maximum stem displacement S_{max}, then we have

$$\frac{Q}{Q_{max}} = \frac{S}{S_{max}}$$

or the percentage change in the flow rate equals the percentage change in the stem displacement.

To illustrate the above, consider the problem of an actuator which has a stem movement at full travel of 30 mm. It is mounted on a linear plug valve which has a minimum flow rate of 0 and a maximum flow rate of 40 m^3/s. What will be the flow rate when the stem movement is (a) 10 mm, (b) 20 mm? Since the percentage flow rate is the same as the percentage stem displacement, then: (a) a percentage stem displacement of 33% gives a percentage flow rate of 33%, i.e. 13 m^3/s; (b) a percentage stem displacement of 67% gives a percentage flow rate of 67%, i.e. 27 m^3/s.

With the **equal percentage** type of plug, equal percentage changes in flow rate occur for equal changes in the valve stem position, i.e.

$$\frac{\Delta Q}{Q} = k\Delta S$$

where ΔQ is the change in flow rate at a flow rate of Q and ΔS the change in valve position resulting from this change. If we write this expression for small changes and then integrate it we obtain

$$\int_{Q_{\min}}^{Q} \frac{1}{Q}\,\mathrm{d}Q = k\int_{S_{\min}}^{S} \mathrm{d}S$$

$$\ln Q - \ln Q_{\min} = k(S - S_{\min})$$

If we consider the flow rate $Q_{\max}$ which is given by $S_{\max}$ then

$$\ln Q_{\max} - \ln Q_{\min} = k(S_{\max} - S_{\min})$$

Eliminating k from these two equations gives

$$\frac{\ln Q - \ln Q_{\min}}{\ln Q_{\max} - \ln Q_{\min}} = \frac{S - S_{\min}}{S_{\max} - S_{\min}}$$

$$\ln \frac{Q}{Q_{\min}} = \frac{S - S_{\min}}{S_{\max} - S_{\min}} \ln \frac{Q_{\max}}{Q_{\min}}$$

and so

$$\frac{Q}{Q_{\min}} = \left(\frac{Q_{\max}}{Q_{\min}}\right)^{(S-S_{\min})/(S_{\max}-S_{\min})}$$

The term **rangeability** R is used for the ratio $Q_{\max}/Q_{\min}$.

To illustrate the above, consider the problem of an actuator which has a stem movement at full travel of 30 mm. It is mounted with a control valve having an equal percentage plug and which has a minimum flow rate of 2 m^3/s and a maximum flow rate of 24 m^3/s. What will be the flow rate when the stem movement is (a) 10 mm, (b) 20 mm?

Using the equation

$$\frac{Q}{Q_{\min}} = \left(\frac{Q_{\max}}{Q_{\min}}\right)^{(S-S_{\min})/(S_{\max}-S_{\min})}$$

we have for (a) $Q = 2 \times (24/2)^{10/30} = 4.6\text{m}^3/\text{s}$ and for (b) $Q = 2 \times (24/2)^{20/30} = 10.5\text{m}^3/\text{s}$.

The relationship between the flow rate and the stem displacement is the inherent characteristic of a valve. It is only realised in practice if the pressure losses in the rest of the pipework etc. are negligible compared with the pressure drop across the valve itself. If there are large pressure drops in the pipework so that, for example, less than half the pressure drop occurs across the valve, then a linear characteristic might become almost a quick-opening characteristic. The linear characteristic is thus widely used when a linear response is required and most of the system pressure is dropped across the valve. The effect of large pressure drops in the pipework with an equal percentage valve is to make it more like a linear characteristic. For this reason, if a linear response is required when only a small proportion of the system pressure is dropped across the valve, then an equal percentage value might be used.

7.7.2 Control valve sizing

The term **control valve sizing** is used for the procedure of determining the correct size of valve body. The equation relating the rate of flow of liquid Q through a wide open valve to its size is

$$Q = A_V\sqrt{\frac{\Delta P}{\rho}}$$

where A_V is the valve flow coefficient, ΔP the pressure drop across the valve and ρ the density of the fluid. This equation is sometimes written, with the quantities in SI units, as

$$Q = 2.37 \times 10^{-5} C_V\sqrt{\frac{\Delta P}{\rho}}$$

where C_V is the valve flow coefficient. Alternatively it may be found written as

$$Q = 0.75 \times 10^{-6} C_V\sqrt{\frac{\Delta P}{G}}$$

where G is the specific gravity or relative density. These last two forms of the equation derive from its original specification in terms of US gallons. Table 7.1 shows some typical values of A_V, C_V and valve size

Table 7.1 Flow coefficients and valve sizes.

Flow coefficients	Valve size (mm)							
	480	640	800	960	1260	1600	1920	2560
C_V	8	14	22	30	50	75	110	200
$A_V \times 10^{-5}$	19	33	52	71	119	178	261	474

To illustrate the above, consider the problem of determining the valve size for a valve that is required to control the flow of water when the maximum flow required is $0.012\ m^3/s$ and the permissible pressure drop across the valve at this flow rate is 300 kPa. Using the equation

$$Q = A_V\sqrt{\frac{\Delta P}{\rho}}$$

then, since the density of water is 1000 kg/m^3,

$$A_V = Q\sqrt{\frac{\rho}{\Delta P}} = 0.012\sqrt{\frac{1000}{300 \times 10^3}} = 69.3 \times 10^{-5}$$

Thus, using Table 7.1, the valve size is 960 mm.

Summary

Pneumatic systems use air, **hydraulic systems** use oil. The main drawback with pneumatic systems is the compressibility of air. Hydraulic systems can be used for 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.

Pneumatic and hydraulic systems use **directional control valves** to direct the flow of fluid through a system. Such valves are on/off valves. The symbol used for such a valve is a square for each of its switching positions, the symbols used in each square indicating the connections made when that switching position is activated.

The **hydraulic** or **pneumatic cylinder** consists of a cylindrical tube along which a piston/ram can slide. There are two basic types, **single-acting cylinders** and **double-acting cylinders.** With single-acting, 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. The other side of the piston is open to the atmosphere. Double-acting cylinders are used when the control pressures are applied to each side of the piston.

Servo and **proportional control valves** are both infinite position valves which give a valve spool displacement proportional to the current supplied to a solenoid.

Process control valves are used to control the rate of fluid flow. 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. There are many forms of valve body and plug, these determining how the valve controls the fluid flow.

Problems

7.1 Describe the basic details of (a) a poppet valve, (b) a shuttle valve.

7.2 Explain the principle of a pilot-operated valve.

7.3 Explain how a sequential valve can be used to initiate an operation only when another operation has been completed.

7.4 Draw the symbols for (a) a pressure-relief valve, (b) a 2/2 valve which has actuators of a push-button and a spring, (c) a directional valve.

7.5 State the sequence of operations that will occur for the cylinders A and B in Figure 7.28 when the start button is pressed (a−, a+, b− and b+ are limit switches to detect when the cylinders are fully retracted and fully extended).

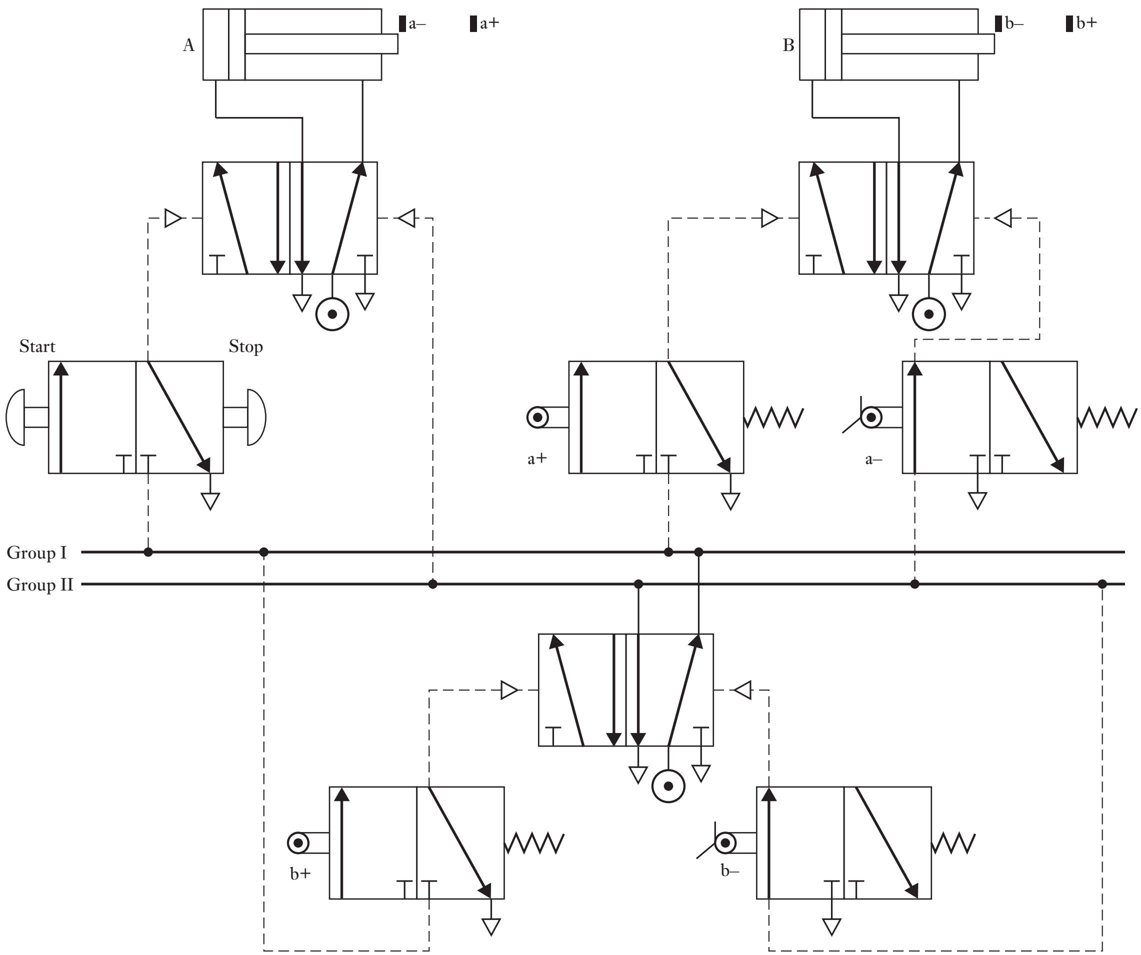

Figure 7.28 Problem 7.5.

7.6 Design a pneumatic valve circuit to give the sequence A+ followed by B+ and then simultaneously followed by A− and B−.

7.7 A force of 400 N is required to open a process control valve. What area of diaphragm will be needed with a diaphragm actuator to open the valve with a control gauge pressure of 70 kPa?

7.8 A pneumatic system is operated at a pressure of 1000 kPa. What diameter cylinder will be required to move a load requiring a force of 12 kN?

7.9 A hydraulic cylinder is to be used to move a workpiece in a manufacturing operation through a distance of 50 mm in 10 s. A force of 10 kN is required to move the workpiece. Determine the required working pressure and hydraulic liquid flow rate if a cylinder with a piston diameter of 100 mm is available.

7.10 An actuator has a stem movement which at full travel is 40 mm. It is mounted with a linear plug process control valve which has a minimum flow rate of 0 and a maximum flow rate of 0.20 m^3/s. What will be the flow rate when the stem movement is (a) 10 mm, (b) 20 mm?