Module
6

Actuators

Lesson 29

Pneumatic Control Components

Instructional Objectives

At the end of this lesson, the student should be able to

- Explain with a sketch the principle of operation of a flapper nozzle amplifier.
- Derive the approximate relationship between the output pressure and displacement for a flapper nozzle amplifier.
- Justify the use of air relay in conjunction with a flapper nozzle amplifier.
- Explain the advantage of using closed loop configuration of flapper nozzle amplifier.
- Sketch and explain the operation of a flapper nozzle amplifier in closed loop.
- Explain the limitation of a direct acting type valve positioner.
- Explain the principle of operation of a feedback type valve positioner.

Introduction

A number of pneumatic components are present in a process control scheme. In earlier days, the complete control system was built up on these components; with the advent of electronics many of them are now replaced by electronic components. Still then, the importance of the pneumatic components cannot be underestimated. Many of the industrial actuators used in steel and automobile industries nowadays are pneumatic. The major advantages of using pneumatic systems are (i) they are intrinsically safe and can be used in hazardous atmospheres, (ii) cheap compared to hydraulic systems (air costs nothing) and (iii) a pneumatic actuator can generate more torque (force) to its own weight and thus have a better torque-weight ratio compared to an electrical actuator. However pneumatic components are slow in response. In this lesson we will discuss different pneumatic components used in process control.

Flapper nozzle amplifier

A pneumatic control system operates with air. The signal is transmitted in form of variable air pressure (often in the range 3-15 psi, i.e. 0.2 to 1.0 bar) that initiates the control action. One of the basic building blocks of a pneumatic control system is the flapper nozzle amplifier. It converts very small displacement signal (in order of microns) to variation of air pressure. The basic construction of a flapper nozzle amplifier is shown in Fig.1. Constant air pressure (20psi) is supplied to one end of the pipeline. There is an orifice at this end. At the other end of the pipe there is a nozzle and a flapper. The gap between the nozzle and the flapper is set by the input signal. As the flapper moves closer to the nozzle, there will be less airflow through the nozzle and the air pressure inside the pipe will increase. On the other hand, if the flapper moves further away from the nozzle, the air pressure decreases. At the extreme, if the nozzle is open (flapper is far off), the output pressure will be equal to the atmospheric pressure. If the nozzle is blockes, the output pressure will be equal to the supply pressure. A pressure measuring device in the pipeline can effectively show the pressure variation. The characteristics is inverse and the pressure decreases with the increase in distance. Typical characteristics of a flapper nozzle amplifier is shown in Fig.2. The orifice and nozzle diameter are very small. Typical value of the orifice diameter is 0.01 inch (0.25 mm) and the nozzle diameter 0.025 inch (0.6 mm). Typical change in pressure is 1.0 psi (66 mbar) for a change in displacement of 0.0001 inch (2.5 micron).

There is an approximate linear range in 3-15 psi, of the characteristics of the amplifier, that is the normal operating range.

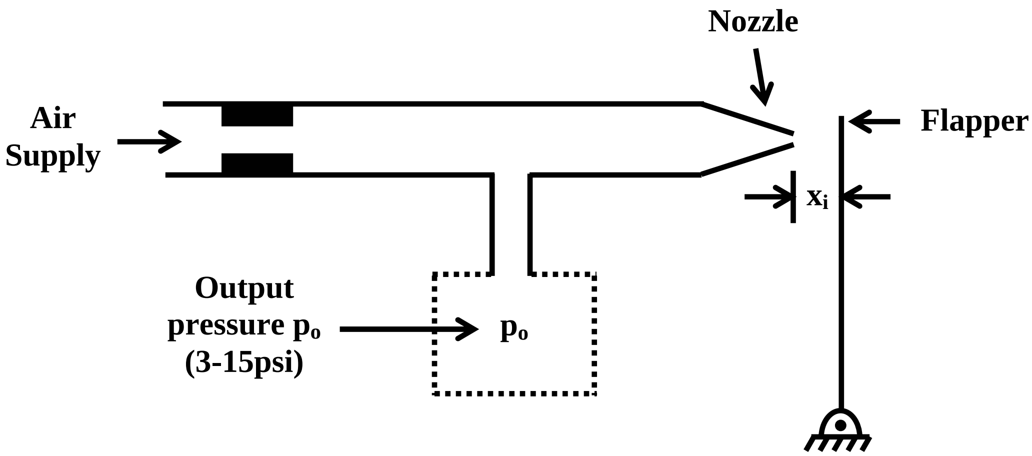

Fig. 1 Flapper nozzle amplifier

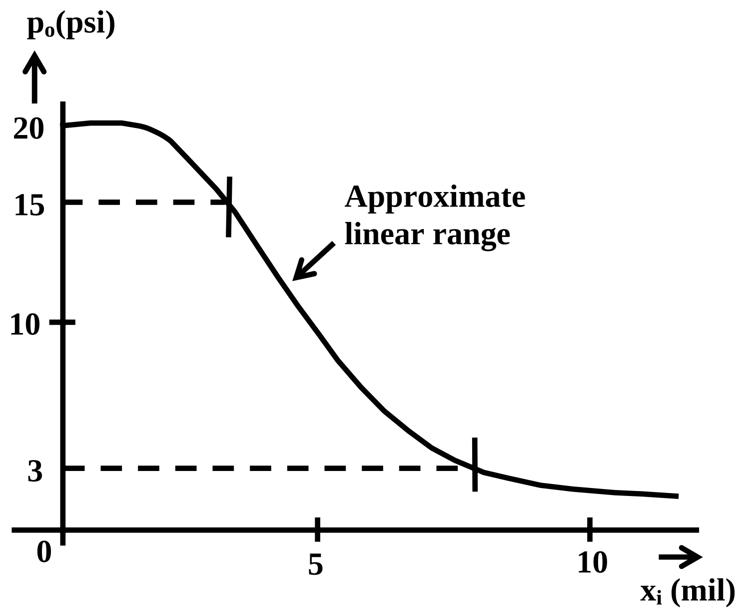

Fig. 2 Characteristics of a flapper nozzle amplifier.

Performance Analysis

The performance analysis of the flapper nozzle amplifier can be carried out in two ways: neglecting the compressibility of air and taking compressibility of air into account. For the sake of simplicity, we shall neglect the compressibility in this section and carry out the simplified analysis.

The mass flow rate through the orifice can be expressed as:

$$G_s = \frac{C_d \pi d_s^2}{4} \sqrt{2\rho (p_s - p_o)} \tag{1}$$

where, C_d is the discharge coefficient of the orifice, d_s is the inside diameter of the orifice, ρ is the density of air, p_s is the supply pressure and p_o is the pressure inside the pipe. The above expression comes directly from the Bernoulli's equation, considering that the area of the orifice is much smaller than the area of the pipe.

For finding out the flow through the nozzle, the flow area is taken as the peripheral area of a cylinder of diameter d_n (nozzle diameter) and length x_i (distance between the flapper and the nozzle). That means that if we imagine a cylinder of diameter d_n and length x_i, the air is going out of the nozzle to the atmosphere in the radial direction and the area of the orifice thus formed will be surface area of the cylinder. Noting that the air pressure outside the cylinder surface is ambient pressure (p_{amb}), similar to (1), we can write the expression for the mass flow rate through the nozzle as:

$$G_n = C_d \pi d_n x_i \sqrt{2\rho (p_o - p_{amb})} \qquad (2)$$

We have assumed air to be incompressible. The discharge coefficient is also assumed to be the same for both the orifice and the nozzle. So at steady state,

$G_s = G_n$, and $p_{amb} = 0$.

Equating (1) and (2) and simplifying, one can obtain:

$$\frac{d_s^4}{16}(p_s - p_o) = d_n^2 x_i^2 p_o$$

or, $$\frac{p_o}{p_s} = \frac{1}{1 + \frac{16 d_n^2}{d_s^4} x_i^2} \qquad (3)$$

Now denoting the normalized pressure $p_n = \frac{p_o}{p_s}$, and the normalized displacement as $x_n = \frac{d_n}{d_s^2} x_i$, we can write,

$$p_n = \frac{1}{1 + 16\, x_n^2} \qquad (4)$$

The p_n vs. x_n characteristics is similar to that shown in Fig.2. The sensitivity can be obtained as:

$$\frac{dp_n}{dx_n} = -32 x_n \frac{1}{(1 + 16 x_n^2)^2} \qquad (5)$$

For sensitivity to be maximum,

$$\frac{d^2 p_n}{dx_n^2} = 0 = -\frac{32(1+16x_n^2)^2 - 32x_n.2(1+16x_n^2).32x_n}{(1+16x_n^2)^4}$$

Solving, one obtains the condition for maximum sensitivity as:

$$x_n^2 = \frac{1}{48}; \text{ or } x_n \approx 0.144$$

The maximum sensitivity, at $x_n = 0.144$ is

$$\frac{dp_n}{dx_n} = -2.59$$

and at this value of x_n,

$$p_n = \frac{1}{1+16x_n^2} = \frac{1}{1+16.\frac{1}{48}} = \frac{3}{4} = 0.75$$

If the supply pressure is 20 psi, the sensitivity is maximum when the output pressure p_0 is around 15 psi. In order to avoid zero or very low sensitivity, the minimum workable pressure is chosen as 3 psi. Thus the working output pressure range of 3-15 psi is normally used for practical applications.

Air Relay

The major limitation of a flapper nozzle amplifier is its limited air handling capacity. The variation of air pressure obtained cannot be used for any useful application, unless the air handling capacity is increased. The situation can be compared with an operational amplifier in an electronic circuit. Though the operational amplifier is useful in amplifying small voltage signals, the output current delivered by the operational amplifier is limited and a power amplifier is used at the output stage in order to drive any device. An air relay serves the similar purpose as a power amplifier. It is used after the flapper nozzle amplifier to enhance the volume of air. The principle of operation of an air relay can be explained using the schematic diagram shown in Fig. 3.

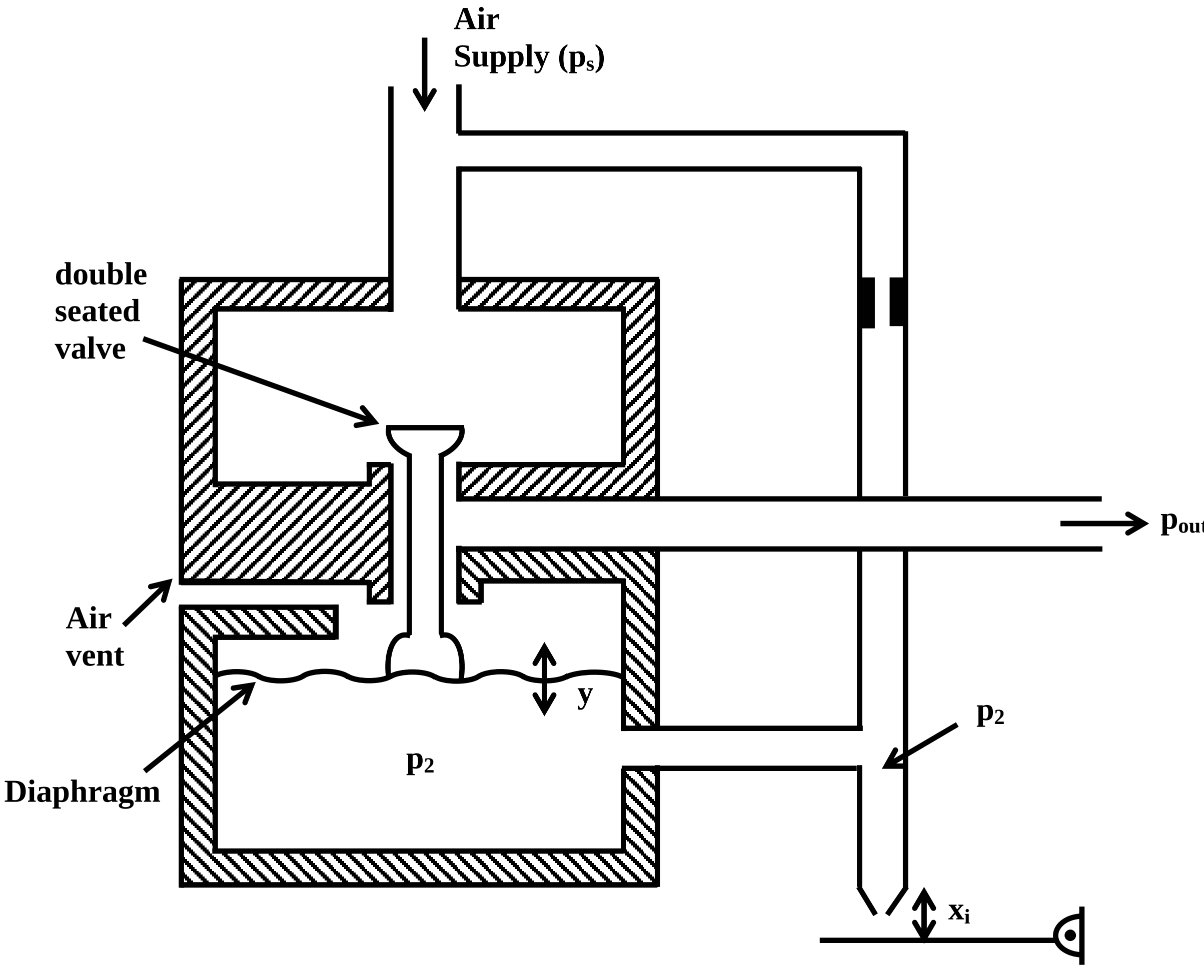

Fig. 3 Schematic diagram of an air relay

It can be seen from Fig.3 that the air relay is directly connected to the supply line (no orifice in between). The output pressure of the flapper nozzle amplifier (p_2) is connected to the lower chamber of the air relay with a diaphragm on its top. The variation of the pressure p_2 causes the movement (y) of the diaphragm. There is a double-seated valve fixed on the top of the diaphragm. When the nozzle pressure p_2 increases due to decrees in x_i, the diaphragm moves up, blocking the air vent line and forming a nozzle between the output pressure line and the supply air pressure line. So more air goes to the output line and the air pressure increases. When p_2 decreases, the diaphragm moves downward, thus blocking the air supply line and connecting the output port to the vent. The air pressure will decrease.

Flapper Nozzle Amplifier with Feedback

Another problem of a flapper nozzle amplifier is its sensitivity variation. It can be easily seen from Eqn. (3) that the output pressure p_0 is dependent on the supply pressure, orifice diameter and the nozzle diameter. Any variation of the supply pressure will affect its sensitivity. Moreover, accumulation of dirt at the nozzle or at the orifice will alter the sensitivity. As a result, some measure is needed to reduce this parameter dependence of the sensitivity. Use of feedback is an effective method for reducing the variation of the sensitivity. Flapper nozzle amplifiers are never used in open loop; it is always used in closed loop (we can draw an analogy with operation amplifiers in this respect: operational amplifiers are always used in closed loop). A typical application of flapper nozzle application with feedback for measurement of pressure and converting the signal in terms of air pressure variation is shown in Fig. 4. The scheme is called a torque balance arrangement.

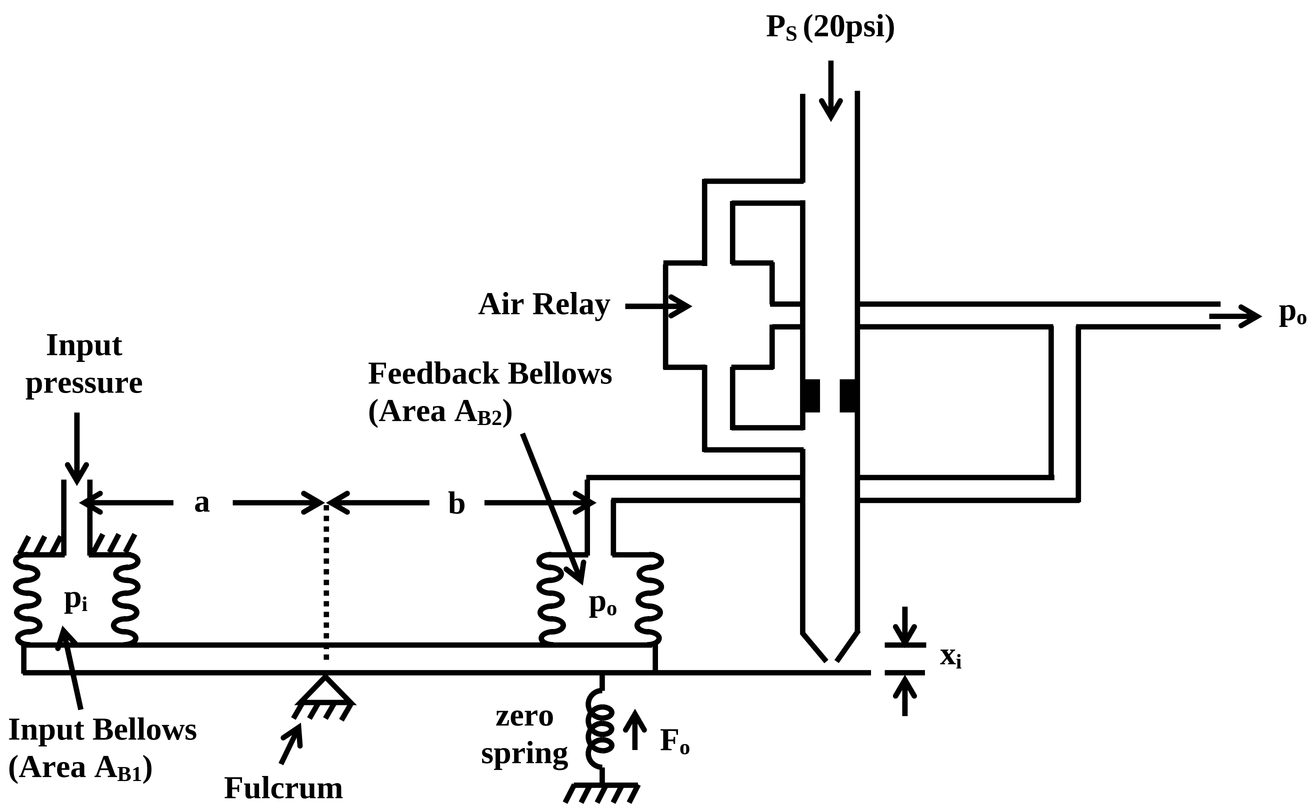

Fig. 4 Flapper nozzle amplifier with feedback.

The basic scheme shown here has two bellows, one measuring the unknown pressure (p_i); the other, known as output bellows is connected to the output pressure line of the system. These two bellows are attached to the two ends of a link, pivoted at some intermediate position. The link towards the output bellows is extended and forms the flapper of the flapper-nozzle amplifier. The output of the flapper nozzle amplifier is connected to the air relay whose output is the output pressure (p_0) of the system. A spring is also attached to the link as shown in Fig.4. One end of the spring is fixed and the other end is connected to the link. The fixed end of the spring can be adjusted so that the spring generates a variable upward force F_0 to the link. This spring is used for zero adjustment, say, when we want that p_0 = 3psi for p_i= 0.

Suppose initially the rigid link is at stable horizontal position. In that case the clockwise and anticlockwise torques on the beam would balance. Looking at Fig.4,

Anticlockwise moment: $T_A = P_i A_{B_1} a + F_0 b$, and

Clockwise moment: $T_C = p_0 A_{B2} b$

Where A_{B1} and A_{B2} are the areas of the two bellows, *a* and *b* are the corresponding lengths of the link segments.

Thereby at balance:

$$p_0 = \frac{A_{B_1}}{A_{B_2}} \frac{a}{b} p_i + \frac{F_0}{A_{B_2}} \tag{6}$$

When the input pressure increases, the left side of the link moves down, thus moving the flapper on the right hand side closer to the nozzle. This will increase the nozzle pressure and subsequently the pressure p_0 at the outlet of the air relay. The bellows in the right hand side is connected to this output pressure line. Increase in this pressure will result in more downward force by the output bellows, thus moving the nozzle back to almost its original position. From the expression given in (6), it is apparent that the output pressure here is independent of the diameters of the orifice and nozzle, thus is not affected by the accumulation of dirt or sensitivity variation due to variation of the supply pressure. Moreover the sensitivity can be adjusted by varying the lengths *a* and *b*.

Electro-pneumatic Signal Converter

It has been mentioned earlier, that the controller used in process control is normally electronic and for actuation pneumatic actuator is the preferred. Thus there is a need for converting the electrical signal (often 4-20 mA) from the controller to pneumatic 3-15 psi signal. Such a scheme is shown in Fig.5. It is similar to that one shown in Fig.4, except there is an electromagnet and a permanent magnet on the left of the link. The current flowing through the electromagnet causes a force of repulsion between the electromagnet and the permanent magnet. An increase in current through the coil increases the repulsive force, thereby moving the link upward on the left hand side and decreasing the gap between the flapper and the nozzle. The feedback action causes the increase in the output pressure and brings back the link in its equilibrium position.

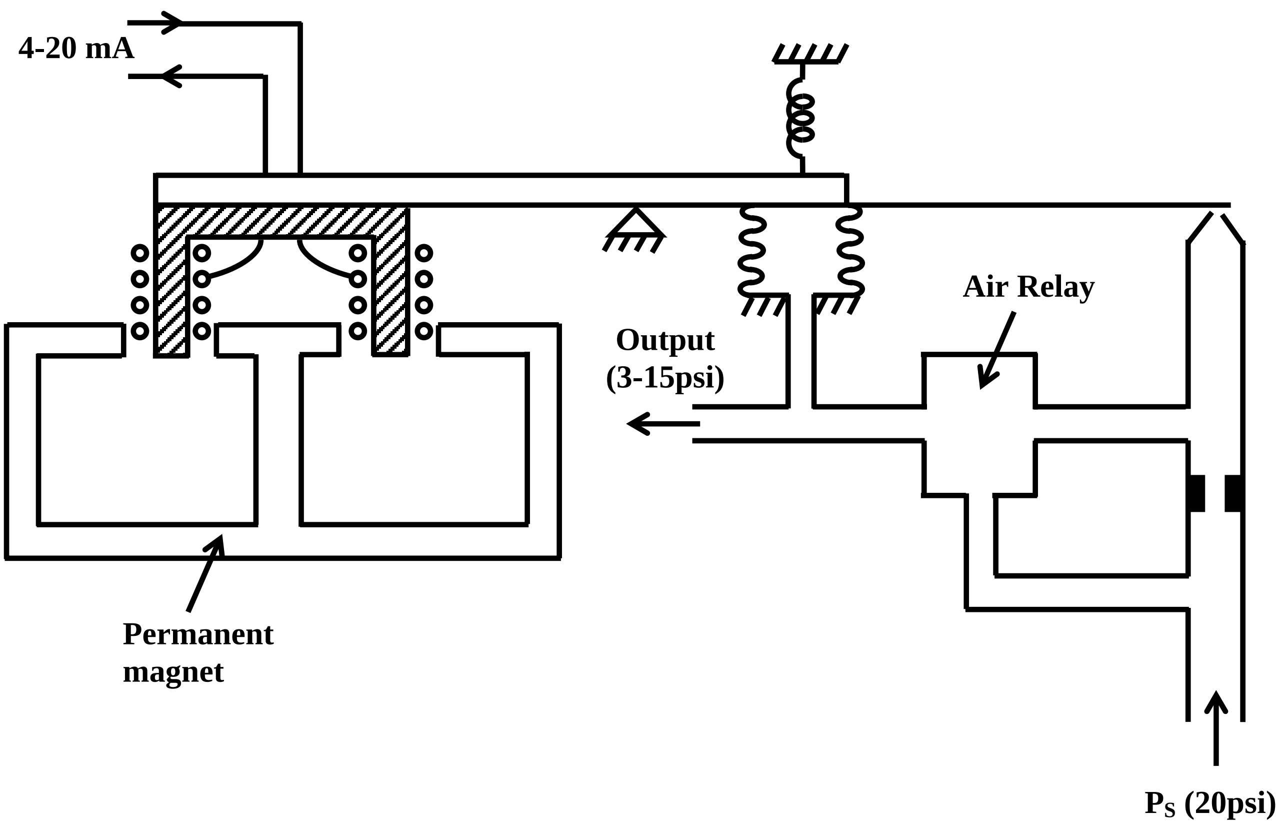

Fig. 5 Electro-pneumatic Signal Converter

Pneumatic Valve Positioner

Pneumatic valve positioner is another important component used in process control. The control valve should be moved up or down, depending on the air pressure signal (3-15 psi). The valve postioner can be of two types, (a) *direct acting type* and (b) *feedback type*. The direct acting type valve positioner is shown in Fig.6. Here the control pressure creates a downward pressure on the diaphragm against the spring, and the stem connected to the diaphragm moves up or down depending on the control pressure p_c. At equilibrium the displacement of the stem can be expressed as:

$$p_c A = K x \qquad (7)$$

where A is the area of the diaphragm and K is the spring constant.

But the major shortcoming of this type of positioner is the nonlinear characteristics. Though ideally, the stem displacement is proportional to the control pressure (from (7)), the effective area of the diaphragm changes as it deflates. The spring characteristics is also not totally linear. Moreover, in (7) we have neglected the upward thrust force exerted by the fluid. The change in thrust force also causes the change in performance of the positioner. Besides the force exerted on the control valve is also not sufficient for handling valves for controlling large flow. As a result, the use of direct acting type valve positioner is limited to low pressure and small diameter pipelines.

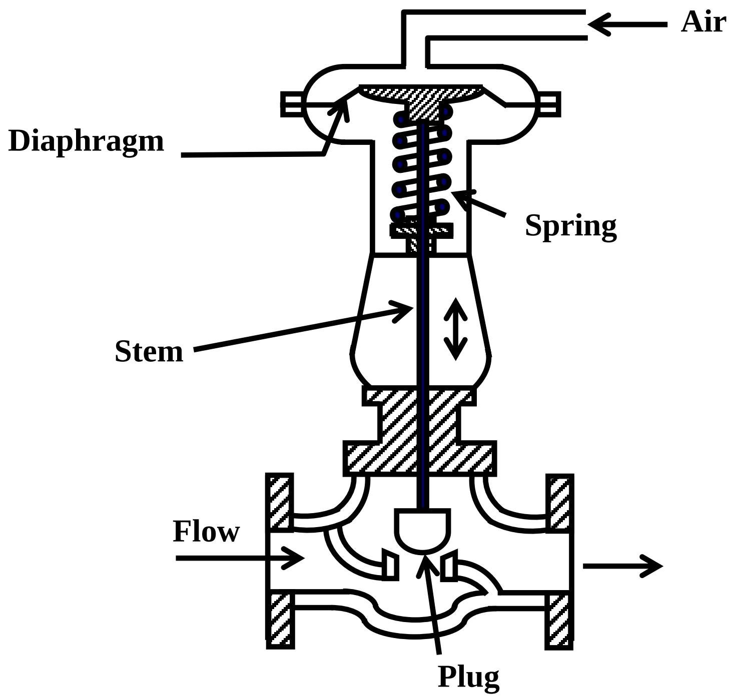

Fig. 6 Direct acting type valve positioner

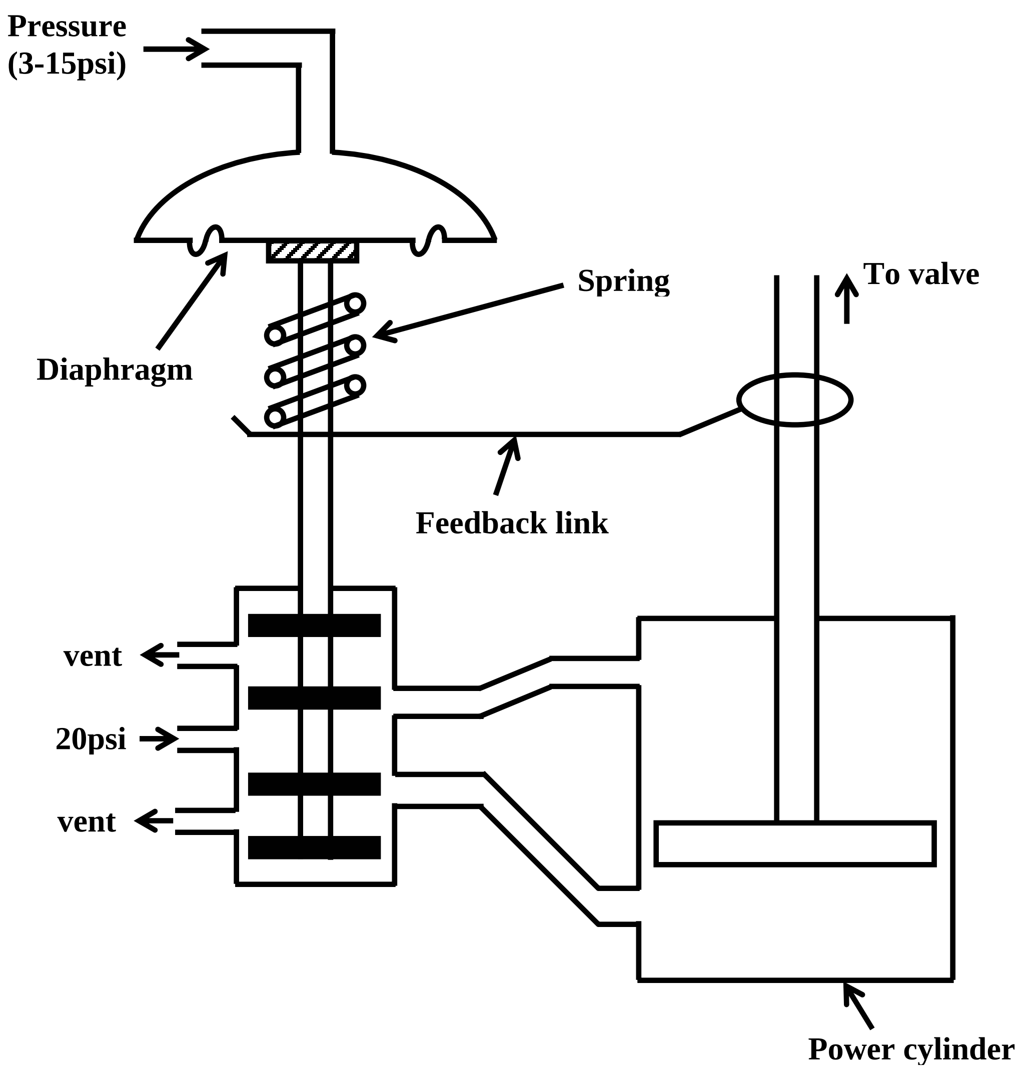

Fig. 7 Feedback type valve positioner

The feedback type valve positioner (Fig.7) has a pilot cylinder with which the diaphragm is attached. The piston of this pilot cylinder opens or closes the air supply and vent ports to the main cylinder whose piston is connected to the stem of the control valve (not shown). There is a mechanical link connected to the stem that adjusts the fixed end of the spring connected to the diaphragm. This link provides the feedback to the postioner. As the control pressure increases, the diaphragm moves down, so is the piston of the pilot cylinder. This causes the lower chamber of the main cylinder to be connected to the 20 psi line and the upper chamber to the vent line. Compressed air enters the bottom of the main cylinder and the piston moves up. As the piston moves up, the feedback link compresses the spring further and this causes the diaphragm to move back to its original position. The air supply and the vent ports are now closed and the piston of the main cylinder remains at its previous position. The relationship between the control pressure and movement of the stem in this case is more or less linear. Moreover due to presence of power cylinder, the scheme is more suitable to position large control valves.

Conclusion

In this lesson we have discussed the construction and principle of operation of a number of pneumatic components normally used in a process control scheme. A flapper nozzle amplifier is most important component among these, the simplified characteristics of a flapper nozzle amplifier, assuming the air to be compressible has been presented in this lesson. The need for using air relay and feedback mechanism with a flapper nozzle amplifier is also elaborated. Majority of the valve positioners are pneumatic. Different types of pneumatic valve postioners are also discussed in this lesson. However two important pneumatic components have been left out. The first one is air pressure regulator and the second one is air filter. Air pressure regulator is needed to provide constant pressure air supply (20 psi) irrespective of air flow variation. Air filter removes moisture and dirt present in the air before it is used in the pneumatic components. Interested readers are requested to consult the books referred for understanding the construction and principle of operation of these two devices.

Pneumatic controllers, though not so popular nowadays, are built up on these basic components discussed in this lesson. The details of pneumatic P-I-D controllers would be discussed in the next lesson.

References

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Review Questions

1. Explain with a simple sketch the principle of operation of a flapper nozzle amplifier.
2. Sketch the input-output characteristics of a flapper nozzle amplifier.
3. Identify the factors those affect the sensitivity of a flapper nozzle amplifier.
4. What is the function of air relay in pneumatic control?
5. What is the major advantage of using a flapper nozzle amplifier in closed loop?
6. Sketch and explain the working principle of a pneumatic torque balance transducer.
7. Explain the construction and working principle of a direct acting type pneumatic valve postioner. What are the limitations of this type of positioners?
8. How can you convert a 4-20mA current signal to a 3-15 psi pressure signal? Explain with a schematic.