1 Final Control Elements

Operation of the closed-loop control system depends on the performance of each loop component, including the final control element, whether it be damper, variable speed pump, motor relay, saturable reactor, or valve. Each of these elements requires an actuator that will make the necessary conversion from controller output signal to element input. This controller output may be pneumatic or electric and in some cases hydraulic or mechanical. The first need, then, is a device, an actuator, that will convert this control signal into a force that will position the final control element [1].

The control valve, or final control element, is the last device in the control loop. It takes a signal from the process instruments and acts directly to control the process fluid. Control valves maintain process variables such as pressure, flow, temperature, or level at their desired value, despite changes in process dynamics and load [2]. At least 90\% of all analogue output channels terminate in an automatic control valve, and some 50\% of all discrete output channels terminate in an automatic isolating valve [6].

1.1 Valves

There is much variety in valve design. The most widespread types are ball, butterfly, diaphragm, and globe.

The most versatile of the control valves are the sliding-stem valves. Sliding-stem valves are built ruggedly to handle conditions such as piping stress, vibration, and temperature changes. For many extreme applications, sliding stem valves are the only suitable choice. This includes valves for high pressure and temperature, antinoise valves, and anticavitation valves [7].

Globe Valves

The actuator, often referred to as the motor, and the valve body are functionally distinct although in practice they are normally supplied as a single unit.

The essential feature of a globe valve is its plug and seat assembly. Upwards movement of the stem causes the plug to lift out of its seat. This varies the cross sectional area of the annulus between the plug and its seat resulting in a change in flow. The relationship between the stem position and the flow through the annulus is known as the valve’s characteristic.

Differential pressure of the process fluid \((P_1 - P_2)\) across a valve plug will generate a force parallel to the stem as described by the formula \(F = PA\), with \(A\) being the plug’s effective area presented for the pressure to act upon. In a single-ported globe valve, there will only be one force generated by the process pressure. In a double-ported globe valve, there will be two opposed force vectors, one generated at the upper plug and another generated at the lower plug. If the plug areas are approximately equal, then the forces will likewise be approximately equal and therefore nearly cancel. This makes for a control valve that is easier to actuate (i.e. the stem position is less affected by process fluid pressures) [5]. Because double seated valves are used in highly turbulent situations,
it is necessary for the stem to be guided at both top and bottom of the body. This prevents the stem from vibrating and avoids fracture due to metal fatigue. The principal disadvantage of a double seated valve is that it is difficult to achieve-shut off in both seats. This is especially true at high temperatures due to differential expansion effects. For this reason double seated valves should not be used for isolating purposes.

Acoustic noise is a potential problem for valves. Noise is caused, if the pressure drop across the valve is large, by virtue of the high velocities involved. A basic strategy in valve design is to counter noise at source by minimizing velocities within the plug and seat assembly, and by avoiding sudden expansions and changes in direction of the flow path.

Advantages

- Reduced actuator force due to balancing.
- Action easily changed (Direct/Reverse).
- High flow capacity.

Disadvantages

- Poor shutoff.
- Only semi-balanced.
**Butterfly Valves**

The valve consists of a circular disc which is rotated in a body. The maximum rotation is about 90°. The body has integral rims against which the disc seats. The rims often have some elastomeric ring to provide a tight seal. The rotation of the disc may be symmetrical with respect to the axis of the pipe, or offset. The cross section of the disc is usually contoured to enhance the valve’s characteristic.

![Figure 2: Butterfly valve](image)

Its main advantage is high capacity in a small package and a very low initial cost. The high performance butterfly valve is a development from the conventional valve where the rotation axis of the disc is offset from both the centreline of flow and the plane of the seal. This design produces a number of advantages, including better seal performance, lower dynamic torque, and higher allowable pressure drops. The seal performance is improved because the disc cams in and out of the seat, only contacting it at closure and so wear is reduced. As the disc only approaches the seal from one side, the pressure drop across the valve can be used to provide a pressure assisted seal. This further improves performance.

The modified shape and contour of the disc are used to reduce dynamic torque and drag. This also permits higher pressure drops. As the disc is never hidden behind the shaft, good control through the 90 degrees of operation is possible with a linear characteristic [8].

**Advantages**

- Low cost and weight.
- High flow capacity.
- Low stem leakage.

**Disadvantages**

- Oversizing.
Ball valve

![Ball valve diagram](image)

Figure 3: Ball valve

It consists of a ball that rotates in a body. The ball is normally of stainless steel and the body of mild steel. Rotation of the ball varies the alignment of a cylindrical port through the ball with the flow passage through the body and pipework. The standard ball valve has a port diameter that is about 80% of the pipe diameter, which makes for a compact valve. The alternative full-port ball valve has a port that is the same diameter as the pipeline which enables full bore flow. The full-port ball valve is the only type of valve that is wholly non-invasive. However, it is more bulky and requires a more powerful actuator [2].

**Advantages**

- Lower cost and weight.
- Higher flow capacity (2-3 times that of the globe valve).
- Tight shutoff.
- Low stem leakage.

**Disadvantages**

- Oversizing.

**Diaphragm valve**

The most common diaphragm valve is the weir type as shown [4]. The valve is shown open; closure is achieved by forcing a flexible membrane down onto the weir. Diaphragm valves are good for slurries and liquids with suspended solids, are low cost devices, but tend to require high maintenance, and have poor flow characteristics.
Figure 4: Weir type diaphragm valve

Table 1: Essential characteristics [6]

<table>
<thead>
<tr>
<th></th>
<th>Globe</th>
<th>Butterfly</th>
<th>Ball</th>
<th>Diaphragm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>0.5 – 40 cm</td>
<td>2 – 500 cm</td>
<td>1.5 – 90 cm</td>
<td>0.5 – 50 cm</td>
</tr>
<tr>
<td>$T_{\text{max}}$</td>
<td>650 °C</td>
<td>1200 °C</td>
<td>750 °C</td>
<td>175 °C</td>
</tr>
<tr>
<td>$P_{\text{max}}$</td>
<td>10 – 500 bar</td>
<td>5 – 400 bar</td>
<td>5 – 100 bar</td>
<td>2 – 15 bar</td>
</tr>
<tr>
<td>Applications</td>
<td>Good for extreme conditions</td>
<td>Large size. Good with viscose fluids.</td>
<td>Good for slurries but not gritty materials.</td>
<td>Good for difficult fluids: corrosive, suspended solids, sticky liquids.</td>
</tr>
</tbody>
</table>

1.2 Control Valve Characteristics

$$Q = C_v \sqrt{\frac{P_1 - P_2}{G}}$$

where $Q$ - flow rate,
$C_v$ - valve sizing coefficient,
$P_1$ - upstream pressure,
$P_2$ - downstream pressure,
$G$ - liquid specific gravity (water = 1).

The flow characteristics of a control valve show the rate of flow for the range of valve operation. There are two types of flow characteristics for control valves:

- inherent
- installed

The inherent characteristic is determined by testing the valve flow versus valve lift using a constant differential pressure drop across the valve throughout the test.

It should be noted that the manufacturer’s characteristic curves are different from installed flow characteristic. In operation, the differential pressure across the valve varies throughout the valve position due to the system characteristics.

Control valve trim is manufactured in a variety of different “characteristics” to provide the desired installed behavior.

- Linear
- Equal percentage
- Quick-opening

“Linear” valve trim exhibits a fairly proportional relationship between valve stem travel and flow capacity ($C_v$), while “equal percentage” trim is decidedly nonlinear. A control valve with “linear” trim will exhibit consistent responsiveness only with a constant pressure drop, while “equal percentage” trim is designed to counteract the droop caused by changing pressure drop when installed in a process system. "Quick-opening", where the valve’s $C_v$ increases dramatically during the initial stages of opening, but then increases at a much slower rate for the rest of the travel. Quick-opening valves are often used in pressure-relief applications, where it is important to rapidly establish flow rate during the initial portions of valve stem travel [5].

Different valve characteristics may be achieved by re-shaping the valve trim.

**Control valve problems**

1. Mechanical friction
2. Flashing
3. Cavitation
4. Choked flow
5. Noise
6. Corrosive chemicals

If the fluid being throttled by the valve is a liquid (as opposed to a gas or vapor), and its absolute
pressure ever falls below the vapor pressure of that substance, the liquid will begin to boil. This phenomenon, when it happens inside a control valve, is called flashing. As the Fig. 9 shows, the point of lowest pressure inside the valve (called the vena contracta pressure, or $P_{vc}$) is the location where flashing will first occur, if it occurs at all [5]. If, however, the pressure recovers to a point greater than the vapor pressure of the liquid, the vapor will re-condense back into liquid again. This is called cavitation. As destructive as flashing is to a control valve, cavitation is worse. When vapor bubbles recondense into liquid they often do so asymmetrically, one side of the bubble collapsing before the rest of the bubble. This has the effect of translating the kinetic energy of the bubble’s collapse into a high-speed “jet” of liquid in the direction of the asymmetrical collapse. No substance known is able to continuously withstand this form of abuse, meaning that cavitation will destroy any control valve given enough time [5]. When the flow stream partly changes to a vapor, as in the case of flashing, the space that it occupies is increased. Because of the reduced available area, the capacity for the valve to handle larger flows is limited. Choked flow is the term used when the flow capacity is limited in this way.
1.3 Actuators

An actuator is a device that applies the force (torque) necessary to cause a valve’s closure member to move. Actuators must overcome pressure and flow forces as well as friction from packing, bearings or guide surfaces, and seals; and must provide the seating force. In rotary valves, maximum friction occurs in the closed position, and the moment necessary to overcome it is referred to as breakout torque. The rotary valve shaft torque generated by steady-state flow and pressure forces is called dynamic torque. It may tend to open or close the valve depending on valve design and travel. In linear stem-motion valves, the flow forces should not exceed the available actuator force, but this is usually accounted for by default when the seating force is provided.

Actuators often provide a fail-safe function. In the event of an interruption in the power source, the actuator will place the valve in a predetermined safe position, usually either full-open or full-closed. Safety systems are often designed to trigger local fail-safe action at specific valves to cause a needed action to occur, which may not be a complete process or plant shutdown.

Actuators are classified according to their power source. The nature of these sources leads naturally to design features that make their performance characteristics distinct [7].

Pneumatic

Despite the availability of more sophisticated alternatives, the pneumatically driven actuator is still by far the most popular type. Historically the most common has been the spring and diaphragm design. The compressed air input signal fills a chamber sealed by an elastomeric diaphragm. The pressure force on the diaphragm plate causes a spring to be compressed and the actuator stem to move. This spring provides the fail-safe function and contributes to the dynamic stiffness of the actuator.

The spring also provides a proportional relationship between the force generated by air pressure and stem position. The pressure range over which a spring and diaphragm actuator strokes in the absence of valve forces is known as the bench set. The chief advantages of spring and diaphragm actuators are their high reliability, low cost, adequate dynamic response, and fail-safe action—all of which are inherent in their simple design [4].

Advantages

- Fail safe operation

Disadvantages

- Actuator force must work against spring.
- Temperature limitations
Motion Conversion

Actuator power units with translational output can be adapted to rotary valves that generally need $90^\circ C$ or less rotation. A lever is attached to the rotating shaft, and a link with pivoting means on the end connects to the linear output of the power unit, an arrangement similar to an internal combustion engine crankshaft, connecting rod, and piston.

Friction and the changing mechanical advantage of these motion conversion mechanisms mean the available torque may vary greatly with travel [4].

Hydraulic

The design of typical hydraulic actuators is similar to that of double-acting piston pneumatic types. One key advantage is the high pressure [typically 35 to 70 bar], which leads to high thrust in a smaller package. The incompressible nature of the hydraulic oil means these actuators have very high dynamic stiffness. The incompressibility and small chamber size connote fast stroking speed and good frequency response. The disadvantages include high initial cost, especially when considering the hydraulic supply. Maintenance is much more difficult than with pneumatics, especially on the hydraulic positioner [4].

Advantages

- Fast response to control signals.
- High loads.
- Variable stroking speed and stiffness.

Disadvantages

- Requires external hydraulic supply.
- Not spring loaded, generally not fail-safe.

Electromechanical

The most common electric actuators use a typical motor through a gearbox. Electric actuators are often used for on/off service.

Advantages

- High thrust.
- Easily interfaced to control system.
Disadvantages

- Large.
- More expensive than pneumatic.
- High power electrical source.
- Poor controllability.

Manual

A manually positioned valve is by definition not an automatic control valve, but it may be involved with process control.
Bibliography


