Calculation of On/off Valve Actuation Time and Study on Air Circuit Optimization

I. Introduction

Pneumatic control systems are an important part of modern industrial automation control, whose main function is to achieve automated control of industrial processes. As the core component in pneumatic control systems, the actuation time of on/off valves directly affects the system's response time and control precision. Therefore, how to calculate the actuation time of on/off valves and optimize the air circuit is an important issue in the design and optimization of pneumatic control systems.

II. Calculation Method for the Actuation Time of On/off Valves

The calculation of the actuation time of On/off valves is an important issue in the design and optimization of pneumatic control systems. In practical applications, the actuation time of on/off valves is influenced by various factors, such as supply air pressure, spool mass, and air circuit design. This article needs to derive the calculation formula for the actuation time of on/off valves through theoretical analysis.

2.1 Schematic Diagram and Principle of the Air Circuit of On/off Valves【2】

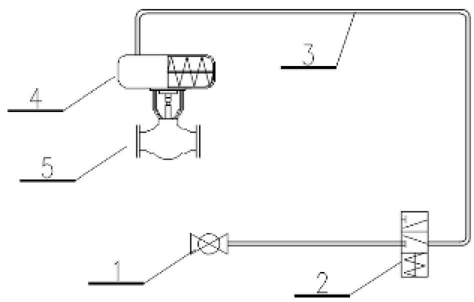

Figure 2: Schematic Diagram of the Air Circuit of the On/off Valve

1. Pneumatic Ball Valve
2. Solenoid Valve
3. Air Supply Tubing
4. On/off Valve with Single-Acting Pneumatic Actuator
5. On/off Valve Body

When the solenoid valve is energized:

The solenoid valve (2) is activated by energization, the air tubing is opened, and the instrument air at 0.45MPa from the main air supply flows through the air supply pipe (3) to the pneumatic actuator (4), compressing the spring, moving the rack inside the actuator, which turns the valve stem, rotating the ball inside the valve body, and achieving a fully open (or close) action.

When the solenoid valve is de-energized:

The internal spring of the solenoid valve resets, cutting off the main air intake tubing, and the air inside the pneumatic actuator is exhausted through the exhaust end of the solenoid valve along the air supply pipe, the spring inside the pneumatic actuator resets, and the rack inside the actuator moves in the reverse direction, achieving a fully close (or open) action.

The above is the working principle of the interlocking on/off valve's opening and closing process.

Theoretical Analysis of the Actuation Time of the On/off Valve

In pneumatic control systems, the total actuation time of a on/off valve can be divided into two parts: the opening time and the closing time. The opening time refers to the time required for the valve spool to start moving to the open position; the closing time refers to the time required for the valve spool to start moving to the closed position. Therefore, the total actuation time of the on/offvalve can be represented as:

$$t = t1 + t2$$

where (t1) is the opening time, and (t2) is the closing time.

To simplify the analysis, only the opening actuation time of the on/off valve is analyzed.

The opening action of the on/off valve can be divided into three stages according to the principle: the energization action of the solenoid valve, the flow of instrument air inside the air supply pipe, and the movement of the piston in the pneumatic valve cylinder, with the rotation of the valve core and the movement of the piston being synchronized.

Assuming that the energization action time of the solenoid valve is t1, the transmission time of instrument air inside the air supply pipe is t2, and the movement time of the piston in the pneumatic valve cylinder is t3, then the single-trip actuation time t of the on/off valve can be represented as:

$$t=t1+t2+t3$$

a) Energization action time of the solenoid valve:

The energization action time of the solenoid valve is related to the inherent characteristics of the solenoid valve and can be obtained through experiments or manufacturer's data.

b) Transmission time of instrument air inside the air supply pipe:

Assuming:

L: Length of the supply pipeline (m)

D: Diameter of the supply pipeline (m)

P in: Supply pressure (Pa)

P out: Working pressure required by the pneumatic valve (Pa)

ρ: Density of the gas (kg/m^3)

μ: Dynamic viscosity of the gas (Pa·s)

Q: Flow rate of the supply pipeline (m^3/s)

Pipeline pressure loss:

$$\Delta P = \frac{f\,((L / D)\,(\rho\,(Q^2)))}{((2\,\pi\,(D^4) / 16))} \qquad (1)$$

Among these, ΔP represents the pressure loss in the pipeline, and f is the friction factor. The friction factor f is related to the pipeline surface's relative roughness (ϵ/D) and the number of bends in the pipeline tubing. The air supply pipe is an internally smooth seamless steel pipe with very low surface roughness. After obtaining the pressure loss in the pipeline, we can calculate the time t required for the gas to be transmitted from the source to the pneumatic valve. Assuming the pressure needed for the valve's action is Pout, the following formula can be derived based on the motion formula:

$$t2 = \frac{V\,L}{(Q\;(P\_in - \Delta P - P\_out\;))} \qquad (2)$$

Where, V is the average velocity of the gas in the pipeline (m/s).

c) Movement time of the piston in the pneumatic valve cylinder:
A mathematical model has been established based on the motion formula.

$$t3 = \frac{m\,Ls}{A\;(p - F\;)} \qquad (3)$$

Where:
t - movement time of the cylinder piston;
m - mass of the cylinder piston;
Ls - stroke length of the cylinder;
A - effective area of the cylinder piston;
P - supply pressure;
F_ - friction force and other resistances faced by the cylinder piston during movement.
From the formula, it can be derived that.

The main factors affecting the movement time of the piston in the pneumatic on/off valve include the following:

1. **Supply pressure:** The pressure of the air source affects the movement speed of the cylinder piston; the higher the pressure, the faster the piston moves.
2. **Effective area of the cylinder piston:** The effective area of the cylinder piston directly affects the pneumatic pressure it receives; the larger the effective area, the greater the pneumatic pressure,

and the faster the piston moves.

3. Cylinder stroke: The stroke length that the cylinder piston needs to complete affects its movement time; the longer the stroke, the longer the movement time.

4. Mass of the cylinder piston: When the piston mass is large, it requires greater pneumatic pressure to move, thereby affecting the piston's movement speed and time.

5. Airflow and valve switching speed: The switching speed of the pneumatic valve and airflow affect the piston's movement speed; the faster the switching speed and the greater the airflow, the faster the piston moves.

6. Internal friction and other resistances: During movement, the cylinder piston needs to overcome internal friction and other resistances; the magnitude of these resistances also affects the piston's movement speed and time.

Translation:

Combining the formulas, thus the one-way actuation time of the on/off valve equals:

$$T = \frac{V\,L}{\left(Q\ \left(P\_in - \frac{((L/D)\,(\rho\,(Q^2)))}{((2\,\pi\,(D^4)/16))} - P\_out\right)\right)} + \frac{m\ lS}{A\,(p - F)} + \text{Action time of Solenoid Valve}$$

Consider Pin=P;

$$T = \frac{V\,L}{\left(Q\ \left(P\_in - \frac{8L\rho Q^2}{\pi D^3} - P\_out\right)\right)} + \frac{m\ \ Ls}{A\,(P\_in - F)} + \text{Action time of Solenoid Valve} \qquad (4)$$

Several parameters are inherent characteristics related to the mechanical processing of the equipment or the physical properties of the gas, which cannot be changed: such as P_{out} (the working pressure required by the pneumatic valve), ρ (gas density), μ (gas dynamic viscosity), m (mass of the cylinder piston), Ls(stroke length of the cylinder), A (effective area of the cylinder piston), F_ (friction force and other resistances faced by the cylinder piston during movement). These parameters do not need to be considered in the analysis.

There are three parameters related to the actuation time T:

a. The supply pressure (P_{in}) is in the denominator, the larger it is, the smaller T becomes.

b. The length of the supply pipeline (L) has a certain positive correlation with T; the larger it is, the larger T becomes.

c. The diameter of the supply pipeline (D) appears in the denominator as a cubic term, so even a small change can have a magnified effect on the final result. The larger D is, the smaller T becomes.

III. Methods for Air Circuit Optimization

Air circuit optimization refers to reducing the system's response time and errors and improving the system's control accuracy by changing the design and parameters of the air circuit. In practical applications, air circuit optimization is an important part of the design and optimization of pneumatic control systems.

Through the analysis of Formula 4, it can be started by changing the supply pressure (P_{in}), the length of the supply pipeline (L), and the diameter of the supply pipeline (D).

a. Optimization of Air Circuit Design

In air circuit design, factors such as the length, diameter, bends, and branches of the air tubing need to be considered. To reduce the resistance and pressure loss in the air tubing, the following air circuit design methods can be adopted in engineering design:

(1) Minimize the bends in the air tubing and avoid bends and branches, which can reduce the pressure loss of instrument air transmission inside the air supply pipe.

(2) In plane supply design, place the main supply pipe close to the equipment. For pneumatic valves that consume a large amount of air or have large fluctuations, a single-line supply method should be adopted, and the supply branch pipes should be designed to take the shortest possible tubing, reducing the length of the air tubing, which can achieve the goal of shortening the full-stroke actuation time of the interlocking shutoff valve. As shown in Figure 3.1.

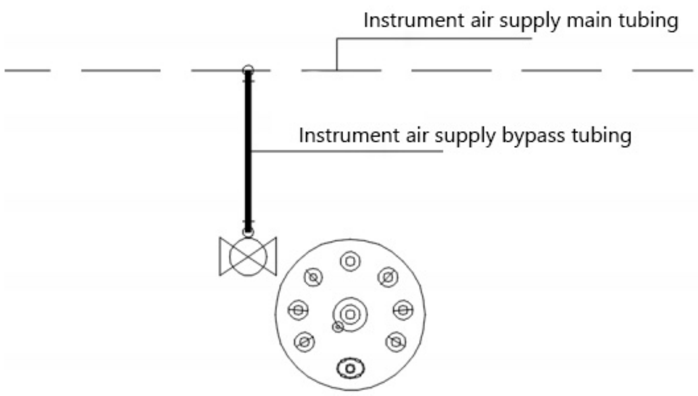

Figure 3.1 Schematic diagram of valve air supply layout

b. Optimization of Air tubing Parameters

In the optimization of air tubing parameters, factors such as the volume, pressure, and flow rate of the air tubing need to be considered. To reduce the system's response time and error, the following air tubing parameter optimization methods can be adopted in nominal design:

(1) Increase the cross-sectional area of the air tubing.

According to design standards, the minimum recommended pipe diameter for the upstream supply system of the valve is 1/2in. The specification selection for piping downstream of the air source ball valve is determined based on instrument selection, with common stainless steel pipe specifications including Ø 12x1.2mm, Ø 10x1mm, Ø 8x1mm, and Ø 6x1mm【3】. Larger valves, which have greater cylinder piston mass and stroke distance, require larger stainless steel piping specifications to compensate for these parameter effects, based on past experience.

For valves with DN100 diameter and above, Ø 10x1 stainless steel piping is suitable, while valves with smaller diameters can uniformly use Ø 8x1mm or Ø 6x1mm piping.

(2) Equip on/off valves with quick exhaust valves

Installed at the outlet of the pneumatic actuator so that the cylinder's exhaust does not have to go through the directional valve but is quickly expelled, accelerating the reciprocating speed of the cylinder, shortening the exhaust tubing of the cylinder, and improving the response speed. As shown in Figure 3.2.

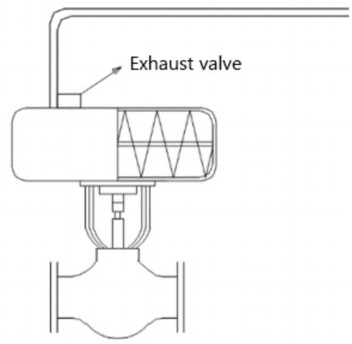

Figure 3.2 Valve equipped with quick exhaust valve diagram

(3) Increase the supply pressure of the air source to the valve

This measure will increase the energy consumption of the system, so it can be applied to valves that require fast action in emergencies by equipping them with independent air source tanks, which are set to a higher supply pressure.

IV. Conclusion

This article studied the calculation method for the actuation time of on/off valves and methods for air circuit optimization. Through theoretical analysis, the calculation formula for the actuation time of on/off valves was derived, and air circuit optimization schemes were analyzed, providing certain reference significance for improving the response speed of on/off valves.

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