Analysis and Simulation of Throttle Speed Regulation in hydraulic system

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Abstract. The throttle speed control loop has a simple structure and is an important speed control loop in hydraulic transmission. The working characteristics of three throttling speed control loops are studied. The simulation model of the outlet throttling speed control loop and the bypass throttling speed control loop is established by AMESIM software, and their respective load characteristics and speed characteristics are analysed. This provides a theoretical basis for selecting the right and appropriate hydraulic system speed control loop.

1. Introduction

Throttle speed regulation is an important speed regulation method in hydraulic transmission[1]. The speed of the actuator in the hydraulic system can be adjusted by adjusting the opening area of the throttle valve in the hydraulic circuit. The speed control loop has the advantages of simple structure, reliable operation, low cost and large speed regulation range, and is generally applicable to occasions where power is not large. According to the different installation positions of the throttle valve in the hydraulic pipeline, the hydraulic system speed control loop can be divided into an inlet throttle speed control loop, an outlet throttle speed control loop and a bypass throttle speed control loop[2]. The load characteristics and speed characteristics of different speed control loops are different. The AMESIM software can be used to build the throttle speed control model[3], which can easily analyse the working characteristics of different speed control loops and facilitate the research on hydraulic throttle speed control system[4].

2. Analysis of throttling speed control loop characteristics

2.1. Inlet throttle speed control loop

Figure 1 shows the inlet throttle speed control loop. The flow rate of the metering pump is constant, the oil supply pressure is set by the overflow valve, and the throttle valve is connected in series between the metering pump and the hydraulic cylinder. The hydraulic oil is pressurized by the hydraulic pump and enters the hydraulic cylinder through the throttle valve to overcome the load and push the piston to move to the right at a certain speed. The excess portion of the pressure oil output from the pump flows back to the tank through the relief valve. Ignoring the volume loss of the circuit and the mechanical efficiency of the hydraulic cylinder, when the hydraulic cylinder piston runs stably, the piston force equation is:

\[ p_1A_1 - p_2A_2 = F \]  

(1)
In the formula: \( A_1 \) is the effective working area of the rodless cavity of the hydraulic cylinder; \( A_2 \) is the effective working area of the cylinder with the rod cavity; \( P_1 \) is the hydraulic cylinder inlet pressure; \( P_2 \) is the hydraulic cylinder return chamber pressure; \( F \) is the output force of the hydraulic cylinder.

When the pipeline pressure loss is not counted, then \( P_2 = 0 \),

\[
P_1 = \frac{F}{A_1}
\]

(2)

The formula shows that the pressure of the hydraulic cylinder working chamber depends on the external load.

The working pressure \( P_1 \) of the hydraulic pump must be greater than the working pressure \( P_1 \) of the working chamber of the hydraulic cylinder, so that the hydraulic oil can flow into the hydraulic cylinder through the throttle valve, and the pressure difference on the throttle valve is

\[
\Delta p = P_2 - \frac{F}{A_1}
\]

(3)

In this throttle speed control circuit, a part of the flow generated by the hydraulic pump enters the hydraulic cylinder through the throttle valve, and excess oil flows back to the oil tank through the overflow valve. According to the principle of flow continuity\(^5\), the flow into the hydraulic cylinder is the flow through the throttle:

\[
q_1 = C_T A_T \Delta p^{rac{1}{2}}
\]

(4)

Where: \( C_T \) depends on the coefficient of the flow resistance of the throttle valve, which can be regarded as a constant, and \( A_T \) is the flow area of the throttle valve. Then the working speed of the hydraulic cylinder is

\[
v = \frac{C_T A_T}{A_1} (P_1 - \frac{F}{A_1})^{rac{1}{2}}
\]

(5)

It can be known from formula (5) that for the determined effective working area of the hydraulic cylinder, the working speed of the hydraulic cylinder is related to the throttle opening area, the hydraulic pump working pressure and the load. When other conditions are constant, the speed of movement of the piston is proportional to the throttle area of the throttle valve, the speed of the hydraulic cylinder can be adjusted by adjusting the area of the throttle valve. When the area of the throttle valve is adjusted and the load is increased, the speed of the hydraulic cylinder is reduced, and the load is decreased, and the speed of the hydraulic cylinder is increased. Therefore, the inlet throttle speed control loop is only used in applications where the load changes little or the speed stability is not high.

2.2. Outlet throttling speed control loop

Figure 2 is the outlet throttle speed control loop. The throttle valve is connected in series on the circuit of the hydraulic cylinder, it is used to control the oil discharge amount \( q_2 \) of the hydraulic cylinder to realize the speed adjustment. The excess flow of the hydraulic pump flows back to the oil tank through the overflow valve. Then the speed of the hydraulic cylinder is:

\[
v = \frac{q_2}{A_2}
\]

(6)
The pressure difference between the front and back of the relief valve is the pressure of the return chamber. From the hydraulic cylinder piston force equation, the pressure difference of the throttle valve is:

\[ \Delta P = \frac{A_1}{A_2} (p_r - \frac{F}{A_1}) \]  

(7)

The speed of the hydraulic cylinder can be expressed as:

\[ v = \frac{C_r A_r}{3} (p_r - \frac{F}{A_1})^{\frac{1}{2}} \frac{1}{A_1 n^2} \]  

(8)

Where: \( n = \frac{A_2}{A_1} \),

It can be known from equation 8 that in the outlet throttle speed control loop, when the area of the throttle valve is adjusted, the running speed of the hydraulic cylinder is reduced when the load becomes larger, and the running speed of the hydraulic cylinder is increased when the load becomes smaller. Therefore, the outlet throttling speed control loop is also only applicable to occasions where the flow rate is small and the load does not change much. Because the outlet throttling speed control loop has back pressure on the return line, it can withstand negative load and run smoothly during the working process.

2.3. Bypass throttling speed regulating circuit

Figure 3 shows the bypass throttling speed control circuit. The throttle valve will be connected in parallel with the oil inlet branch of the hydraulic cylinder, and the speed of the cylinder piston can be adjusted by controlling the flow rate through the throttle valve to indirectly adjust the flow rate into the cylinder. When the hydraulic cylinder is running stably, the piston is balanced:

\[ p_r A_1 - p_2 A_2 = F \]  

(9)

Ignoring the pipeline loss, the differential pressure before and after the throttle valve is:

\[ \Delta p = p_r = \frac{F}{A_1} \]  

(10)

The flow through the throttle valve:

\[ q_r = C_r A_r \left(\frac{F}{A_1}\right)^{\frac{1}{2}} \]  

(11)

Then the flow into the hydraulic cylinder:

\[ q_t = q_r - C_r A_r \left(\frac{F}{A_1}\right)^{\frac{1}{2}} \]  

(12)

The operating speed of the hydraulic cylinder can be expressed as:

\[ v = \frac{q_r}{A_1} - \frac{C_r A_r}{A_1} \left(\frac{F}{A_1}\right)^{\frac{1}{2}} \]  

(13)

It can be seen from the formula (13) that when the other conditions are constant, the operating speed of the hydraulic cylinder can be adjusted by adjusting the opening degree of the throttle valve. When the opening degree of the throttle valve is constant, the working speed of the hydraulic cylinder
decreases as the load increases, and increases as the load decreases. Therefore, the bypass throttling speed control circuit should only be used in applications where the load does not change much and the speed stability is not high.

3. Research on Simulation of Throttle Speed Regulation Circuit

In the throttle speed control loop, the characteristic that the operating speed of the actuator changes with the load is usually called the load characteristic\(^6\). When the load is constant, the characteristic of the actuator speed as a function of the orifice area is called the speed characteristic\(^7\). It can be known from Equations 8 and 13 that the load characteristics and speed characteristics of the inlet throttle speed regulation and the outlet throttle speed regulation loop are the same. Therefore, only the simulation model of the inlet throttling speed regulation loop and the bypass throttling speed regulation loop is constructed with AMESIM software\(^8\), and its working characteristics are analysed.

3.1. Import throttling speed control loop simulation

3.1.1 Simulation Analysis of load characteristics of Inlet Throttle Speed Regulation

Figure 4 shows the simulation results of the load characteristics of the inlet throttle speed control loop. The three curves in the figure are the changes of the speed with the external load when the throttle area of the throttle valve is different, and the throttle valve area \(a_1 < a_2 < a_3\). When the throttle opening is constant, the change of speed with load is called the rigidity of the speed, and the speed rigidity is represented by the slope of the curve on the load characteristic curve. The smaller the slope at a point on the characteristic curve, the smaller the speed at which the loop is affected by the load change, the better the resistance to speed changes, and the better the speed stability. The analysis results show that when the external load is constant, the smaller the opening of the throttle valve, the better the speed rigidity of the speed regulation loop; when the opening area of the throttle valve is constant, the smaller the external load, the better the speed rigidity of the speed regulation loop. Therefore, the inlet throttling speed control loop is suitable for applications where the load is small and the speed does not change much.

3.1.2 Simulation Analysis of Speed characteristics of Inlet Throttle Speed Regulation

The simulation of the inlet throttling speed control loop speed characteristics is shown in Figure 5. The three curves in the figure are the characteristics of the piston rod running speed changing with the opening of the throttle valve under different external load conditions, and the external load \(F_1 < F_2 < F_3\). When the external load is kept constant, the characteristic of the piston rod running speed with the opening of the throttle valve is called the speed characteristic. The opening of the throttle valve is larger, the greater the speed of the piston rod. When the throttle opening is constant, the smaller the external load, the faster the piston rod runs. Under various load conditions of external load from zero...
to maximum, the speed of the piston rod can be changed by changing the throttle opening to achieve stepless speed regulation.

3.2. Simulation and Analysis of Bypass Throttle Speed Control

3.2.1 Analysis of the Load Characteristics of the Bypass Throttle Speed-regulating Circuit

The maximum linear change of the external load in the model is set to 117810N, and other important parameters are shown in Table 1. The bypass throttling speed regulation load characteristic is shown in Figure 6. The three curves in the figure are the speed change with the external load when the throttling area of the throttle valve is different, and the throttle valve area $a_1 < a_2 < a_3$. The analysis results show that when the external load is constant, the smaller the opening of the throttle valve, the better the speed rigidity of the speed regulation loop. When the opening area of the throttle valve is constant, the larger the external load, the better the speed rigidity of the speed regulation loop. Therefore, the bypass throttling speed regulation circuit is suitable for the situation of little change of load, low requirement of speed stability and high speed and large load.

3.2.2 Simulation Analysis of Speed characteristics of Bypass Throttle Speed Regulation

The simulation results of speed characteristics of bypass throttling speed regulation loop are shown in figure 7. When the external load is constant, the speed of piston rod decreases with the increase of throttle valve opening, and in the initial stage of throttle valve opening, the piston rod speed fluctuates greatly. In order to improve the stability of regulation speed, the bypass throttle speed regulation loop should avoid working in the small opening state of throttle valve as far as possible.
4. conclusion
The hydraulic speed regulation system has important application value in engineering machinery. By comparing the three forms of throttling speed regulation schemes and analysing their working characteristics, it is found that the speed of hydraulic cylinders in the three throttling speed regulation circuits varies with the change of load, which is only suitable for the situations where the load changes little and the speed stability requirements are not high. In the outlet throttling speed regulation circuit, because of the back pressure on the oil return road, it can bear the negative load. In the bypass throttle speed regulation circuit, the relief valve is not responsible for regulating the flow into the hydraulic cylinder, but only for the safety valve. This speed regulating loop has only throttling loss and no overflow loss, so it is more efficient than the other two speed regulating circuits. It is of great significance to analyse the working characteristics of hydraulic speed regulation system correctly for the design of hydraulic system of construction machinery.

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