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Modeling and Simulation of Screw-in Cartridge Three-Way Flow Control Valve Based on AMESim

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1. Introduction

Load-sensitive systems are widely adopted in various construction machinery due to their outstanding cooperative driving performance for multiple actuators, enabling the compound operation of multiple actuators supplied by a single pump [1-2]. By real-time detection and acquisition of the maximum load pressure signal of the whole machine, the system dynamically adjusts the displacement of the variable pump to precisely match the real-time flow demand, thus achieving energy-saving control with on-demand oil supply [3-4]. Meanwhile, equipped with an independent pressure compensation structure for each branch, the system stabilizes the pressure difference across the throttle orifice of the multi-way valve. In this way, the branch flow is regulated solely by the spool opening, which thoroughly eliminates load coupling interference among different actuators and realizes stable, independent, synchronous, and disturbance-free driving of multiple actuators by a single pump [5-6]. As the core control component of load-sensitive hydraulic systems, the three-way flow control valve works by maintaining a constant pressure difference between the pump outlet pressure and the maximum system load pressure, serving as a critical part to guarantee accurate flow matching and stable pressure output of the system [7-8].

Extensive targeted research on three-way flow control valves has been conducted by scholars worldwide. Quan et al. [9-10] focused on pressure compensation valves, investigated the effects of throttle groove structures and spring parameters on system response speed, and proposed a pressure compensation valve scheme with an adjustable compensation pressure difference to address pressure shock during rapid system unloading, which greatly improves the control accuracy of load-sensitive systems. Lisowski et al. [11] developed a novel cartridge three-way flow control valve and analyzed the effects of valve structure on throttling energy consumption and steady-state flow characteristics via CFD simulation and prototype bench tests. For load-sensitive systems with fixed-displacement pumps, Luo et al. [12] studied the damping characteristics of three-way flow control valves, clarified the influence of damping hole size, cavity volume, and spool opening shape on overall system performance, and summarized comprehensive design principles for these valves. Zhao et al. [13] innovatively proposed a three-way pressure compensation valve configuration featuring a small spool and double valve ports; tests verified that this structure reduces system pressure shock by up to 89%. To match high-flow LUDV multi-way valves, Yang et al. [14] designed a large-flow three-way pressure compensation valve equipped with one main passage and two overflow passages. Bench and field tests demonstrated that it effectively resolves the insufficient flow capacity of conventional three-way valves under fixed-displacement pump conditions, achieving a maximum flow rate of 400 L/min and an unloading pressure as low as 3 MPa, fully satisfying the operating demands of high-flow LUDV hydraulic systems. Li et al. [15] adopted CFD simulation to analyze the steady-state flow force of a three-way ball high-speed on-off valve. Optimizing the valve port structure shortened the opening-closing cycle, effectively compensated flow force, and greatly improved the valve's dynamic response performance. Conventional three-way flow control valves generally suffer from limited flow capacity, high unloading pressure, severe pressure shock during operating condition switching, and poor damping matching, making them difficult to meet the high-precision operation requirements of high-flow load-sensitive systems.

Currently, studies on traditional overflow-throttle three-way flow valves have reached a mature stage, yet two prominent drawbacks persist. First, the bypass throttle port can normally only be connected to the oil tank and fails to bear loads directly, acting merely as a standard throttle valve under heavy-load operating conditions. Second, the valve consists of separate throttling and overflow components, resulting in a bulky overall structure. To address these issues, this paper designs a screw-cartridge three-way flow valve. Its working principle and dynamic performance characteristics are analyzed, followed by the establishment of a mathematical model of the system. Simulation experiments are conducted on the AMESim platform to systematically explore how structural parameters and load conditions affect the valve's pressure stability. This research provides theoretical support for structural optimization design and practical engineering deployment of similar valves. Compared with conventional overflow-throttle three-way flow valves, the designed valve possesses the following merits:

1. featuring a compact structure, high flow capacity, and easy installation;

2. allowing the bypass throttle port to be connected to either the oil tank or actuators to achieve bypass loaded speed regulation, thereby broadening the applicable range of flow regulation under heavy-load conditions;

3. integrating pressure compensation, throttling, and overflow functions into a single unit, which saves the

assembly space required for separate components. By adopting a screw-cartridge layout, it can be directly embedded inside valve manifolds, satisfying the assembly requirements for lightweight design.

2. Working Principle of the Screw-in Cartridge Three-Way Flow Control Valve

The screw-in cartridge three-way flow control valve consists primarily of a constant-pressure differential valve, a spring, and throttle orifices. Fig. 1 illustrates its structural schematic. Based on the principle of constant pressure differential control, the valve regulates both the bypass throttle orifice A and the priority throttle orifice D simultaneously through the axial movement of spool B within the constant-pressure differential valve.

The steady-state position of the constant-pressure differential spool B is determined by the pressure differential across the flow-sensing port C and the spring force, eventually stabilizing at a position within its operational stroke (i.e., not at the mechanical limits). Under such steady-state conditions, the pressure differential across port C balances the spring force, thereby maintaining a constant value. Accordingly, when the opening area of port C is fixed, the flow rate passing through it remains essentially constant and is insensitive to fluctuations in inlet and outlet pressures.

For the screw-in cartridge three-way flow control valve, when bypass port 2 is connected to a secondary load, stable flow control against load pressure fluctuations is achieved via the simultaneous regulation of priority port 3 and bypass port 2 by the constant-pressure differential spool (B). The detailed regulation process is as follows: as the pressure at bypass port 2 (p_2) increases, the inlet pressure (p_1) rises correspondingly, driving spool B to move upward. During this movement, the opening area of bypass throttle orifice A increases, while that of priority throttle orifice D decreases. Through this mechanism, the pressure at priority port 3 (p_3) rises synchronously, ensuring that the pressure differential between the inlet and the priority port ($p_1 - p_3$) remains constant. Consequently, a steady flow rate is maintained through the priority throttle orifice (D).

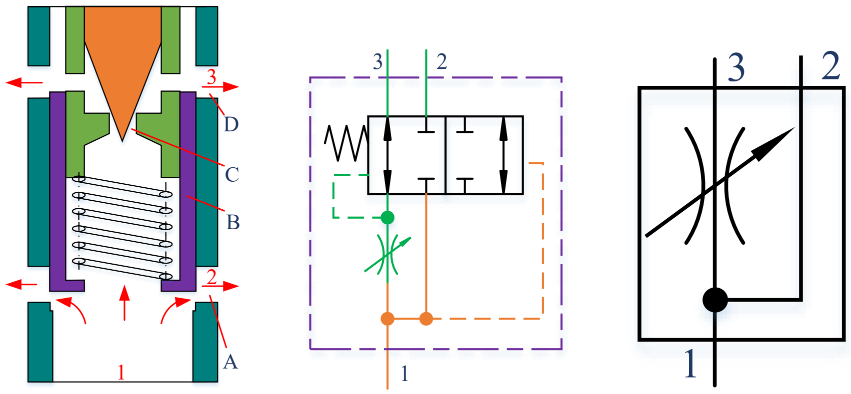

Fig. 1 Screw-in cartridge three-way flow control valve: 1 – inlet port, 2 – bypass port, 3– priority port; A – bypass throttle orifice, B – constant-pressure differential spool, C – flow-sensing port, D – priority throttle orifice; a – structural schematic diagram, b – detailed graphical symbol, c – simplified graphical symbol

3. Mathematical Modeling

To identify the key structural parameters governing the flow performance of the screw-in cartridge three-way flow control valve and to provide a theoretical foundation for design variables in subsequent simulations and optimization, this study establishes a static mathematical model of the valve. Furthermore, a systematic analysis of the derived static equations is conducted. The flow continuity equation for the valve is expressed as follows:

$$q_1 = q_2 + q_3 = C_{d1} A_1 \sqrt{\frac{2(p_1 - p_2)}{\rho}} + C_{d2} A_2 \sqrt{\frac{2(p_1 - p_3)}{\rho}}, \quad (1)$$

where q_1, q_2 and q_3 are total flow rate, bypass port flow rate, and priority port flow rate, respectively in L/min; C_{d1} and C_{d2} are flow coefficients of the bypass port and priority port, respectively. A_1 and A_2 are flow areas of the bypass port and priority port, respectively in m^2; p_1, p_2 and p_3 are inlet pressure, bypass port pressure, and priority port pressure, respectively in MPa.

The force balance equation of pressure compensation spool B is given by

$$p_1 A_1 = p_3 A_3 + F_s. \quad (2)$$

Here F_s is a spring force in N; $F_s = k_s x$ (where x is the spring deformation, m).

In summary, for the screw-in cartridge three-way flow control valve, the flow coefficient and fluid density are assumed to be constant. Therefore, the parameters affecting the valve performance include p_1, p_2, p_3, A_1, A_2 and F_s.

4. Simulation Test Analysis

4.1. Establishment of simulation model

To investigate the performance of the screw-in cartridge three-way flow control valve, a simulation model was established in AMESim based on its schematic diagram (Fig. 1), as shown in Fig 2. the hydraulic pump supplies oil to the entire system; the relief valve provides safety protection, and two variable relief valves are adopted to simulate

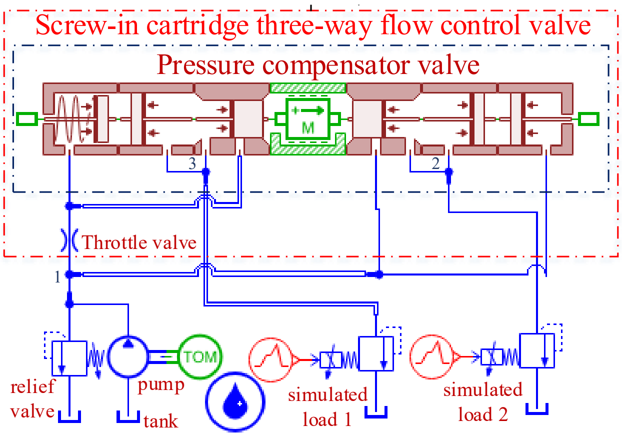

Fig. 2 AMESim simulation model of the screw-in cartridge three-way flow control valve

Table 1

Main parameters

No.	Name	Value
1	Diameter of pressure compensating spool, mm	10
2	Displacement of hydraulic pump, mL·r^{-1}	50
3	Rotational speed of hydraulic pump, r·min^{-1}	1000
4	Spool mass, kg	0.01
5	Spring stiffness, N·m^{-1}	10
6	Spring preload, N	200

the load. The main parameters are listed in Table 1.

4.2. Analysis of Simulation Results

4.2.1. Flow rate of priority throttle orifice D under load variation at priority port 3

This study focuses on the flow rate through priority throttle orifice D and the pressure variation at flow-sensing port C under load changes at priority port 3 of the screw-in cartridge three-way flow control valve. In the simulation model, the orifice diameter of port C is set to 2 mm. The load at port 3 increases linearly from 0 to 5 MPa within 0–2 s, remains constant for 1 s, and then decreases linearly from 5 to 0 MPa over the subsequent 2 s. During the test, bypass port 2 is connected to the hydraulic tank. The flow rate at priority throttle orifice D and the pressure before and after flow-sensing port C, obtained from the simulation, are shown in Fig. 3.

Test results show that when a load disturbance occurs at priority port 3, the inlet and outlet pressures at flow sensing port C fluctuate briefly within the interval of 0–0.5 s, after which the pressure variation trend aligns with the load variation pattern. Meanwhile, the flow rate passing through priority throttle port D of the cartridge three-way flow control valve also fluctuates during the 0–0.5 s period and remains constant once the fluctuation subsides. This dynamic response characteristic is consistent with the steady-state evaluation criteria for hydraulic systems proposed in Reference [16], verifying that the cartridge three-way flow control valve adopted in this study can maintain stable pressure and flow under load disturbance conditions.

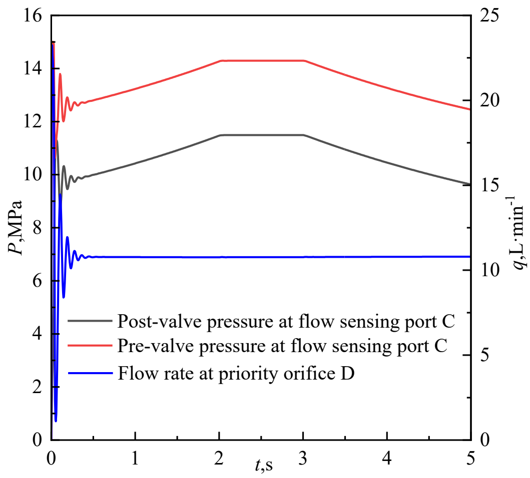

Fig. 3 Pressure and flow characteristic curves of priority orifice D under different loads

4.2.2. Flow rate of priority throttle orifice D under load variation at bypass port 2

As mentioned in Section 1, the flow rate at priority throttle orifice D does not fluctuate significantly, even when Bypass Port 2 is connected to a load in the secondary circuit. To investigate this characteristic, two test conditions were established in AMESim: the load pressure at Bypass Port 2 was set to 0 MPa and 10 MPa, respectively, while the load pressure at Priority Port 3 was varied linearly from 0 to 5 MPa. The simulated pressure and flow rate variations at orifice D are shown in Figs. 4 and 5.

Analysis reveals that when the load at Bypass Port 2 is 0 MPa, the absolute pressure across priority throttle orifice D increases with the load at Priority Port 3; however, the pressure differential remains essentially constant, stabilizing the flow rate at 10.75 L/min. When the load at Bypass Port 2 is 10 MPa, it exceeds the maximum load at Priority Port 3. In this case, the inlet pressure (Port 1) is determined by the bypass pressure. Consequently, the pressure differential across orifice D does not vary with the priority load, and the flow rate remains constant at 10.75 L/min.

The above analysis confirms that the flow rate at priority throttle orifice D is unaffected by loads connected to Bypass Port 2 in the secondary circuit.

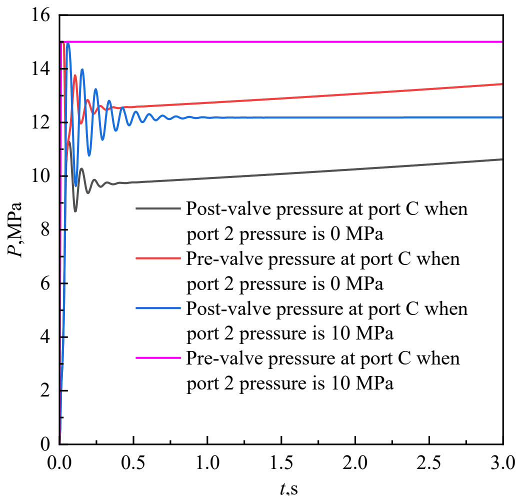

Fig. 4 Pressure conditions before and after port C under different loads at bypass port 2

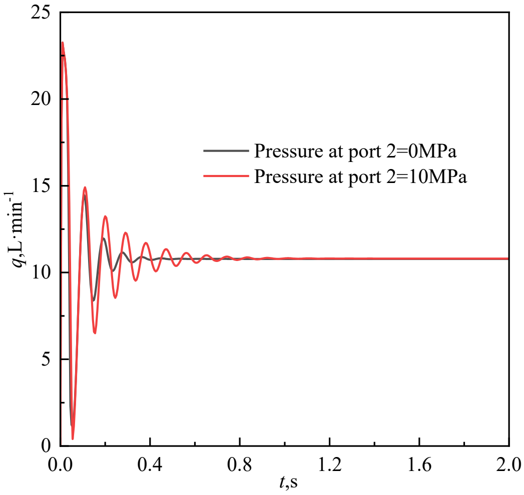

Fig. 5 Flow rate at port D under different loads at bypass port 2

4.2.3. Flow rate of priority throttle orifice D under different flow areas of flow-sensing port C

In the screw-in cartridge three-way flow control valve, the influence of different opening areas of flow-sensing port C on the flow variation at priority throttle orifice D was investigated. The opening areas of port C were set to 3.14 mm², 4.91 mm², and 7.07 mm², respectively. The simulated flow rates at priority throttle orifice D are shown in Fig. 6. It can be concluded that the flow rate through port C increases correspondingly with its opening area.

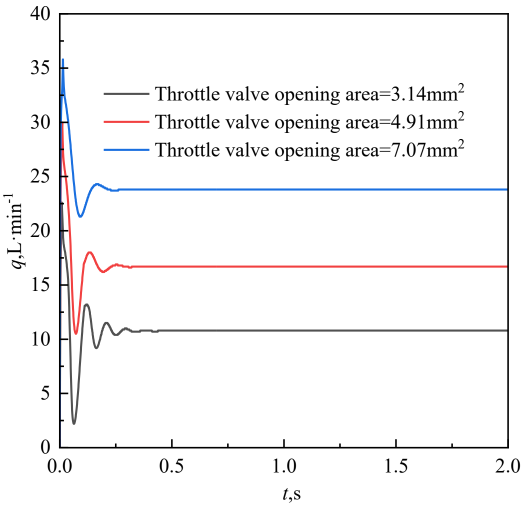

Fig. 6 Flow characteristic curves of port D under different opening areas of port C

4.2.4. Effect of different spring preload on the flow rate of priority throttle orifice D

To investigate the effects of spring preload and stiffness on the flow variation at priority throttle orifice D, simulation analyses were carried out. First, with other parameters unchanged, the spring preload was set to 150 N, 200 N, and 250 N, respectively. The simulated flow curves for orifice D are shown in Fig. 7. The results show that the flow rate through orifice D increases with spring preload. Next, the spring stiffness was set to 10 N/m, 25 N/m, and 40 N/m, respectively. The flow curves for orifice D are

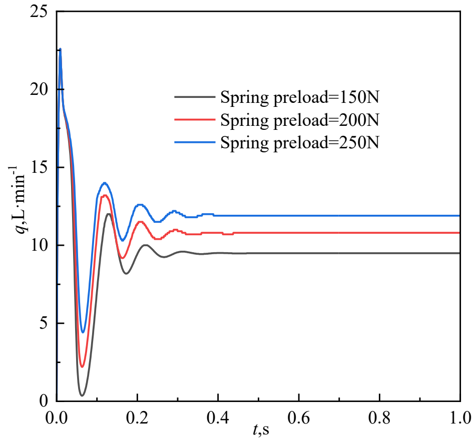

Fig. 7 Flow characteristic curves of port D under different spring preload

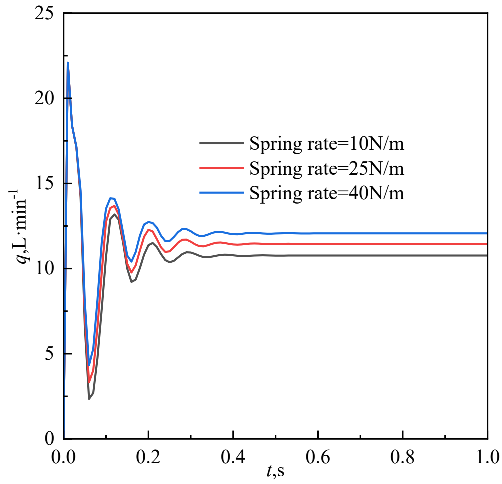

Fig. 8 Flow characteristic curves of port D under different spring rate

shown in Fig. 8. It is observed that the flow rate at orifice D also increases with spring stiffness.

5. Conclusions

To investigate the operating characteristics of the screw-in cartridge three-way flow control valve, the effects of key parameters – including load conditions at the priority and bypass ports, flow-sensing port area, spring preload, and stiffness – were systematically studied via simulation. The results demonstrate that:

1. with other parameters held constant, the flow rate through priority throttle orifice D remains stable, regardless of load changes at either the priority or bypass ports;

2. the flow rate through orifice D increases with a larger flow-sensing port area, as well as with higher spring preload and stiffness.

These simulation results are consistent with theoretical analysis, providing a solid theoretical basis for the design of screw-in cartridge three-way flow control valves.

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S. X. Zhou, J. H. Ying, W. Wang

MODELING AND SIMULATION OF SCREW-IN CARTRIDGE THREE-WAY FLOW CONTROL VALVE BASED ON AMESIM

S u m m a r y

Due to their compact structure and high flow capacity, screw-in cartridge three-way flow control valves are widely used in high-end equipment. Therefore, by analyzing the functional characteristics of such valves, this paper establishes its mathematical model during operation. AMESim software is adopted to investigate the influences of structural parameters and load conditions on its performance. Simulation results show that the flow rate through the priority port remains constant when the load at the priority port or the bypass port changes. Increasing the opening area of the flow sensing port, the spring preload, and the spring stiffness leads to an increase in the flow rate through the priority port. The simulation results are consistent with the theoretical analysis, which provides a theoretical basis for the design of screw-in cartridge three-way flow control valves.

Keywords: screw-in cartridge three-way flow control valve, mathematical modeling, operational performance.

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