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Research Article

Characteristic Analysis of Digital Large Flow Emulsion Relief Valve

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The relief valve is an important control and overload protection component of the emulsion pumping station. Its performance will affect the overall performance of the emulsion pumping station and the stable and intelligent control of the working surface. However, the research on high pressure and large flow relief valve for mine emulsion pumping station is still inadequate. In order to meet the requirements of emulsion pump station for large flow sensitivity, stability, reliability, and remote intelligent control of overflow valve, this paper uses the digital control method to establish the mathematical model of the relief valve and uses the software such as AMESim to its dynamic characteristics. The simulation results show that the structural parameters such as spool quality, damping hole, and spring stiffness have an effect on the working characteristics of the relief valve. It also provides reference for the intelligent control research of the large flow relief valve for the emulsion pumping station.

1. Introduction

As an important control and overload protection component of emulsion pumping station, the relief valve directly determines the quality of liquid supply and energy consumption index of the system and also directly affects the working quality and service life of the pumping station system. With the increase in flow and pressure required by emulsion pump station, higher requirements are put forward for the sensitivity, stability, and reliability of relief valves in the work site. Hydraulic simulation can not only reduce the research cost and time of the relief valve but also intuitively observe and judge the performance of the relief valve, so as to optimize the structure.

Since the 1980s, some scholars have studied the pilot relief valve. Leng et al. analyzed the dynamic characteristics of cartridge pilot relief valve by power bond graph and AMESim simulation software and obtained the influence of main structural parameters on its dynamic performance [1]. Lei and Wu simulated and analyzed the stability and fast responsiveness of the relief valve and optimized the structure of the relief valve through the simulation results [2]. Sang and Kang mainly studied the main spool damper hole of pilot relief valve. Fluent was used to simulate the flow field near the damper hole with different diameters. The structure of the relief valve was optimized through the damper hole [3]. But at present, the transmission medium of the relief valve is pure water or traditional hydraulic oil, and the research on the emulsion relief valve is less. Dasgupta et al. used the bond graph method to study the dynamic characteristics of the pilot relief valve and obtained the influence of spring, damper hole, and other structures on the response of relief valve system [4, 5]. Vallet et al. used the bond graph method to study the dynamic characteristics of the pilot relief valve. Considering the steady-state hydrodynamic force and hydraulic compressibility of the valve core, the effect of valve body structure parameters on response time was obtained by simulation. The influence of the change in the diameter of the damper hole and the half cone angle of the main spool on the peak time and the adjustment time of the relief valve is obtained [6]. Hao et al. studied the influence of structural parameters on the opening of pilot relief valve under alternating pressure [7]. Gad conducted a comprehensive nonlinear modeling and simulation on the performance of a kind of pilot relief valve, deduced the mathematical model of the performance prediction of the valve under the steady and transient conditions, and studied it with Matlab/Simulink and bond graph [8, 9]. Yang et al. carried out simulation research on self-excited vibration of pilot valve core of pilot relief valve [10]. Gong et al. conducted simulation and experimental research on the pilot hydraulic relief valve and established the AMESim model of the valve. Through simulation, the influence of pilot valve lead clearance, damping hole diameter, sensitive chamber volume, valve core mass, spring stiffness, and other parameters on system performance is studied [11]. Mao et al. designed a kind of hydraulic back pressure valve with a flow range of no less than 100 L/min by using the pilot type. The effects of the main structural parameters such as the front volume of the main throttle, the volume of the main spring chamber, the size of the slim hole of the damper plug, and the main throttle on the performance of the damper are obtained by simulation [12, 13]. Some scholars have established the mathematical model of relief valve and linearized the dynamic equation near the stable working point of the valve to get the transfer function model of the relief valve. The dynamic performance of the relief valve and the influence of structural parameters on the performance of the relief valve are simulated and analyzed by using Matlab/Simulink and other simulation methods [14–17]. However, most of the existing research about relief valves are difficult to meet the current demand for high pressure and large flow in emulsion pumping stations.

In view of these problems, this study takes into account the special properties of the emulsion and designs a digital control scheme for the large flow emulsion relief valve. The mathematical model and physical model are comprehensively analyzed by using software such as Matlab/Simulink and AMESim, so as to improve the control accuracy of the relief valve and the working performance of the relief valve.

2. Establishment of the Digital Model of Large Flow Relief Valve

In order to improve the control accuracy and remote automatic control level of the relief valve, this paper proposes a pilot digital control scheme based on the traditional direct-acting spool and manually controlled relief valve, as shown in Figure 1. The working pressure of the relief valve is obtained in real time by the pressure sensor at the relief valve type inlet and is transmitted to the controller, and the actual pressure is compared with a predetermined pressure. The mathematical relationship between the linear step increment of the linear stepper motor, the preload force of the pilot valve spring, and the inlet pressure of the main valve is obtained by the controller through calculation of the mathematical model of the relief valve. According to the pressure comparison result, the pulse is output through the motor drive circuit. The steering of the stepping motor and the number of steps is controlled, and then the spring preload is adjusted to realize real-time regulation of the working pressure of the digital relief valve.

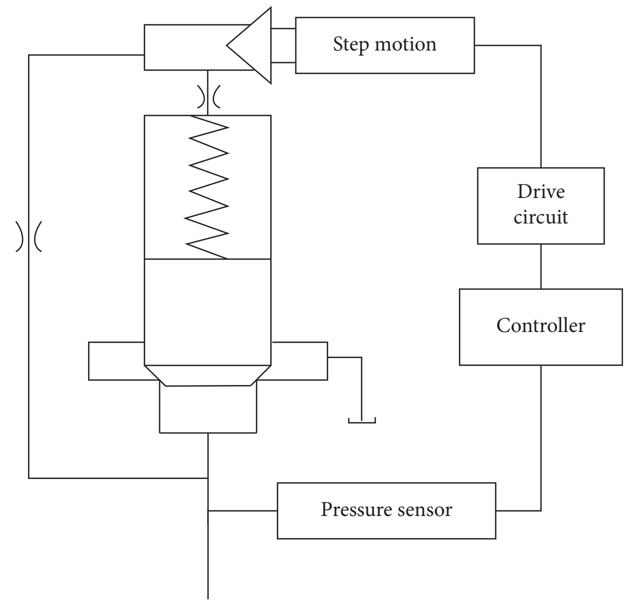

Figure 1: Control scheme of digital relief valve.

The structure of the digital relief valve used in this paper is shown in Figure 2, which is divided into two parts: the main valve and the pilot valve. The emulsion enters the lower chamber of the main valve through the oil inlet, enters the front chamber of the pilot valve through the left passage of the main valve core and the damping hole of the pilot valve, and enters the upper chamber of the main valve through the damping hole of the main valve. When the emulsion pressure is less than the rated pressure of the relief valve, the pressure of the upper and lower chambers of the main valve is the same, and the pressure area of the upper chamber is larger than that of the lower chamber. With the effect of the spring force of the main valve, the main valve core is fixed on the main valve seat. When the emulsion pressure is greater than the rated pressure of the overflow valve, the oil pressure in the front chamber of the pilot valve is greater than the force of the spring of the pilot valve, the pilot valve is opened, and the emulsion flows out through the drain port of the pilot valve. As there is oil flow in the damping hole of the main valve, the pressure difference is formed at the upper and lower sides of the main valve core. When the pressure of the lower chamber of the main valve is greater than the sum of the pressure of the upper chamber of the main valve and the spring force of the main valve, the main valve core is opened, and the emulsion flows out through the outlet chamber to realize the overflow function.

The dynamic mathematical model of the pilot relief valve is based on the two basic principles of force balance and flow continuity, which is divided into the pilot valve part and the main valve part. The mathematical model of the main valve and pilot valve of the relief valve is as follows:

Pilot valve spool force model:

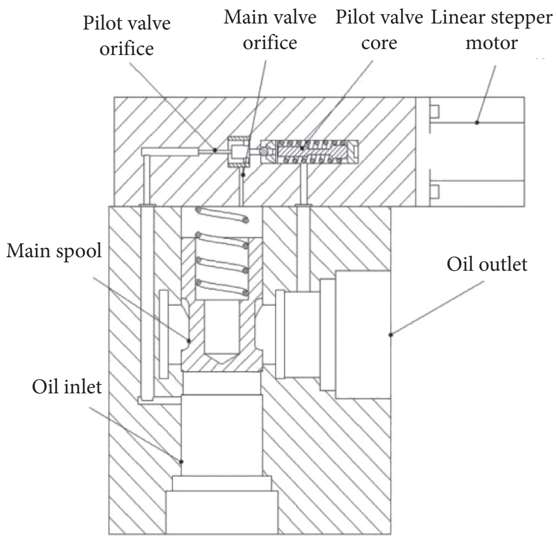

FIGURE 2: Structure diagram of digital relief valve.

$$p_1 A_x = m\frac{d^2 x}{dt^2} + f_x\frac{dx}{dt} + k_x(x_0 + x) + k_{ex} x p_1, \quad (1)$$

where p_1 is the pilot valve inlet pressure, A_x is the force area of the pilot valve seat hole and $A_x = (\pi d^2/4)$, d is the seat hole diameter, m is the pilot valve spool equivalent mass and is 1/3 of the quality of the spool and the quality of the regulator, x is the displacement of the valve core of the pilot valve and the opening direction of the valve port is positive, f_x is the pilot valve spool viscous damping coefficient, k_x is the pilot valve spring stiffness, x_0 is the pilot valve spring precompression, and k_{ex} is the pilot valve port hydraulic dynamic stiffness and $k_{ex} = C_2 \pi d \sin 2\beta$ [18].

Pilot valve port flow model:

$$\begin{aligned} q_1 + q_2 &= \frac{V_1}{E}\frac{dp_1}{dt} + q_x, \\ q_1 &= G_{R1}(p - p_1), \\ q_x &= C_2 \pi d x \sin\beta\sqrt{\frac{2}{\rho}}\sqrt{p_1} = k_{qx} x + k_{cx} p_1, \end{aligned} \quad (2)$$

where q_1 is the flow through the pilot valve orifice, G_{R1} is the hydraulic guide of pilot valve damping hole, p is the main valve inlet pressure, q_2 is the main valve upper chamber emulsion flow, V_1 is the pilot valve front cavity volume, E is the emulsion elastic modulus, q_x is the flow at the pilot valve port, C_2 is the flow coefficient at the pilot valve port, d is the pilot valve seat bore, β is the pilot valve port half cone angle, ρ is the emulsion density, k_{qx} is the pilot valve port flow gain and $k_{qx} = \partial q_x/\partial x$, and k_{cx} is the pilot valve port flow pressure coefficient and $k_{cx} = \partial q_x/\partial p_1$.

Main valve spool stress model:

$$pA_1 - p_2 A_2 = M\frac{d^2 y}{dt^2} + f_y\frac{dy}{dt} + k_y(y_0 + y) + k_{ey} y p, \quad (3)$$

where P_2 is the main spool pressure, A_1 is the main spool lower chamber force area, A_2 is the main valve core upper chamber stress area, M is the main spool equivalent mass, y is the displacement of main valve core and opening direction of valve port is positive, f_y is the main valve spool motion viscous damping coefficient, k_y is the main valve spring stiffness, y_0 is the main valve spring precompression, and k_{ey} is the main valve port hydraulic dynamic stiffness and $k_{ey} = C_1 \pi d \sin 2\alpha$ [18].

Main valve inlet flow model:

$$\begin{aligned} q &= q_1 + q_y + \frac{V_0}{E}\frac{dp}{dt} + A_1\frac{dy}{dt}, \\ q_y &= C_1 \pi D y \sin\alpha\sqrt{\frac{2}{\rho}}\sqrt{p} = k_{qy} y + k_{cy} p, \end{aligned} \quad (4)$$

where q is the flow into the relief valve, q_y is the flow from the main valve port, C_1 is the flow coefficient at the main valve port, D is the main valve seat diameter, α is the main valve port half cone angle, V_0 is the main valve inlet cavity volume, k_{qy} is the main valve port flow gain and $k_{qy} = \partial q_y/\partial y$, and k_{cy} is the main valve port flow pressure coefficient and $k_{cy} = \partial q_y/\partial p$.

The overall control block diagram of the relief valve is shown in Figure 3.

3. Dynamic Characteristic Analysis of Relief Valve Based on Simulink

Under the condition of different initial support forces of the hydraulic support, the emulsion relief valve should be able to recover the steady state quickly under the sudden abrupt condition, so it is necessary to analyze the dynamic performance of the relief valve.

In the Matlab environment, the Simulink module library is used to build the Simulink simulation block diagram, as shown in Figure 3, establish the Simulink simulation model of the relief valve, and use step input signals. The ode45 solver and variable step size are selected, and the simulation time is set to 0.05 seconds.

The simulation shows the pressure dynamic response curve of the pilot valve part of the relief valve and the inlet of the main valve part, as shown in Figure 4. The pressure at the inlet of the main valve is 57.3 MPa, the overshoot is 27.1%, and the settling time is 53 ms. The pressure at the inlet of the pilot valve is 23.02 MPa, the overshoot is 21.1%, and the settling time is 22 ms. As can be seen in Figure 4, the designed valve portion of the relief valve has a short response

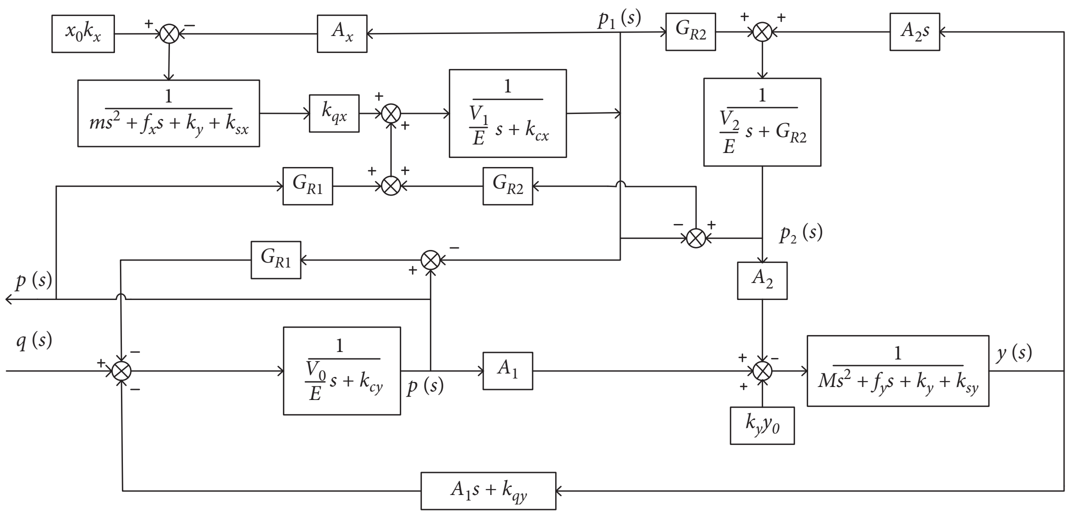

Figure 3: Control block diagram of whole relief valve.

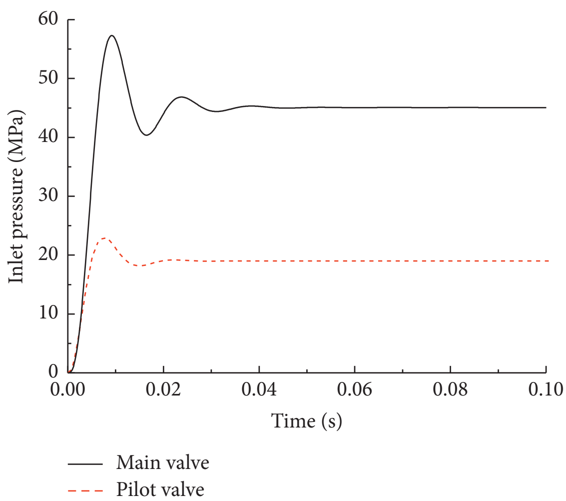

Figure 4: Dynamic response curves of relief valve.

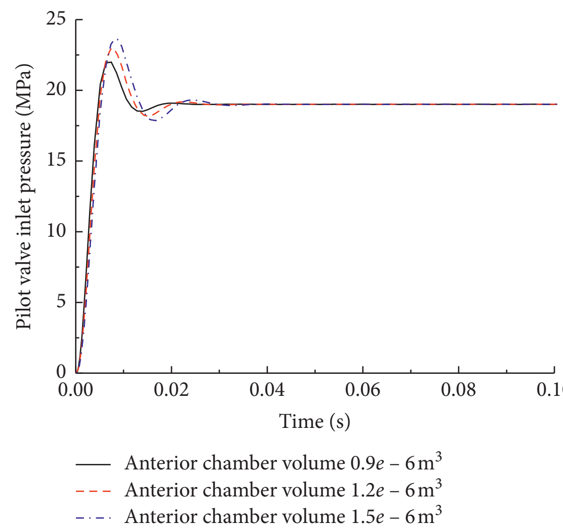

Figure 5: The influence of the front cavity volume of the pilot valve on the pilot valve pressure.

time, a good steady state, a small number of vibrations in the main valve, a stable inlet pressure, and a good dynamic response characteristic of the relief valve.

3.1. Contrastive Simulation of Main Structural Parameters

3.1.1. Influence of the Volume of the Pilot Chamber on the Dynamic Response of the Pilot Valve. The volume of the front chamber of the pilot valve is set to be $0.9e-6\,\mathrm{m}^3$ $1.2e-6\mathrm{m}^3$, and $1.5e-6\,\mathrm{m}^3$, and the other parameters are kept unchanged, and the model is simulated. The dynamic response curve of the inlet pressure of the pilot valve under different front cavity volumes is shown in Figure 5. According to the simulation results, it can be concluded that as the volume of the pilot chamber increases, the time taken for the pressure to reach the peak increases, the pressure overshoot gradually increases, and the stabilization time increases, but the steady-state pressure value remains unchanged. Therefore, the volume of the pilot valve front cavity should be minimized during the structural design process to shorten the settling time, reduce the pressure oscillation, and reduce the volume of the relief valve.

3.1.2. Influence of Pilot Valve Spool Quality on Dynamic Response of Pilot Valve. The other parameters are kept unchanged, the pilot valve spool quality is set to 0.01 kg, 0.02 kg, and 0.03 kg, respectively, the model is simulated separately, and the simulation results are shown in Figure 6. According to the simulation results, it can be seen that, with the increase in the quality of the pilot valve spool, the inlet pressure of the pilot valve is 23.05 MPa, 24.31 MPa, and 25.66 MPa, the steady-state pressure values are the same, and the stabilization times are 34 ms, 49 ms, and 57 ms, respectively. Therefore, under the premise of meeting the design requirements, the weight of the pilot valve spool can

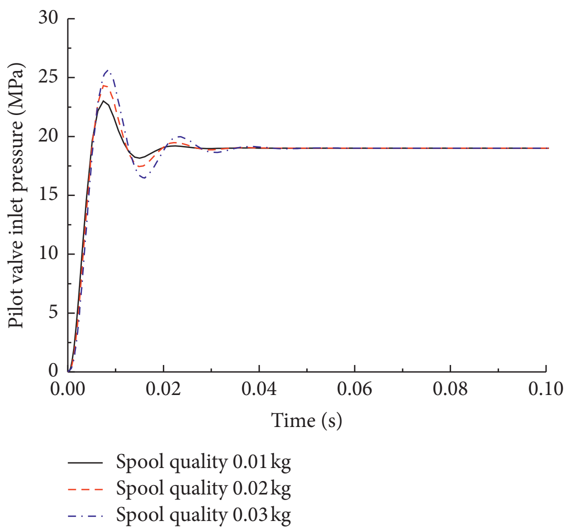

FIGURE 6: The influence of the pilot valve quality on the pilot valve pressure.

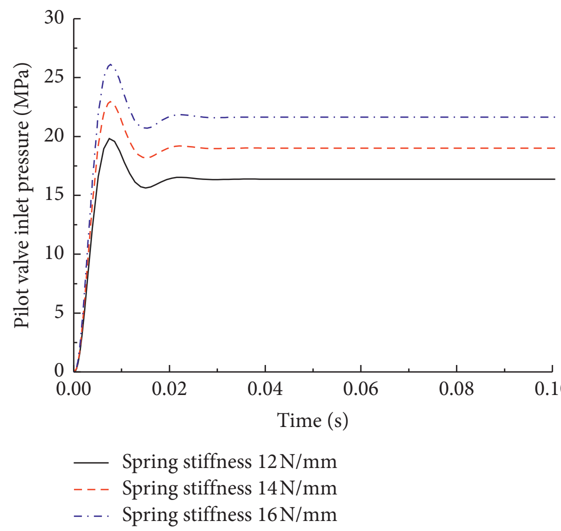

FIGURE 7: The influence of the pilot spring stiffness on the pilot valve pressure.

be appropriately reduced, thereby reducing the oscillation of the valve core and shortening the stabilization time.

3.1.3. Influence of the Spring Stiffness on the Dynamic Response of the Pilot Valve. The stiffness of the pilot valve springs is set to 12 N/mm, 14 N/mm, and 16 N/mm, and the other simulation parameters remain unchanged. The models are simulated separately, and the simulation results are shown in Figure 7. According to the simulation results, as the stiffness of the pressure-regulating spring increases, the inlet pressure of the pilot valve is 19.82 MPa, 23 MPa, and 26.18 MPa, and the steady-state pressure is also significantly increased. The stabilization time is basically the same, and the overshoot is 21.0%. It is indicated that the stiffness of the pilot valve pressure regulating spring mainly affects the steady-state value and peak value of the pilot valve pressure and has no significant influence on the overshoot amount and the stabilization time.

3.1.4. Influence of Main Valve Inlet Volume on Dynamic Response of Main Valve. The main valve inlet volume is set to be $2e-4\,\mathrm{m}^3$, $4e-4\,\mathrm{m}^3$, and $6e-6\,\mathrm{m}^3$, other parameters are kept unchanged, and the model is simulated, respectively. The dynamic response curve of the main valve inlet pressure under different inlet volumes is shown in Figure 8. It can be seen that, under different inlet volumes, the main valve pressure peaks are 57.24 MPa, 55.25 MPa, and 49.47 MPa, respectively; the pressure steady-state values are the same, and the stabilization time is basically the same, but the pressure oscillation amplitude is obviously slowed down. Therefore, the inlet volume of the main valve should not be too small to reduce the instantaneous impact on the main spool and prolong the service life of the spool.

3.1.5. Influence of Main Valve Spool Quality on Dynamic Response of Main Valve. Only the quality of the main valve spool was changed to 0.06 kg, 0.12 kg, and 0.18 kg. The other parameters were unchanged and simulated separately. The simulation results are shown in Figure 9. It can be seen from the figure that the influence of the quality of the main valve spool on the dynamic response of the main valve is the same as the influence of the quality of the pilot valve spool on the pilot valve: as the mass of the spool increases, the pressure peak increases, the fluctuations increase, and the stability time is extended, but the steady-state pressure remains unchanged. Therefore, the quality of the main valve spool should not be too large in the design.

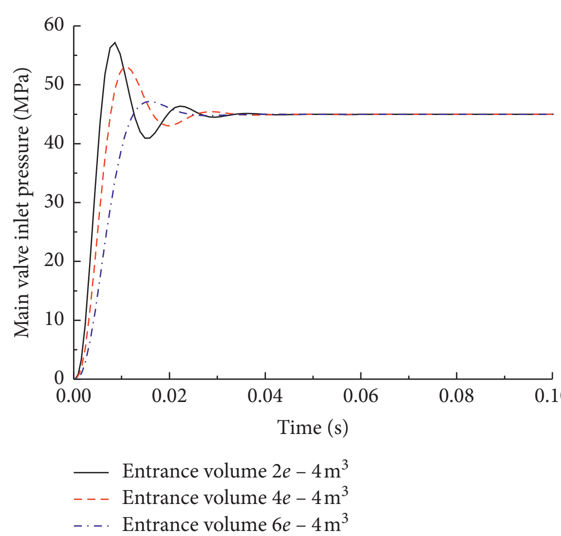

FIGURE 8: The influence of the front chamber volume of the main valve on the main valve pressure.

3.1.6. Influence of Main Valve Spring Stiffness on Dynamic Response of Main Valve. The spring stiffness of the main valve was adjusted to 7 N/mm, 9 N/mm, and 11 N/mm, and

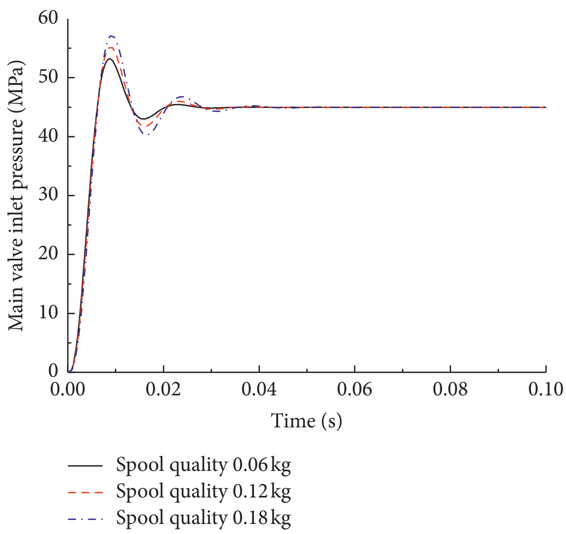

FIGURE 9: The influence of the main valve mass on the main valve pressure.

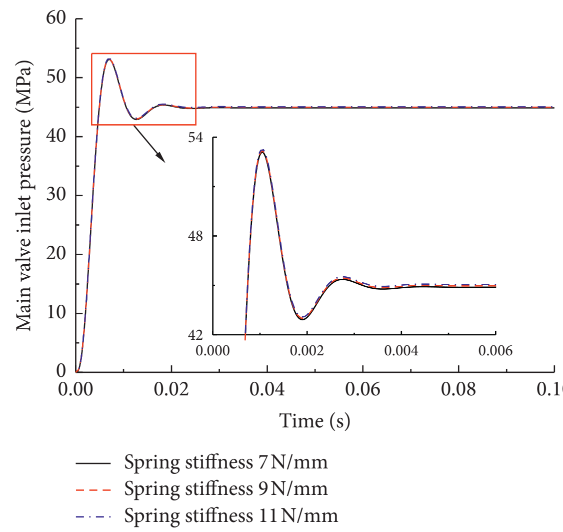

FIGURE 10: The influence of the main spring stiffness on the main valve pressure.

the simulation results were obtained, as shown in Figure 10. It can be seen that as the spring stiffness increases, the main valve inlet pressure peak and steady-state values increase slightly, but the variation is small. Compared with the pressure regulating spring, the main valve spring only plays the role of resetting the main spool. The difference in stiffness between each set of simulation is also 2 N/mm, but the simulation results are very small.

By establishing the mathematical model of the pilot digital relief valve, the block diagram model of the relief valve is obtained. Using the simulation platform of Matlab/Simulink, the block diagram model is built and the dynamic simulation of the relief valve is carried out. The simulation results show that the designed relief valve has good dynamic response characteristics. In the end, by comparing and simulating the main structural parameters in groups, the influence trend of different structural parameters on the dynamic performance of the main valve and pilot valve is analyzed, so as to provide theoretical reference for the structural optimization design of the relief valve.

4. Structural Characteristic Analysis of Digital Relief Valve Based on AMESim

4.1. AMESim Modeling and Parameter Setting. In the AMESim sketch mode, a simulation model of the pilot relief valve is established, as shown in Figure 11.

Due to the complicated working environment of the relief valve, in order to simplify the simulation process and avoid the interference of redundant factors, the following simplifications and assumptions are made in the simulation: (1) hydraulic oil has a constant absolute viscosity; (2) the hydraulic oil is an incompressible fluid, and the density is independent of temperature; (3) the effects of cavitation are not considered; and (4) the relief valve outlet is

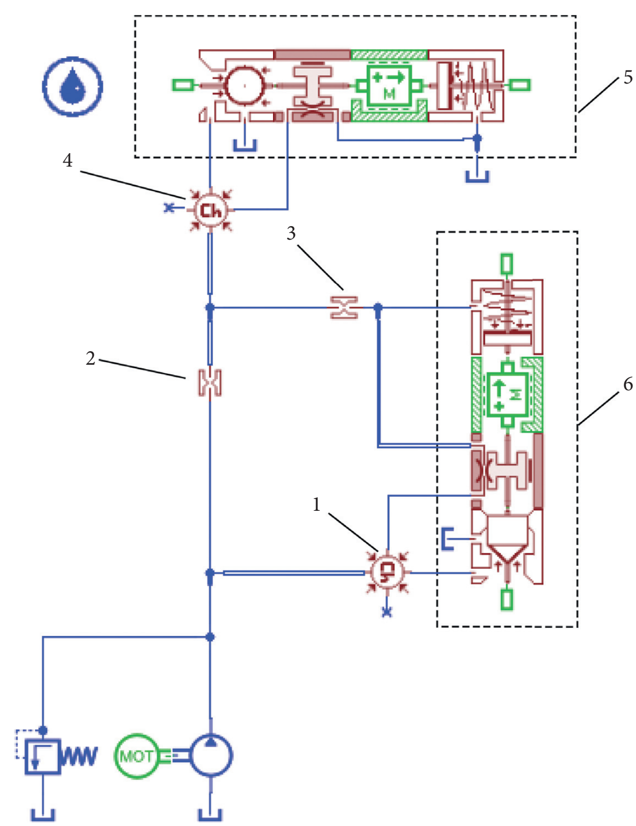

FIGURE 11: AMESim simulation model of pilot-operated relief valve. 1, main valve inlet chamber; 2, pilot valve orifice; 3, main valve orifice; 4, pilot valve front chamber; 5, pilot valve; 6, main valve.

connected to the oil tank, and the outlet pressure is atmospheric pressure.

The detailed parameters of the large flow numerical control relief valve designed in this paper are shown in Table 1.

Table 1: Simulation parameters of each component of relief valve.

Element	Parameter name	Numerical value
Pilot valve	Spool quality (kg)	0.01
	Spool diameter (mm)	5
	Seat aperture (mm)	3.8
	Maximum displacement of the spool (mm)	30
	Pressure regulating spring preload (N)	429
	Regulating spring stiffness (N/mm)	14.3
	Pilot valve front cavity volume (m^3)	1.2×10^{-6}
Emulsion	Temperature (°C)	40
	Density (kg/m^3)	890
	Dynamic viscosity (Pa·s)	0.792×10^{-3}
Main valve	Spool quality (kg)	0.06
	Spool diameter (mm)	50
	Seat aperture (mm)	49
	Maximum displacement of the spool (mm)	18
	Pressure regulating spring preload (N)	654
	Regulating spring stiffness (N/mm)	9.038
	Main valve front cavity volume (m^3)	2×10^{-4}
Damping hole	Damping aperture (mm)	1.2
	Damping hole length (mm)	14.4
	Two orifice diameter relationship	Same

4.2. Simulation of Static Characteristics of the Relief Valve. In the case of no sudden change in the inlet pressure of the relief valve, the force acting on the main spool is balanced, and the pressure is

$$p = \frac{M\left(d^2 y/dt\right) + f_y\,(dy/dt) + k_y\left(y + y_0\right) + p_2 A_2}{A_1 - C_1 \pi d y \sin 2\alpha}. \quad (5)$$

After the spring stiffness and pretightening force are set, the change in the overflow flow causes the valve opening y to change, which changes the steady-state hydraulic power and the force of the spring to the spool, and the pressure at the inlet when the relief valve operates. It changes accordingly. The liquid supply device in the simulation model is changed, as shown in Figure 11, to a constant current source, the flow at the inlet of the relief valve is set from 0 to 1000 L/min, and the time is simulated to 10 s. The simulation results are processed to obtain the designed overflow. The valve static characteristic curve is shown in Figure 12. The red dotted line in the figure represents the ideal rated pressure of 45 MPa, and the solid black line is the actual value obtained by simulation.

According to the simulation results, it can be seen that the designed relief valve opens the pilot valve when the pressure at the main valve port reaches 19.45 MPa and starts to generate overflow flow. When the overflow flow reaches 22 L/min, the pressure curve reaches the inflection point, and a slight fluctuation occurs. The flow rate increases slowly as the flow rate reaches 1000 L/min, and the main valve port pressure is 45.01 MPa, indicating that the rated working pressure meets the design requirements.

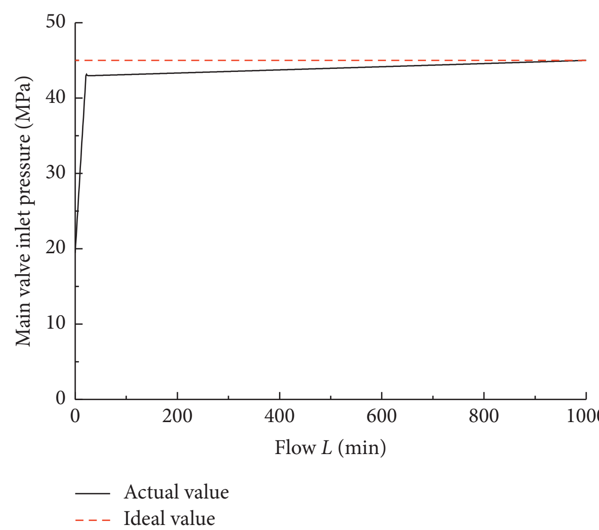

Figure 12: Static characteristic curve of relief valve.

4.3. Simulation of the Dynamic Characteristics of the Relief Valve. The dynamic characteristics of the relief valve are usually measured by indicators such as pressure overshoot, pressure settling time, and pressure recovery time. The simulation model of the relief valve built in Figure 11 to obtain the inlet pressure of the main valve and pilot valve of the relief valve is run, as shown in Figure 13.

It can be seen from Figure 13 that the pressure at the inlet of the main valve reaches 28.9 MPa at the initial stage of the start-up, after which the growth rate slows down, the pressure in the front chamber of the pilot valve grows slowly, and the pressure peak reaches 21.49 MPa at 10.25 ms. The inlet cavity of the main valve reaches the pressure peak of 46.76 MPa at 10.05 ms, and then, the pressure gradually drops to the steady-state value, indicating that the main valve did not overflow after the pilot valve was opened, but the two spool opening time interval was short, and the relief valve worked well.

The pressure at the inlet of the pilot valve and the main valve reached steady-state pressure values of 19.45 MPa and

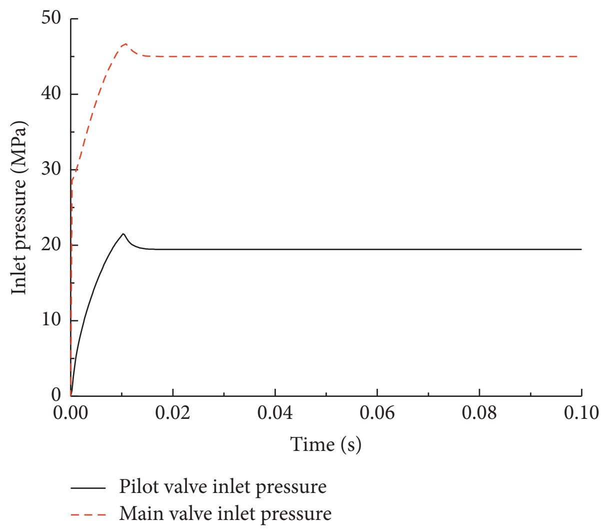

FIGURE 13: Dynamic characteristic curve of relief valve.

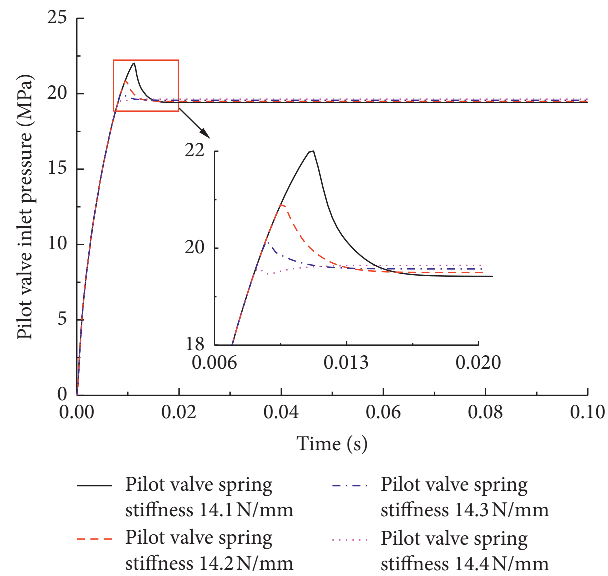

FIGURE 14: Influence of pilot spring on pilot valve.

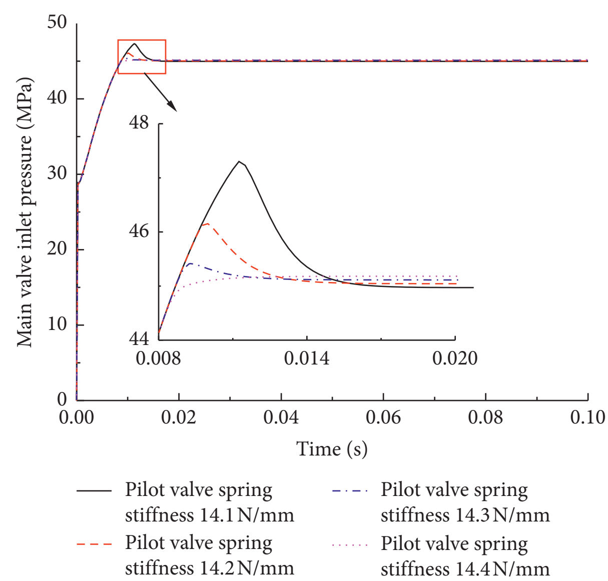

FIGURE 15: Influence of pilot spring on main valve.

45 MPa at 18 ms and 18.75 ms, respectively, and the pressure overshoots were 10.49% and 3.91%, respectively. The usual design requires that the main valve pressure overshoot should be less than 10% ~ 15% of the maximum rated pressure. The simulation results show that the designed relief valve reacts quickly when the pressure is abrupt, and the pressure overshoot at the inlet is small. In particular, the inlet valve pressure of the main valve is less oscillating, and the damage to the hydraulic components and the pipeline is small.

4.4. Analysis of Structural Parameters of Relief Valve. The structural parameters of the relief valve, such as spring, valve core, orifice, leakage clearance, and other structural dimensions, also have a great impact on its dynamic characteristics. Analysis of the effects of different structural parameters can provide a theoretical basis for the optimal design of the relief valve. According to the simulation model built in Figure 11, using the batch processing function in AMESim simulation software, the key structural parameters of the relief valve are compared and simulated, and the influence of different structural parameters on its dynamic characteristics is obtained.

4.4.1. Influence of Spring Stiffness

(1) Influence of the Spring Stiffness of the Pilot Valve on the Dynamic Characteristics. The other structural parameters are kept unchanged, and the spring stiffness of the pilot valve is set to 14.1 N/mm, 14.2 N/mm, 14.3 N/mm, and 14.4 N/mm, respectively. The pressure response curves at the entrance of the main valve and the pilot valve are obtained, as shown in Figures 14 and 15, and the dynamic indexes such as pressure stability value, overshoot, and stability time are shown in Figures 16 and 17.

According to the simulation results, as the stiffness of the pilot spring increases, the preload force acting on the pilot spool and the spring compression force generated when the spool moves are increased, resulting in an increase in the steady-state pressure value of the relief valve. In addition, when the spring stiffness of the pilot valve is increased, the pressure overshoot of the relief valve is significantly reduced, the working stability of the relief valve is improved, the response time is shortened, and the steady flow effect is good. Therefore, on the basis of satisfying the calculation result of the static characteristic parameter design of the relief valve, the spring stiffness of the pilot valve can be appropriately increased.

(2) The Influence of the Main Valve Spring Stiffness on the Dynamic Characteristics. The main valve spring stiffness is set to 9 N/mm, 9.1 N/mm, 9.2 N/mm, and 9.3 N/mm,

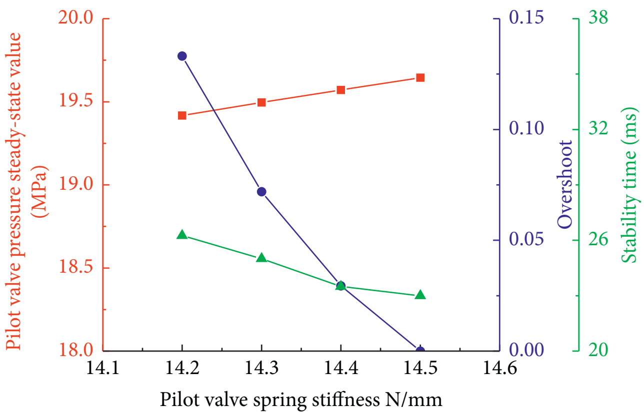

Figure 16: Dynamic response indexes of pilot valve.

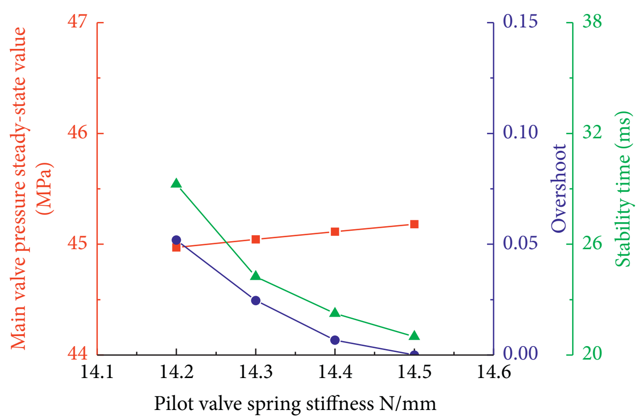

Figure 17: Dynamic response indexes of main valve.

respectively. The pressure response curves at the entrance of the main valve and the guide valve are obtained, as shown in Figures 18 and 19. The dynamic indexes such as pressure stability value, overshoot, and stability time are shown in Figures 20 and 21.

According to the simulation results, it can be seen that since the main valve spring mainly plays a resetting role, the change in its stiffness has little influence on the dynamic response characteristics of the relief valve. As the spring stiffness of the main valve increases, the pressure stability values at the inlet of the pilot valve and the main valve increase by 0.13 MPa and 0.7 MPa, respectively; the overshoot of the pressure at the two valve ports decreases. However, the overshoot of the pilot valve is greater than the overshoot of the main valve, and the variation is greater. The increase in the stiffness of the main valve spring has less effect on the settling time of the relief valve.

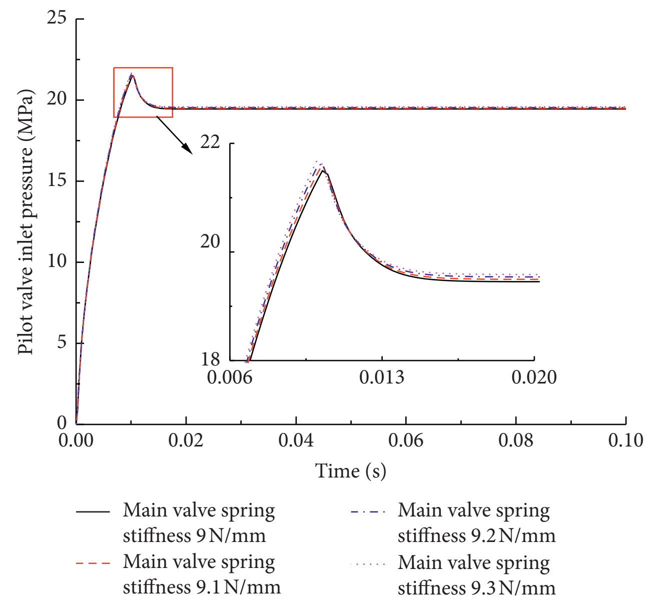

Figure 18: Influence of main spring on pilot valve.

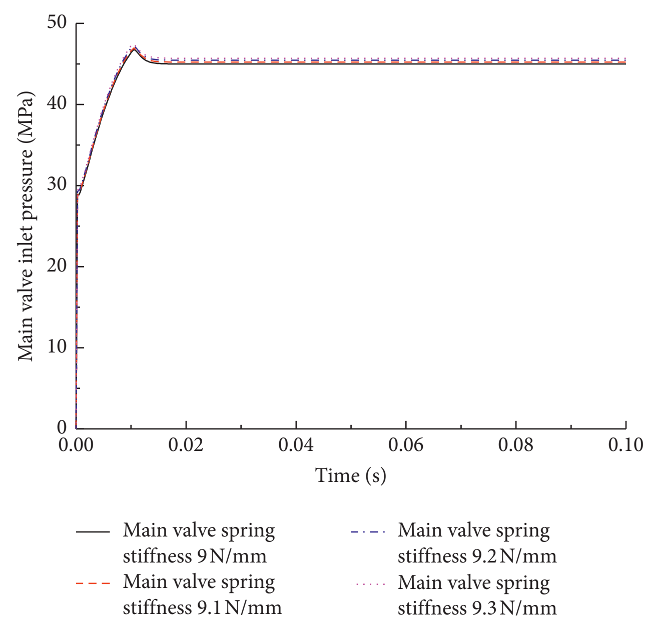

Figure 19: Influence of main spring on main valve.

4.4.2. Influence of Spool Quality

(1) Influence of Pilot Valve Spool Quality on Dynamic Characteristics. The other parameters of the model are kept unchanged, the quality of the pilot valve spool is set to 0.01 kg, 0.02 kg, 0.03 kg, and 0.04 kg. The simulation results and dynamic characteristics are shown in Figures 22–25.

It can be seen from Figure 22 to Figure 25 that the change in the quality of the pilot valve spool does not affect the steady-state working pressure of the relief valve but has a great influence on the dynamic characteristics of the relief valve. According to the partial enlargement chart and the statistical chart, it can be seen that, as the quality of the pilot valve spool increases, the pressure overshoot of the pilot valve and the main valve increases, and the number of oscillations increases, resulting in an increase in the stabilization time of the relief valve. And the influence of the quality change of the pilot valve spool on the dynamic characteristics of the pilot valve is more obvious than that of the main valve. Therefore, the response time of the relief

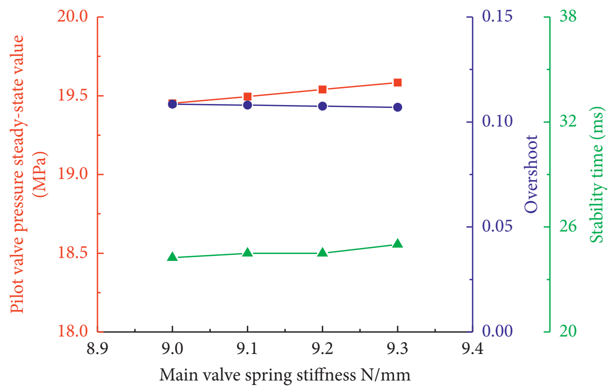

Figure 20: Dynamic response indexes of pilot valve.

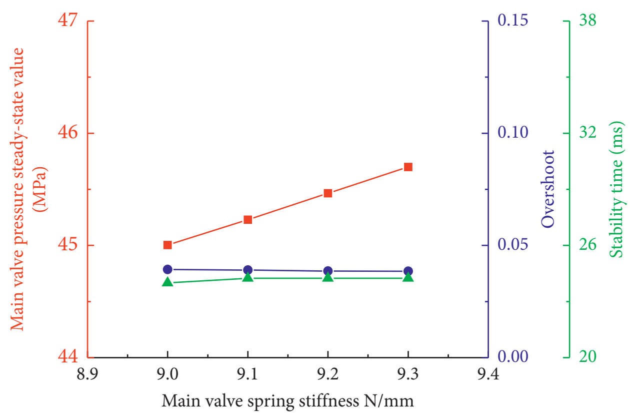

Figure 21: Dynamic response indexes of main valve.

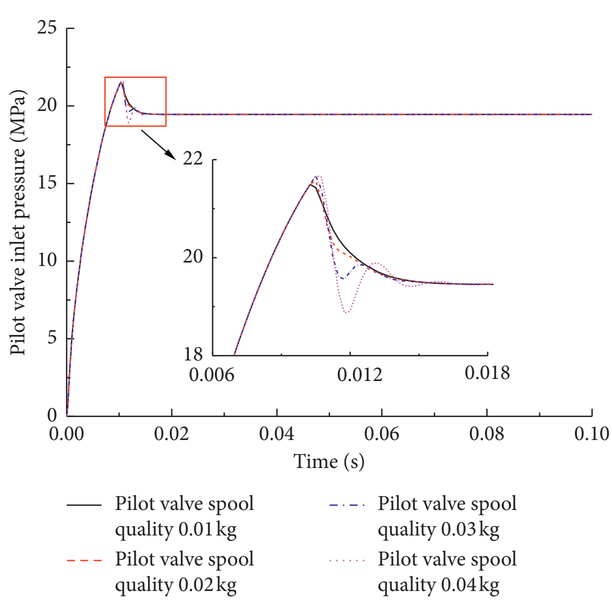

Figure 22: Influence of pilot valve quality on pilot valve.

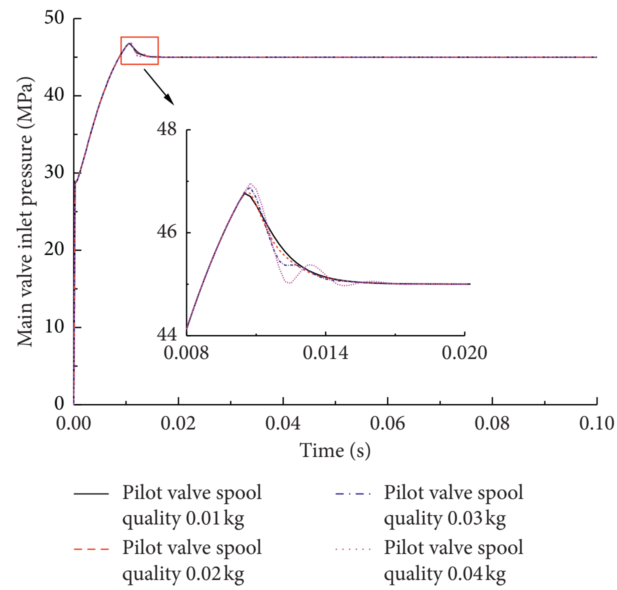

Figure 23: Influence of pilot valve quality on main valve.

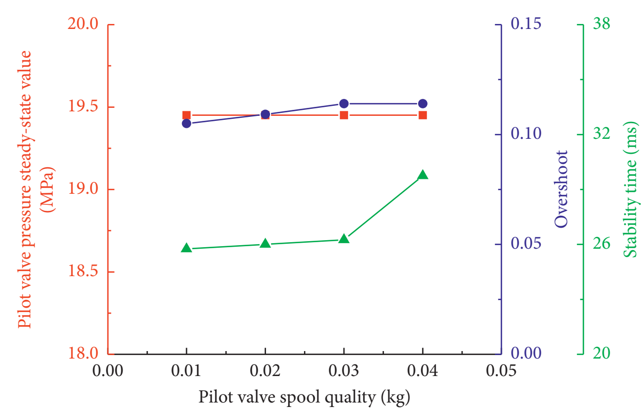

Figure 24: Dynamic response indexes of pilot valve.

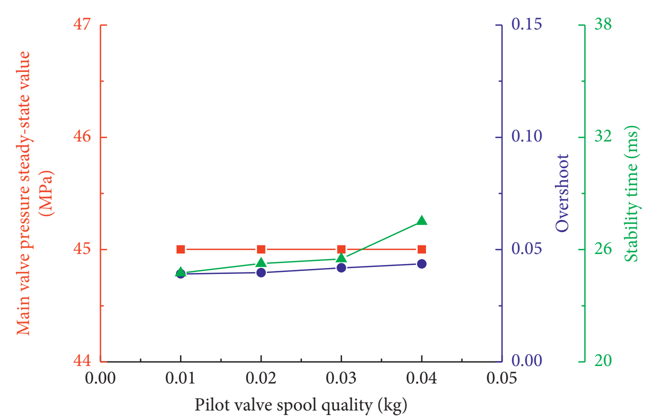

Figure 25: Dynamic response indexes of main valve.

valve can be shortened and the working stability of the relief valve can be increased by appropriately reducing the quality of the pilot valve spool.

(2) Influence of Main Valve Spool Quality on Dynamic Characteristics. The other parameters of the model are kept unchanged, and the quality of the pilot valve spool is set to

0.05 kg, 0.06 kg, 0.07 kg, and 0.08 kg. The simulation results are shown in Figures 26 and 27. The dynamic characteristic change is shown in Figures 28 and 29.

It can be seen from the simulation results that the change in the quality of the main valve spool has little effect on the dynamic performance of the relief valve and the steady-state working pressure. The resulting curves in Figures 26 and 28 illustrate that the increase in quality of the main valve spool has no effect on the pressure response of the pilot valve. In the partial enlarged view of Figure 27, it can be seen that when the quality of the main valve spool is increased to a certain extent, the pressure at the inlet of the main valve begins to oscillate, and the oscillation gradually becomes slower with time, eventually becoming stable. As a result, the overshoot increases and the stabilization time prolongs, but the pressure stability value remains unchanged.

4.4.3. Influence of Damping Hole Diameter. The relief valve designed in this paper contains two slender damper holes. Because the positions and functions of the two damper holes are different, it is necessary to compare and analyze the influence of the diameter of different damper holes on the dynamic characteristics of the relief valve.

(1) Influence of Damping Hole Diameter on Dynamic Characteristics. Three sets of simulation parameters are set, respectively: (1) the diameter of the main valve damping hole d_1 is 1.2 mm, and the diameter of the pilot valve damping hole d_2 is 0.9 mm; (2) the diameter of two damping holes is 1.2 mm; (3) the diameter of main valve damping hole d_1 is 0.9 mm, and the diameter of pilot valve damping hole d_2 is 1.2 mm. The simulation results are shown in Figures 30 and 31, and the dynamic characteristics are shown in Table 2.

The simulation results show that when the diameter of the main valve damper hole is larger than that of the pilot valve damper hole, the steady-state pressure value of the relief valve decreases slightly, the pressure overshoot is the largest, and the stability time is the longest; when the diameter of the two damper holes is the same or the diameter of the pilot valve damper hole is larger, the working pressure of the relief valve is the same, and both conditions can reach the rated value. Under these conditions, the dynamic response of the relief valve has little difference, except that when the diameter of the two damper holes is the same, the stability time of the relief valve is shorter, and when the diameter of the pilot valve damper hole is larger, the pressure overshoot of the relief valve is smaller. Therefore, in the design process of relief valve, the case that the diameter of main valve damping hole is larger than that of pilot valve damping hole should be avoided as far as possible, and the scheme with the same diameter or larger diameter of guide valve damping hole can be selected according to the weight of stability time and overshoot in use.

(2) Influence of the Same Diameter on the Dynamic Characteristics of the Orifice. The diameter of the main valve damping hole and the pilot valve damping hole to the same value is set, which are 1.0 mm, 1.2 mm, 1.4 mm, and 1.6 mm,

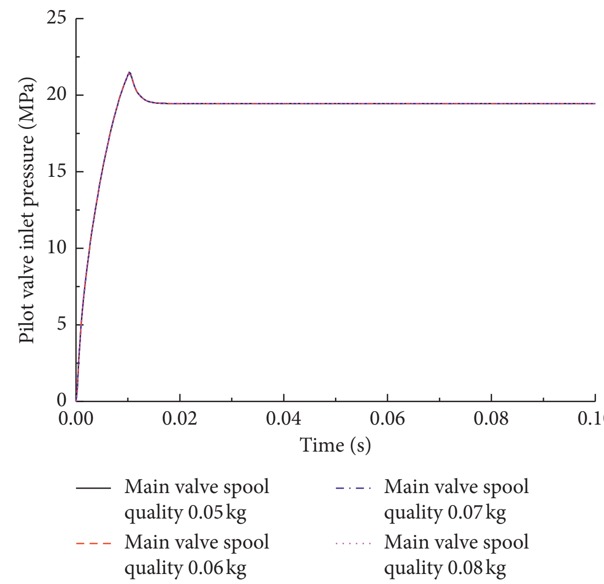

Figure 26: Influence of main valve quality on pilot valve.

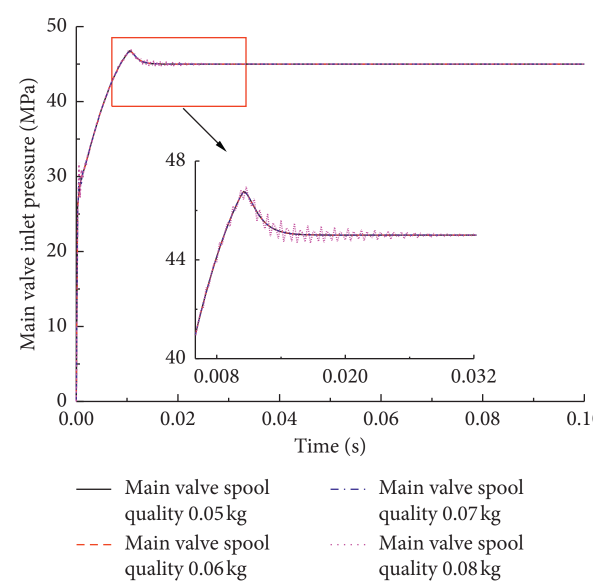

Figure 27: Influence of main valve quality on main valve.

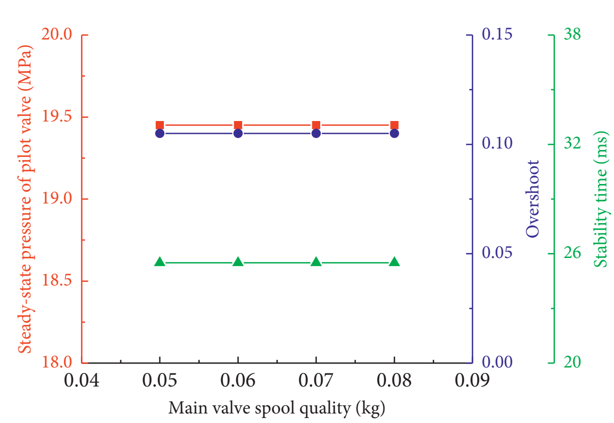

Figure 28: Dynamic response indexes of pilot valve.

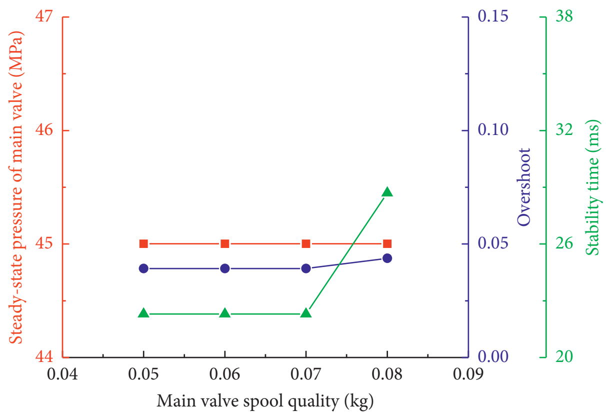

Figure 29: Dynamic response indexes of main valve.

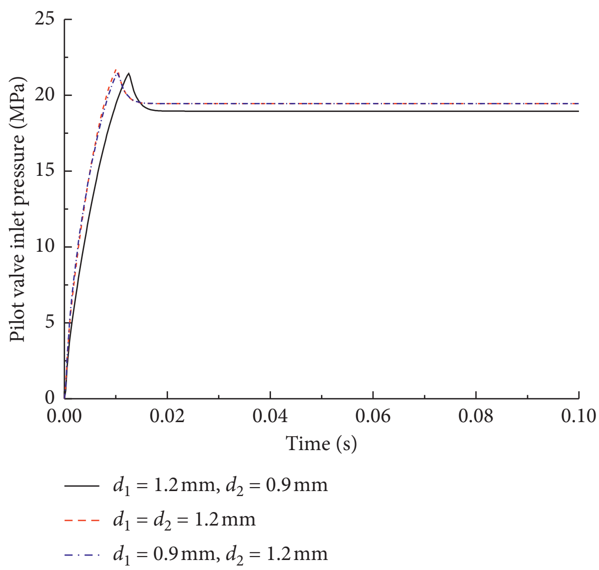

Figure 30: Influence of different diameters of damping hole on pilot valve.

respectively. The batch simulation of the model is carried out. After calculation, the simulation results and dynamic performance indicators are shown in Figures 32–35.

From Figures 32–35, it can be seen that the change in the diameter of the damping hole has a more obvious influence on the working characteristics of the relief valve, and the influence trend of the pilot valve and the main valve is inconsistent. When the diameter of the damping hole increases, the steady-state pressure of the pilot valve and the main valve increases in direct proportion, and the response time decreases gradually. However, the pressure overshoot of the pilot valve decreases with the increase in the diameter of the damping hole, and the overshoot of the main valve increases slightly. Therefore, in the design process, the diameter of the damping hole should be reasonably chosen to avoid pressure oscillation at the entrance of relief valve caused by too large diameter or too long response time and blockage of the damping hole caused by too small diameter.

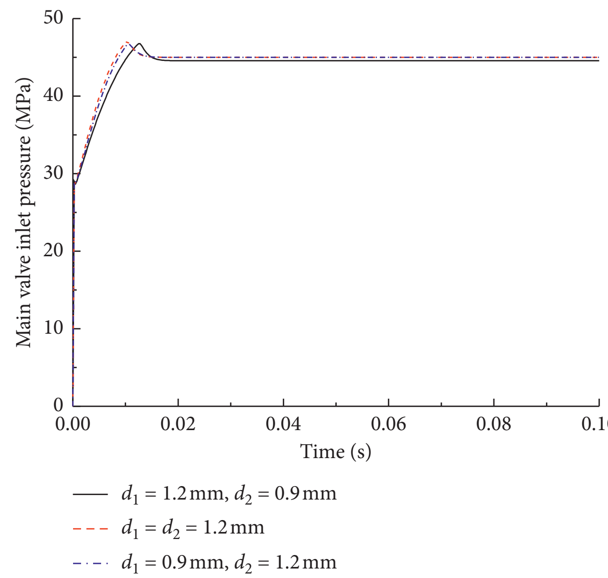

Figure 31: Influence of different diameters of damping hole on main valve.

4.4.4. Influence of Damping Hole Length

(1) The Influence of Different Lengths of Damper Holes on Dynamic Characteristics. Three sets of simulation parameters are set, respectively: (1) the length of main valve damping hole l_1 is 15 mm, and the length of pilot valve damping hole l_2 is 5 mm; (2) the length of two damping holes is 15 mm; (3) the length of main valve damping hole l_1 is 5 mm, and the length of pilot valve damping hole l_2 is 15 mm. Running three groups of simulation, the simulation results are shown in the following figures, and the dynamic characteristics are shown in Table 3.

As can be seen from Figures 36 and 37, the relationship between the lengths of the two damper holes is quite different in the three cases, but the results obtained are basically similar. Under the same other conditions, when the length of the main valve damper hole is longer than that of the pilot valve damper hole, the working pressure of the relief valve is the highest, the overshoot is the smallest, but the pressure stability time is the longest; when the length of the main valve damper hole is less than that of the pilot valve damper hole, the stability time of the relief valve is the shortest, but the pressure overshoot is the largest. When the length of the two damper holes is the same, the steady-state pressure value is small, but the overshoot and the steady-state time are moderate. Therefore, in the design process of relief valve, the relationship between the length of two damper holes can be determined according to the bias degree of rated working pressure, pressure overshoot, and stability time.

(2) Influence of the Same Length of the Orifice on the Dynamic Characteristics. Setting the length of main valve damper hole and guide valve damper hole to the same value, 12 mm, 14 mm, 16 mm, and 18 mm, respectively, the model was simulated by the batch process. The simulation results and

Table 2: Dynamic response indexes of relief valve.

	Pilot valve			Main valve		
	Stable pressure (MPa)	Overshoot	Stable time (ms)	Steady-state pressure (MPa)	Overshoot	Stable time (ms)
$d_1 = 1.2$ mm $d_2 = 0.9$ mm	18.95	0.131	27.75	44.55	0.050	30
$d_1 = d_2 = 1.2$ mm	19.45	0.118	25.25	45.00	0.047	24.25
$d_1 = 0.9$ mm $d_2 = 1.2$ mm	19.45	0.105	25.5	45.00	0.039	24.75

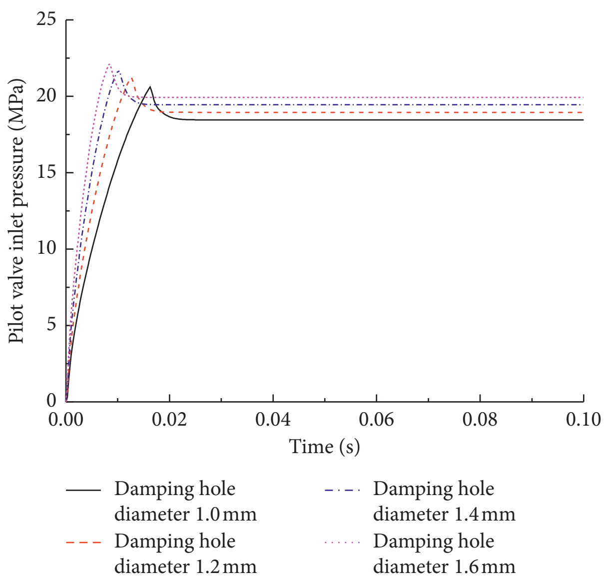

Figure 32: Influence of same diameter of damping hole on pilot valve.

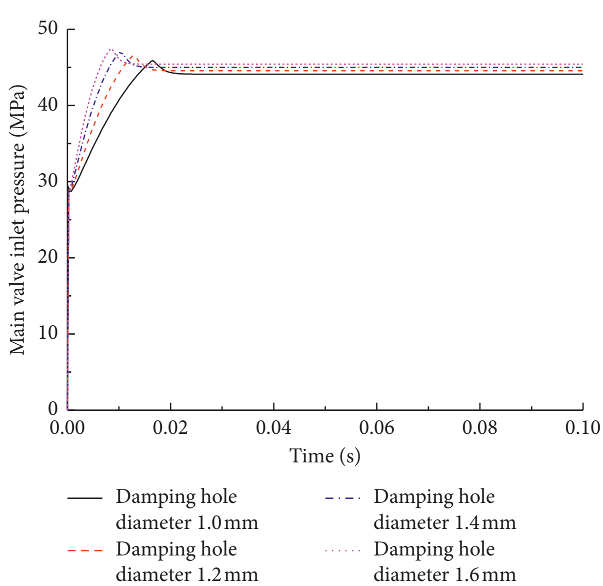

Figure 33: Influence of same diameter of damping hole on main valve.

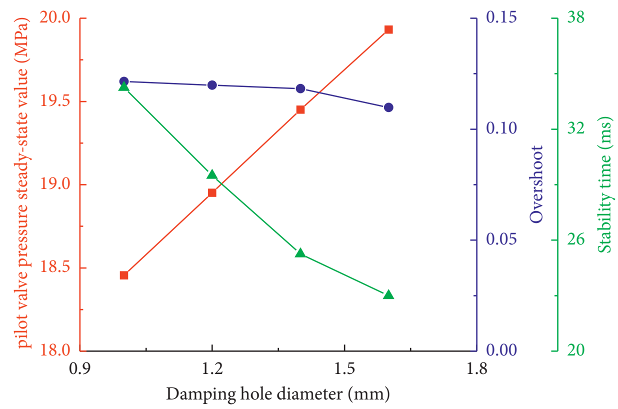

Figure 34: Dynamic response indexes of pilot valve.

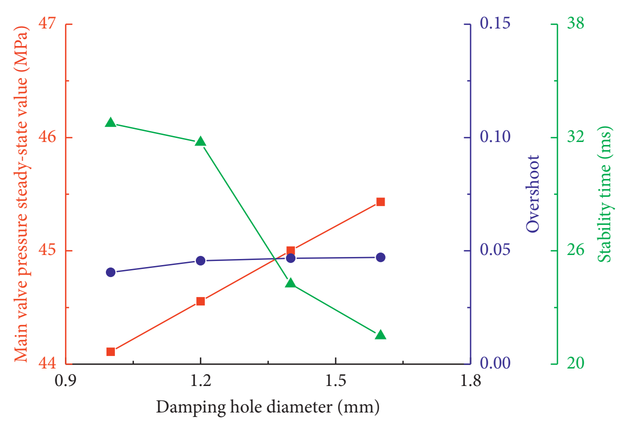

Figure 35: Dynamic response indexes of main valve.

dynamic performance indexes were obtained by calculation and processing, as shown in Figures 38–41.

From the results, it can be seen that the influence of the length of the damping hole on the dynamic response of the pilot valve and the main valve is basically the same. When the length of the damper hole increases, the steady-state working pressure of the relief valve decreases and the overshoot decreases slightly, the pressure overshoot of the main valve is higher than that of the pilot valve, and the stability time is slightly prolonged. Therefore, after determining the relationship between the length of the damper hole and meeting the design requirements, appropriately shortening the length of the damper hole can increase the maximum rated pressure of the relief valve, shorten the stability time, and reduce the volume of the relief valve.

4.4.5. Influence of Leakage Clearance. Other structural parameters are kept unchanged, the leakage clearance is set to 0.01 mm, 0.02 mm, 0.03 mm, and 0.04 mm, respectively, and

Table 3: Dynamic response indexes of relief valve.

	Pilot valve			Main valve		
	Steady-state pressure (MPa)	Overshoot	Stable time (ms)	Steady-state pressure (MPa)	Overshoot	Stable time (ms)
l_1 =15 mm l_2 =5 mm	19.43	0.116	24.75	44.99	0.043	25.5
$l_1 = l_2$ = 15 mm	19.36	0.116	24.5	44.92	0.044	24.5
l_1 =5 mm l_2 =15 mm	19.36	0.117	24.25	44.92	0.046	24.25

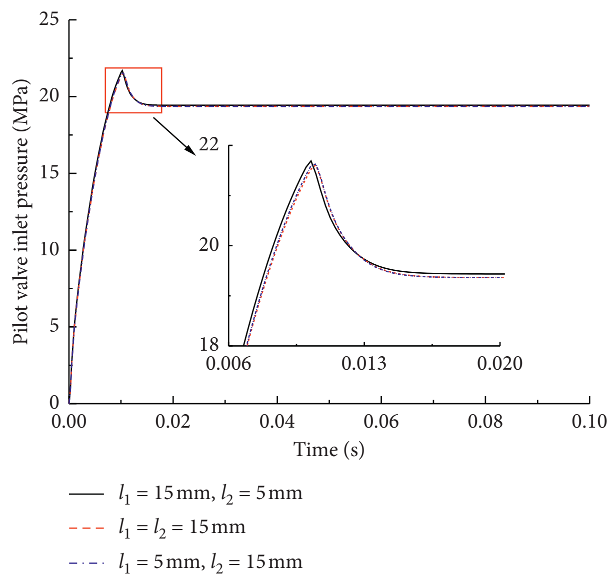

Figure 36: Influence of different lengths of damping hole on pilot valve.

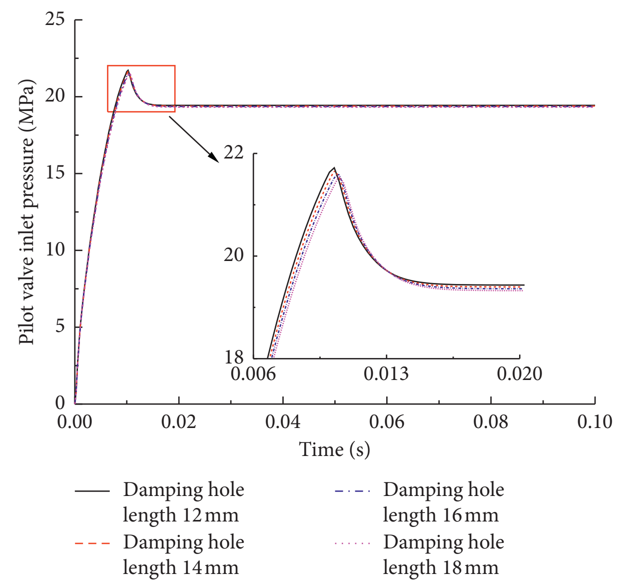

Figure 38: Influence of same length of damping hole on pilot valve.

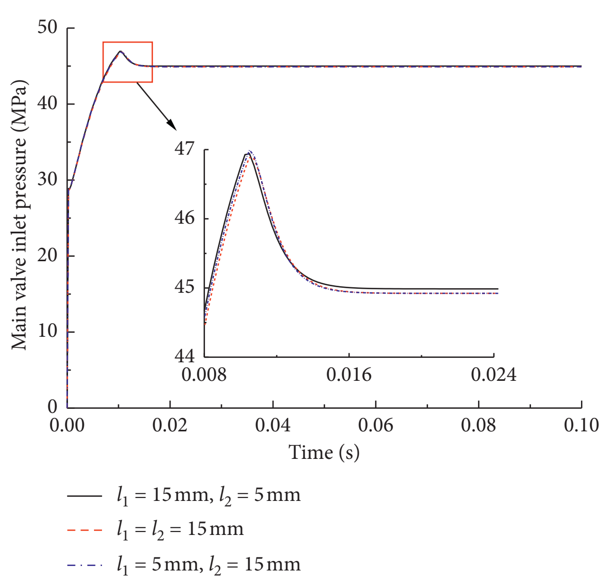

Figure 37: Influence of different lengths of damping hole on main valve.

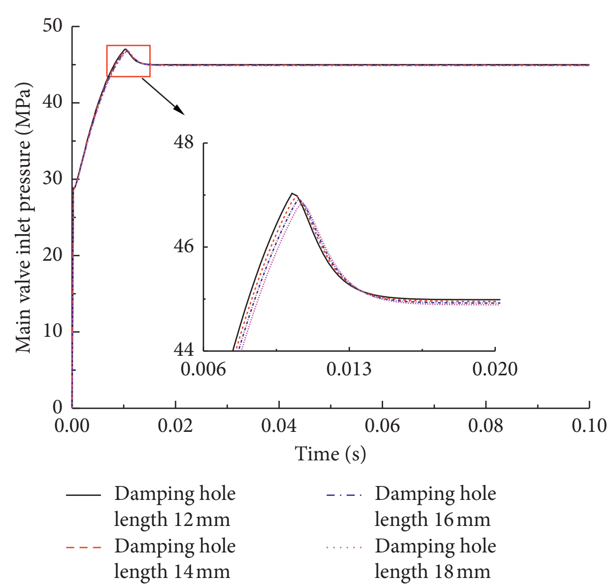

Figure 39: Influence of same length of damping hole on main valve.

the pressure response curve at the inlet of the pilot valve and the main valve is obtained, as shown in Figures 42 and 43, and the dynamic index changes in pressure stability value, overshoot, and stability time, as shown in Figures 44 and 45.

From Figures 42–45, it can be seen that the change in the leakage clearance does not affect the steady-state working pressure of the relief valve but has some influence on the

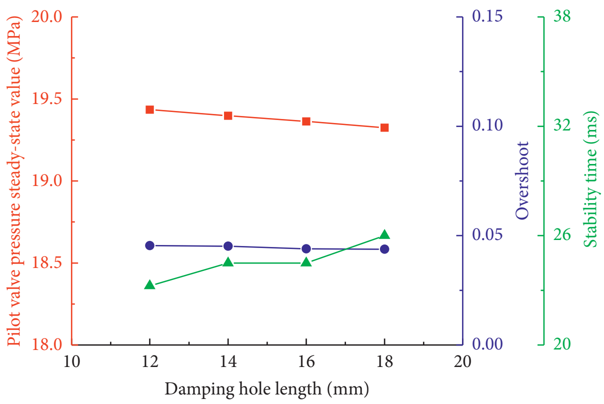

Figure 40: Dynamic response indexes of pilot valve.

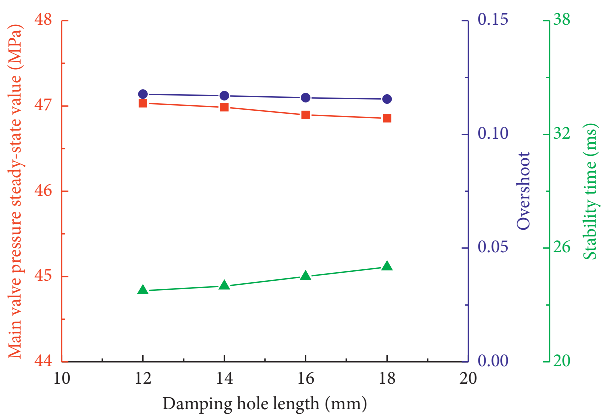

Figure 41: Dynamic response indexes of main valve.

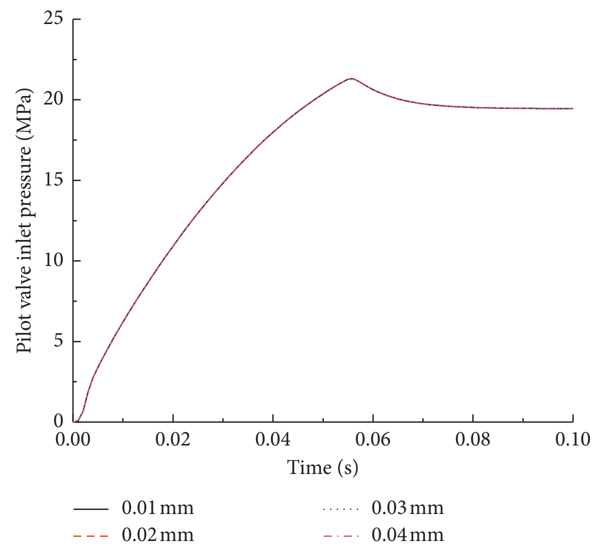

Figure 42: Influence of leakage clearance on pilot valve.

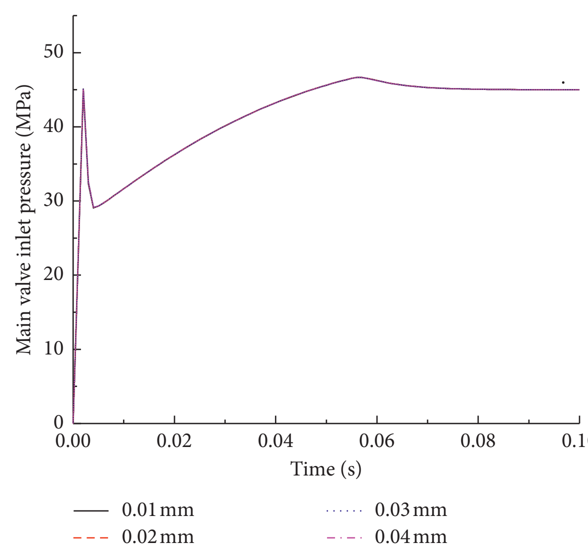

Figure 43: Influence of leakage clearance on main valve.

dynamic characteristics of the relief valve. Before the pilot valve and the main valve are stable, the pressure overshoot increases, the stability time of the relief valve is prolonged, and the influence of the change in leakage clearance on the dynamic characteristics of the main valve is more obvious than that of the pilot valve. Therefore, in the design, the response time of the relief valve can be shortened and the working stability of the relief valve can be increased by properly reducing the leakage clearance.

The physical structure simulation model of the relief valve is built by using AMESim simulation software. The static and dynamic characteristics of the designed relief valve are analyzed by simulation analysis, and the main structural parameters of the relief valve are simulated in groups. The influence of different structural parameters such as spring stiffness, core mass, diameter of damping hole, length of damping hole, and leakage clearance on the working characteristics of relief valve is obtained.

4.5. Field Operation. The developed large flow pilot type emulsion relief valve is installed on high-pressure large flow emulsion pump, and a large number of field tests and industrial operation have been carried out. As shown in Figure 46, the test system includes mechanical system, hydraulic system, data acquisition, and analysis system, which can carry out pressure regulating range, pressure loss test, opening and closing characteristic test, and dynamic response characteristic test.

The physical figure of the pilot type emulsion relief valve is shown in Figure 47, and the key structural parameters are shown in Table 4.

The cumulative running in time of field operation is 100 h. In the process of working high pressure in the process of working face support liquid supply and switching in the process of pump station pressure relief, the response time of pressure regulation is short, the flow rate and pressure stability are good, which verifies the correctness of emulsion overflow valve design.

The simulation platform of Matlab/Simulink uses the mathematical model of relief valve to simulate the characteristics, and the simulation software of AMESim uses its physical structure parameters to build the dynamic response

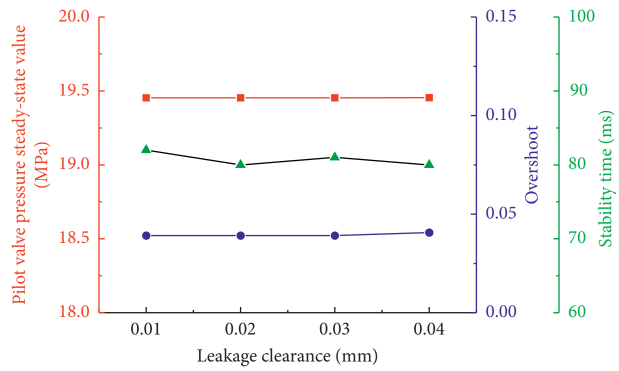

Figure 44: Dynamic response indexes of pilot valve.

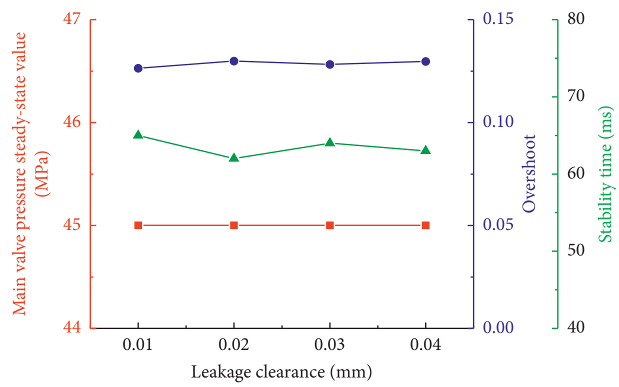

Figure 45: Dynamic response indexes of main valve.

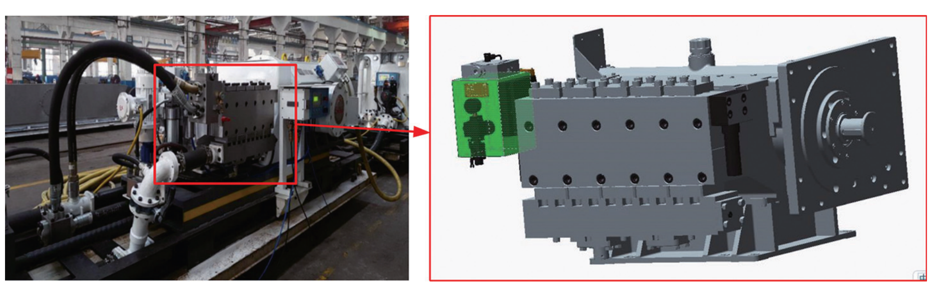

Figure 46: Industrial operation site.

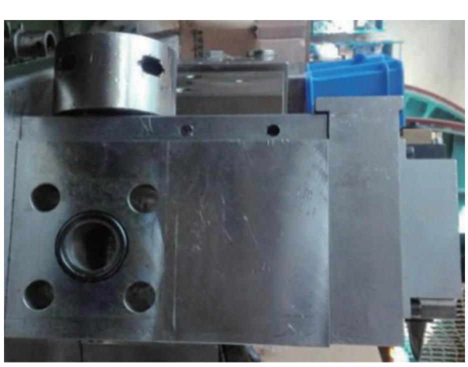

Figure 47: Physical drawing of pilot relief valve.

Table 4: Structural parameters of relief valve.

Parameter name	Numerical value
Inlet and outlet flow diameter (mm)	37
Diameter of main valve core (mm)	46
Main valve seat bore (mm)	36
Damping hole length (mm)	8
Damping hole diameter (mm)	0.8
Main cone valve port half cone angle (°)	30
Pilot valve core half cone angle (°)	20
Pilot valve bore (mm)	3.5
Ceramic ball diameter of pilot valve (mm)	5.2
Spring stiffness of pilot valve (N/mm)	57.4

simulation. The specific figures in the simulation results are different, but the influence of the same structural parameters on the working characteristics of the relief valve has the same trend. It is indicated that the mathematical model and physical structure of relief valve should be considered comprehensively when designing the relief valve. The comparison of the two simulation results verifies the correctness of the simulation results. Meanwhile, the field test shows that the designed relief valve has good working characteristics.

5. Conclusions

In view of the shortcomings in the current research of the digital relief valve, this paper comprehensively analyzed the digital large-flow emulsion relief valve from the aspects of mathematical model, dynamic characteristics, and structural parameters.

The following conclusions can be drawn from the results of this work:

(1) The flow rate of the designed relief valve meets 1000 L/min, which can meet the flow requirements of large flow emulsion pumping stations. The working pressure of the relief valve is acquired by the pressure sensor at the inlet of the relief valve in real time and compared with the preset pressure. According to the results of pressure comparison, the pulse is output to control the direction of stepper motor and the number of rotating steps and then adjust the spring preload to improve the control accuracy, so as to realize the real-time control of the working pressure of digital relief valve.

(2) Through the simulation analysis of relief valve with the software of Matlab/Simulink and AMESim, the overall dynamic response characteristics of the designed relief valve are good, which shows that the designed relief valve has good working characteristics. From the simulation results, it can be seen that the volume of the front chamber of the pilot valve should be reduced as much as possible in order to shorten the stabilization time and reduce the pressure oscillation. At the same time, the working stability of the relief valve can be increased by reducing the quality of the guide valve spool to shorten the response time of the relief valve. By appropriately shortening the length of the damper hole, the maximum rated pressure of the relief valve can be increased and the stability time can be shortened.

(3) Using the software of Matlab/Simulink and AMESim to simulate, the same structural parameters of the two simulation results have the same trend to affect the working characteristics of the relief valve, and the validity of the simulation results is verified by comparison. In the meanwhile, the correctness of the simulation is verified by experiments.

Abbreviations

A_1: Stress area of main valve seat aperture
A_2: Stress area of upper chamber of main valve element
A_x: Force area of the pilot valve seat hole
C_1: Main valve port flow coefficient
C_2: Pilot valve port flow coefficient
d: Pilot seat bore
D: Diameter of main valve core
E: Emulsion elastic modulus
f_x: Pilot valve spool viscous damping coefficient
f_y: Main valve spool motion viscous damping coefficient
G_{R1}: Pilot valve fluid guide
k_x: Pilot valve spring stiffness
k_y: Main valve spring stiffness
k_{cx}: Pilot valve port flow pressure coefficient
k_{ex}: Pilot valve port hydraulic dynamic stiffness
k_{qx}: Pilot valve port flow gain
k_{cy}: Main valve port flow pressure coefficient
k_{ey}: Main valve port hydraulic dynamic stiffness
k_{qy}: Main valve port flow gain
m: Pilot valve spool equivalent mass
M: Main spool equivalent mass
p_1: Pilot valve inlet pressure
p_2: Upper cavity pressure of main spool
p: Main valve inlet pressure
q: Flow into the relief valve
q_1: Flow through the pilot valve orifice
q_2: Main valve upper chamber emulsion flow
q_x: Flow at the pilot valve port
q_y: Flow from the main valve port
V_0: Main valve inlet cavity volume
V_1: Pilot valve front cavity volume
x: Pilot valve spool displacement
x_0: Pilot valve spring precompression
y: Main valve spool displacement
y_0: Main valve spring precompression
α: Main valve port half cone angle
β: Pilot valve port half cone angle
ρ: Emulsion density.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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