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Research on two-step throttle characteristics of double-rotation valve port for hydraulic servo joint①

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Abstract

The hydraulic robot with large output torque is widely used in industry, however, its precision is not high. In order to solve this problem, this paper presents a new structure of rotary valve with double-rotation valve port, which can improve the two-step throttle characteristics of the valve port, reduce the cavitation phenomenon of the valve port, and increase the output accuracy of the hydraulic servo joint. Firstly, the internal flow field of the rotary valve is simulated by using the sliding grid technology of FLUENT software, and the changing rule of the throttle position in the working process of the structure is analyzed. Secondly, compared with the simulation results of rotary valve with single-rotation valve port, it is shown that the two-step throttle characteristics of the structure are less affected by the change of the opening of the rotary valve, and the cavitation index of the joint valve port is reduced. Finally, the influence of the rotation speed of the valve core, oil supply pressure and key dimension of valve core on throttle characteristics of rotary valve have been analyzed.

Key words: double-rotation valve port, cavitation, 3D sliding mesh, transient solution, the two-step throttle, pressure changing frequency

0 Introduction

The hydraulic robot joint has the advantages of stable transmission, large torque inertia ratio, simple structure, high load stiffness, fast response, high precision and easy to realize overload protection. The scholars of Wuhan University of Science and Technology have designed a series of hydraulic joints[1] by using the hydraulic angle self-servo technology. After subsequent improvement, the prototype was developed. But the internal flow field of the joint is complex, which affects the output accuracy of the joint, so it is necessary to optimize the internal flow field.

At present, researches on the flow field, two-step throttle characteristics and cavitation resistance of hydraulic valves have been carried out, and many results have been achieved. Ref. [2] used numerical analysis method to evaluate the driving force of the valve core of the open central directional valve, and compared it with the closed central valve. Then computational fluid dynamics (CFD) technology was used to analyze the flow field in the valve. Ref. [3] used CFD to simulate the flow of cavitating fluid in the spherical valve, and compared with the experiment. It analyzed the flow characteristic coefficient of the valve and the hydraulic pressure on the valve ball. Ref. [4] studied the development process of ball valve cavitation by characteristic diagram method and acoustic measurement method. Ref. [5] studied the influence of cavitation on the performance of hydraulic proportional valve and flow rate and flow coefficient on the change of valve core position. A three-dimensional model of internal flow field, which accurately predicted the position of valve core cavitation, was established. Ref. [6] used CFD software and particle image velocimetry (PIV) technology to study the flow field characteristics of the main valve core of the electro-hydraulic proportional multi-way valve with the dual valve core. It was concluded that ring cavity of the main valve would form a vortex at the oil outlet, the opening and flow rate of the valve port would have greater impact on the inlet throttle and valve port's pressure drop of the main valve. Ref. [7] proposed that when the hydraulic control check valve

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was opened reversely, the dynamic performance of the stepped main valve core was superior. Ref. [8] studied the two-step throttle characteristics of hydraulic spool valves and obtained the pressure and velocity field under different valve port sizes. Ref. [9] studied the two-step throttle characteristics of non full circle opening slide valve, and the calculation principle of valve port area was determined, the formula of valve port area was deduced, the relationship curve between valve port opening and flow area was obtained. Ref. [10] used the two-phase flow of FLUENT software to carry out simulation, and it was concluded that the anti-cavitation performance is the best when the cone angle of the poppet valve is 30 ° and the opening is 0.4 mm. Ref. [11] used two-phase flow method to study the influence of valve core's radial displacement, half cone angle, opening and back pressure on cavitation distribution and strength. A visual experimental platform for cavitation phenomenon of hydraulic cone valve was developed to verify the simulation results. Ref. [12] used CFD software to study the relationship between cavitation flow field and back pressure of conical throttle valve, the relationship between back pressure, cavitation area and cavitation intensity was obtained. In the study of cavitation and two-step throttle characteristics of hydraulic rotary valve, Ref. [13] used the sliding grid technology of FLUENT software and two-phase flow technology to study the cavitation phenomenon of the high-frequency rotary valve port. It was found that the cavitation phenomenon can destroy the stability of the valve-controlled cylinder excitation system. Ref. [14] designed a two degree of freedom high-frequency rotary valve, analyzed its working principle, established a mathematical model, and obtained the relationship between the pressure characteristics of the valve port and the system pressure, the axial opening of the valve port and the reversing frequency. Ref. [15] simulated the flow field in the rotary valve through FLUENT software. It was indicated that the two-step throttle characteristics are influenced by different valve port shapes, opening degrees, axial length of grooves of different valve cores, hollow structure of valve cores and the number of grooves of valve cores in the steady state, especially the change of opening degrees of valve ports had the most obvious effect on the two-step throttle characteristics. However, there are few researches on the two-step throttle characteristics and anti-cavitation performance of the rotary valve in the transient condition. Therefore this paper uses the numerical simulation method to study the throttle characteristics of the rotary valve with different structures.

1 The principle of the two-step throttle

For the cavitation phenomenon, the cavitation index is often used to evaluate the probability of cavitation at the valve port. The larger the cavitation index is, the greater the possibility of cavitation is. The first and second throttle orifice's cavitation indices of the two-step throttle are shown in Eq. (1) and Eq. (2) respectively.

$$\sigma_1 = \frac{P_1 - P_2}{P_1 - P_g} \tag{1}$$

$$\sigma_2 = \frac{P_2 - P_3}{P_2 - P_g} \tag{2}$$

where, P_1 is the inlet pressure, P_2 is the intermediate zone pressure, P_3 is the outlet pressure, and P_g is the air separation pressure of the medium, and its value is 1.5×10^3 Pa. The cavitation index of the first-order throttling is

$$\sigma_0 = \frac{P_1 - P_3}{P_1 - P_g} \tag{3}$$

According to Eq. (3), when $P_1 > P_2 > P_3$ and P_g is fixed, σ_1, $\sigma_2 < \sigma_0$ can be obtained, so the two-step throttle can reduce the cavitation of the valve port[16].

2 Structure of rotary valve with double-rotation valve port

The hydraulic servo joint adopts the structure of built-in servo valve, which simplifies the joint structure and facilitates the miniaturization of the joint. However, during the actual work process, the high-pressure oil will be distributed through the rotary valve inside the joint. In this process, it is inevitable the sudden change of oil pressure will occur, and bubbles will be easily generated inside the system. These local vacuum will cause the inflow of surrounding hydraulic oil, which will cause the phenomenon of hydraulic impact and local high temperature, and cavitation will be caused under the combined effect of local high temperature and hydraulic impact phenomenon. At the same time, the valve sleeve of the rotary valve is connected with the output valve body of the joint, the hydraulic impact inside the rotary valve will inevitably affect the output accuracy of the system, so it is necessary to optimize the structure of the rotary valve to improve the system accuracy.

According to the above principle, this paper proposes a new rotary valve with double-rotation valve port (as shown in Fig. 1). Its working principle is that four pairs of throttle orifices are formed at two different working positions. In the position shown in Fig. 1, port

A and port T are connected, port P and port B are connected. The upper and lower rectangular ports of the valve sleeve in port P area and the upper and lower rectangular grooves of the valve core in port P area form the first throttle orifice. The upper and lower rectangular ports of the valve sleeve in port B area and the upper and lower rectangular grooves of the valve core in port B area form the second throttle orifice. So two pairs of two-step throttle orifices for the inletting oil are formed in the P-port area and B-port area. In the same way, two pairs of two-step throttle orifices for the returning oil are formed in the area of port A and port T. In the other position, two pairs of two-step throttle orifices for the inletting oil are formed in the area of port P and port A, and two pairs of two-step throttle orifices for the returning oil are formed in the area of port B and port T, so as to achieve the purpose of reducing valve port cavitation and improve the system accuracy.

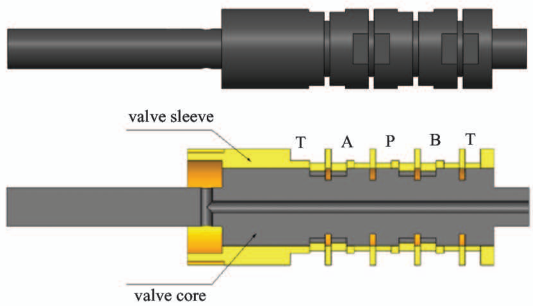

Fig. 1 Structure of rotary valve with double-rotation valve port

3 CFD numerical simulation

In this paper, the FLUENT software's sliding grid technology and transient solution method are used to simulate the internal flow field of the rotary valve with double-rotation valve port and the rotary valve with single-rotation valve port.

3.1 Flow field model and meshing

The internal flow field of the rotary valve with double-rotation valve port is composed of 4 models with the same structure, and the model turned 90 ° in the axial direction. The rotary valve's maximum opening degree is 45 °. Therefore, the mesh model of the flow field in the rotary valve can be simplified as shown in Fig. 2. The flow field comprises 3 parts, including valve sleeve's flow field, valve core's annular flow field and valve core groove flow field. The number of nodes is 160 536.

3.2 Transient simulation analysis of internal flow field of rotary valve

When simulating the internal flow field of the rotary

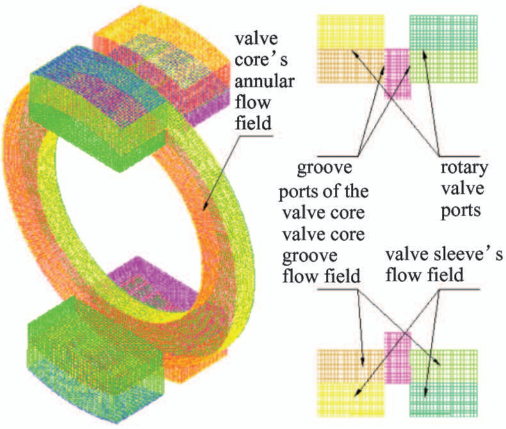

Fig. 2 Flow field grid model and sectional drawing

valve, the solver is set to be based on pressure solution and transient solution. The turbulence model is selected as standard k-ε, and the model equations are shown in Eqs(4), (5) and (6). The fluid medium is hydraulic oil with a density of 870 kg/m^3 (incompressible model) and a viscosity coefficient of 0.02784 kg/(m · s). The time step is set to be 0.035 s and calculation results are saved every 5 steps.

Continuity equation is

$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} + \frac{\partial \bar{w}}{\partial z} = 0 \tag{4}$$

Momentum equations is

$$\begin{cases} \rho \dfrac{D\bar{u}}{Dt} = -\dfrac{\partial P}{\partial x} + \mu \nabla^2 \bar{u} + \rho f_x - \rho \dfrac{\partial(\overline{u'^2})}{\partial x} - \rho \dfrac{\partial(\overline{u'v'})}{\partial y} \\ \qquad - \rho \dfrac{\partial(\overline{u'w'})}{\partial z} \\ \rho \dfrac{D\bar{v}}{Dt} = -\dfrac{\partial P}{\partial y} + \mu \nabla^2 \bar{v} + \rho f_y - \rho \dfrac{\partial(\overline{v'u'})}{\partial x} - \rho \dfrac{\partial(\overline{v'^2})}{\partial y} \\ \qquad - \rho \dfrac{\partial(\overline{v'w'})}{\partial z} \\ \rho \dfrac{D\bar{w}}{Dt} = -\dfrac{\partial P}{\partial z} + \mu \nabla^2 \bar{w} + \rho f_z - \rho \dfrac{\partial(\overline{w'u'})}{\partial x} \\ \qquad - \rho \dfrac{\partial(\overline{w'v'})}{\partial y} - \rho \dfrac{\partial(\overline{w'^2})}{\partial z} \end{cases} \tag{5}$$

Two equations of standard k-ε model are

$$\begin{cases} \dfrac{\partial(\rho k)}{\partial t} + \dfrac{\partial(\rho k u_i)}{\partial x_i} = \dfrac{\partial\left[\left(\mu + \dfrac{\mu_t}{\sigma_k}\right)\dfrac{\partial k}{\partial x_j}\right]}{\partial x_j} + G_k - \rho\varepsilon \\ \dfrac{\partial(\rho \varepsilon)}{\partial t} + \dfrac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \dfrac{\partial\left[\left(\mu + \dfrac{\mu_t}{\sigma_\varepsilon}\right)\dfrac{\partial \varepsilon}{\partial x_j}\right]}{\partial x_j} + \dfrac{C_{1\varepsilon}\varepsilon G_k}{k} \\ - \dfrac{\rho C_{2\varepsilon}\varepsilon^2}{k} \end{cases} \tag{6}$$

In the equation systems, liquid velocity $V = (u,$

$v, w)^{T}$, ρ is the liquid density; P is the pressure; k and ε is the turbulent kinetic energy and turbulent dissipation rate; G_k is the generation term of turbulent kinetic energy k caused by average velocity gradient.

3.2.1 Flow field simulation of the rotary valve with double-rotation valve port

The boundary conditions are set as the pressure inlet and the pressure outlet. The relative pressure of inlet is 5 MPa, the relative pressure of the outlet is 0 MPa. The rotational speed of the valve core is set as 0.5 rad/s, and the width of the valve core's annular flow field is 1.5 mm. After the simulation, the pressure contour plot of the rotary valve at different opening degrees are obtained as shown in Fig. 3, Fig. 4 and Fig. 5.

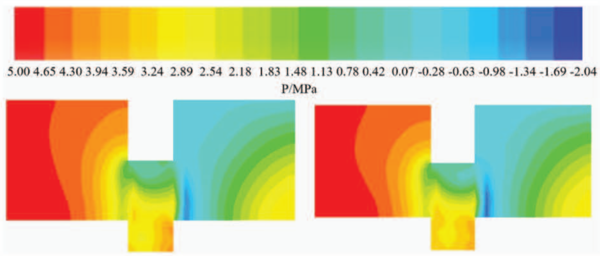

Fig. 3 The pressure change of rotary valve with double-rotation valve port at opening 40 ° (0.175 s) and 35 ° (0.35 s)

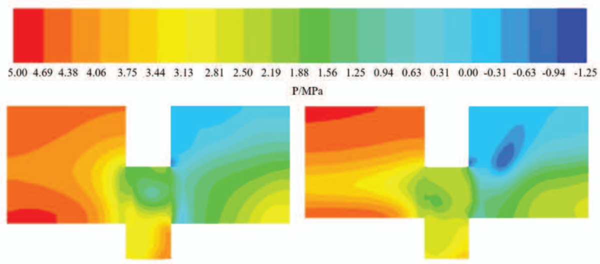

Fig. 4 The pressure change of rotary valve with double-rotation valve port at opening 20 ° (0.875 s) and 15 ° (1.05 s)

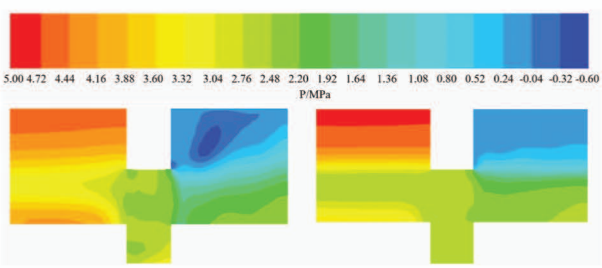

Fig. 5 The pressure change of rotary valve with double-rotation valve port at opening 10 ° (1.225 s) and 5 ° (1.40 s)

From Fig. 5 it can be seen that when the opening degree of the valve port is 40 ° and 35 °, the position of the internal flow field's pressure changes is mainly at the two groove ports of the valve core. Meanwhile, the rotary valve exhibits the two-step throttle characteristics, and it has good cavitation resistance. The area of the negative pressure zone and the area of the minimum negative pressure zone at 0.175 s are greater than that at 0.35 s. When the opening of valve port is smaller than 22.5 °, the pressure change of internal flow field is shown in Fig. 4. The pressure change at the outlet is transferred from the groove ports of the valve core to the rotary valve port, and the pressure change at the inlet are mainly at the groove ports of the valve core and the rotary valve port. For this situation, the rotary valve presents the characteristics of two-step or even multistage throttle. At 1.05 s, the area of the negative pressure area and the area of the minimum negative pressure area are greater than at 0.875 s. When the opening of the valve port is 5 ° and 10 °, the position of pressure change is mainly at the inlet and outlet of the rotary valve port from Fig. 5. For this situation, the rotary valve presents two-step throttle characteristics. At 1.4 s, the area of the negative pressure area and the area of the minimum negative pressure area are greater than that at 1.225 s.

3.2.2 Flow field simulation of the rotary valve with single-rotation valve port

When the size of the rotary valve, the oil supply pressure and the rotation speed of the valve core are constant, the flow field of the rotary valve with single-rotation valve port is simulated and analyzed. The pressure contour plot with the opening of the valve port of 40 °, 35 °, 20 °, 15 °, 10 ° and 5 ° is taken respectively, as shown in Fig. 6, Fig. 7 and Fig. 8.

It can be seen from Fig. 6 – Fig. 8 that the two-step throttle characteristics of the rotary valve with single-rotation valve port are affected by the opening degree of the valve port. When the opening degree of the

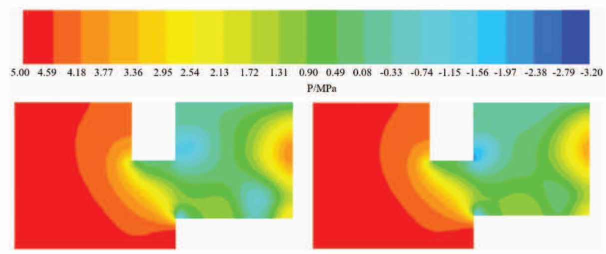

Fig. 6 The pressure change of rotary valve with single-rotation valve port at opening 40 ° and 35 °

Fig. 7 The pressure change of rotary valve with single-rotation valve port at opening 20 ° and 15 °

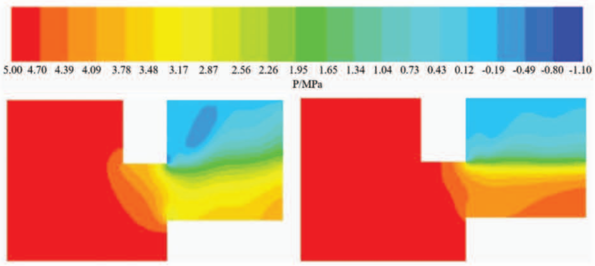

Fig. 8 The pressure change of rotary valve with single-rotation valve port at opening 10 ° and 5 °

valve port is large, the rotary valve has the one-step throttle characteristic, and the pressure change is mainly in groove ports of the valve core. When the valve opening is at 20 ° – 10 °, the rotary valve exhibits the two-step throttle characteristics, and the pressure changes are mainly at the valve core groove and the rotary valve port of rotary valve. When it is small, the rotary valve has a one-step throttle characteristic, and the pressure change is mainly at the rotary valve port of the rotary valve.

In general, the two-step throttle characteristics of the rotary valve with double-rotation valve port are less affected by the valve opening degree, which ensures that the rotary valve always maintains the two-step throttle characteristics throughout the change of the valve opening degree. The rotary valve with single-rotation valve port's throttle characteristic changes significantly with the change of opening degree. According to the pressure contour plot and cavitation index of the two rotary valves, Table 1 shows that the rotary valve with double-rotation valve port has better throttle characteristic at different opening degrees of the valve port and the ability to resist cavitation.

Table 1 Cavitation index of throttle

Vale opening	Rotary valve with double-rotation valve port			Rotary valve with single-rotation valve port	
40 °	0.739	0.630		0.983	
35 °	0.729	0.811		0.940	
20 °	0.599	0.833		0.667	0.998
15 °	0.194	0.487	0.948	0.640	0.993
10 °	0.593	0.873		0.521	0.952
5 °	0.431	0.949		0.974	

According to the above table, when the opening of rotary valve with double-rotation valve port is 15 °, the rotary valve presents three-step throttle, and the corresponding cavitation index of the first, second and third throttle orifices is shown in the 4th row of the 2nd column of Table 1. The rotary valve presents two-step throttle under the other opening, and the corresponding cavitation index of the first and second throttle orifices is shown in the 2nd column of Table 1. However, when the opening of rotary valve with single-rotation valve is 20 °, 15 ° and 10 °, it presents two-step throttle, and when the opening is others, it presents one-step throttle. The cavitation index of each stage of rotary valve is shown in the 3rd column of Table 1. Compared with the cavitation index of the two rotary valves, under the same opening, the cavitation index of the rotary valve with double-rotation valve ports is smaller, and the possibility of cavitation at the throttle port is lower, which proves that it has better anti-cavitation ability. The possibility of hydraulic impact inside the rotary valve is lower and the accuracy of the system is higher.

4 Factors affecting the two-step throttle characteristics of rotary valve with double-rotation valve port

The above two sets of simulation comparisons illustrate the advantages of the structure of double-rotation valve port in the two-step throttle characteristics. The influence of valve core speed, oil supply pressure and critical size of the valve core on its two-step throttle characteristics are analyzed. The aim is to provide reference for the control and design of the subsequent rotary valve.

4.1 Influence of valve core speed

According to the actual situation, the output speed of the hydraulic robot joint is usually controlled at 0.35 – 0.52 rad/s. Because of the self-servo mechanism of the joint, the input speed of the valve core should also be within this range. The simulation is carried out when the rotation rate of the valve core are 0.3 rad/s, 0.4 rad/s and 0.5 rad/s respectively. Set up monitoring points in the process of numerical simulation, and conduct pressure monitoring at the rotary valve port and valve core groove port. The pressure contour plotare obtained as shown in Fig. 9, when the opening of the valve port is 40 °.

From Fig. 9 it can be seen that when the opening of the valve port is 40 °, and the rotation speed of the valve core is 0.3 rad/s, 0.4 rad/s and 0.5 rad/s respectively, the pressure cloud diagrams of the internal flow field are basically the same. It shows that the two-step throttle characteristics and pressure change range of the rotary valve with double-rotation valve ports are less affected by the rotation speed of the valve core. It can be seen from Fig. 10 that when the rotary valve is opened, the pressure at the groove port of the valve core will decrease sharply. Then, with the change of the opening degree of the rotary valve, the pressure changes at the groove port of the valve core and the rotary valve port are periodic. And with the increase of the rotation speed of the valve core, the pressure changing frequency will increase gradually. However, the more frequently the pressure changes, the more serious the cavitation accumulation will be. Compared with the above simulation of rotary valve, the influence of the change of the rotary valve's opening on the pressure change of the internal flow field is far greater than the change of the rotation speed of the valve core, but the rotation speed of the valve core will have greater impact on the pressure changing frequency at the throttle port.

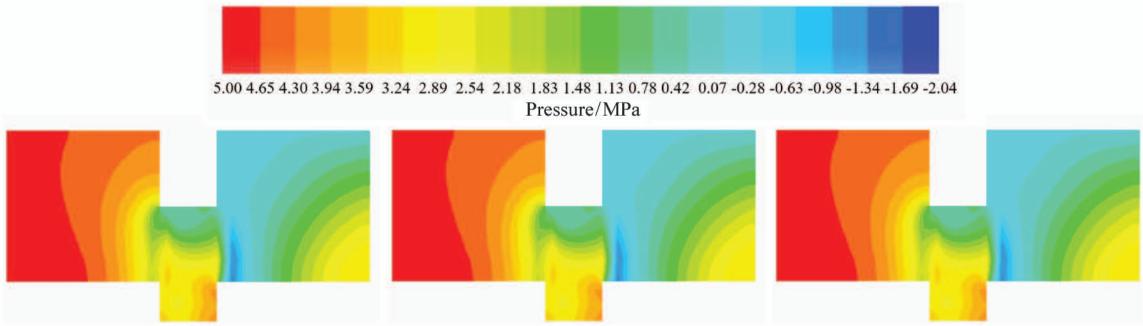

Fig. 9 The pressure change of the rotary valve at valve core speed of 0.3 rad/s, 0.4 rad/s, 0.5 rad/s

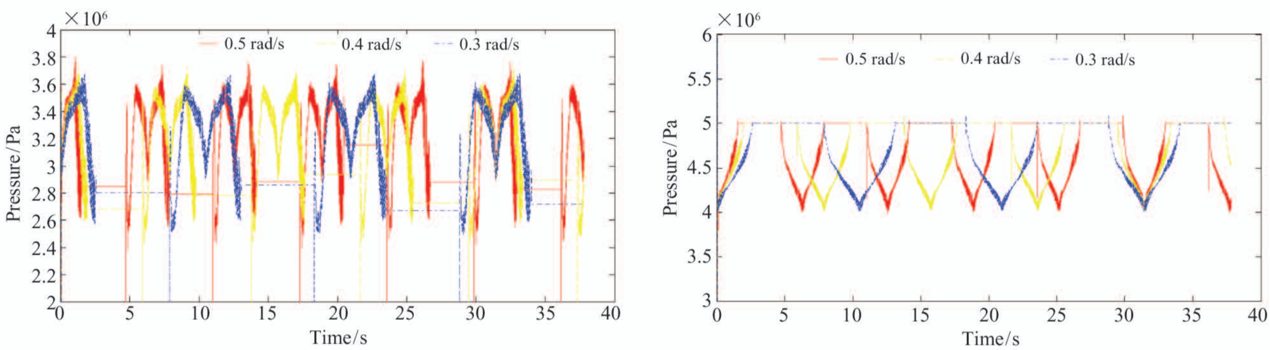

Fig. 10 Pressure change at the groove port of valve core and rotary valve port

4.2 Influence of oil supply pressure

According to the performance requirements of hydraulic robot joints, the response speed of the system should not be less than 2 rad/s, so the joint supply pressure should be greater than 3.2 MPa. The simulation is carried out when the oil supply pressure are 4 MPa, 5 MPa and 6 MPa respectively, and the flow rate monitoring is carried out at rotary valve port. The pressure contour plot are obtained as shown in Fig. 11, when the valve opening is 40 °.

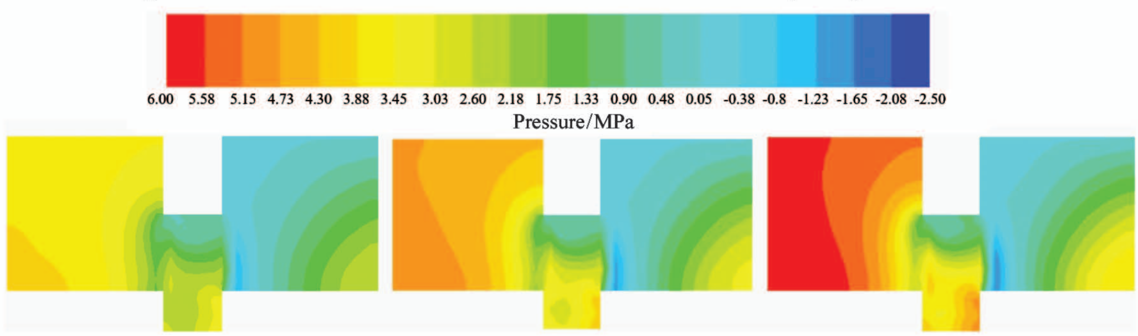

Fig. 11 The pressure change of rotary valve the oil supply pressure of 4 MPa, 5 MPa and 6 MPa

It can be seen from Fig. 11 that the maximum pressure of the rotary valve's internal flow field are different when the valve opening is 40 °, and the oil supply pressure is 4 MPa, 5 MPa, and 6 MPa, but the throttle characteristics and pressure changes are the same. The change of oil supply pressure will not change the two-step throttle characteristics of the rotary valve, but it will affect the range of the pressure change at the throttle. As shown in Fig. 12, at the same opening degree, the flow rate at the rotary valve port of the rotary valve is changed according to the opening degree of the valve port, and the higher the oil supply pressure is,

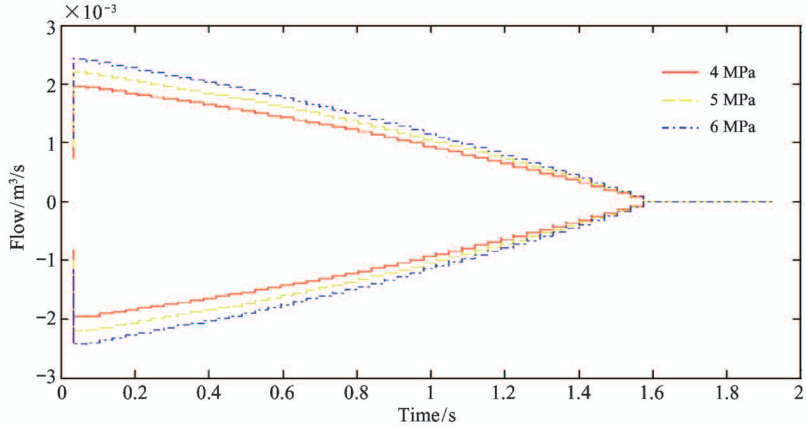

Fig. 12 Flow change at rotary valve port

the larger the flow rate at the rotary valve port will be.

4.3 Influence of spool size

The valve core of the rotary valve with double-rotation valve port has many sizes, and the width of the valve core's annular flow field has a great influence on the oil passing capacity of the entire rotary valve, so it is separately studied here. The width of the valve core's annular flow field is 1 mm, 1.5 mm and 2 mm, and the pressure contour plot are obtained as shown in Fig. 13 and Fig. 14, when the valve opening is 35 ° and 5 °.

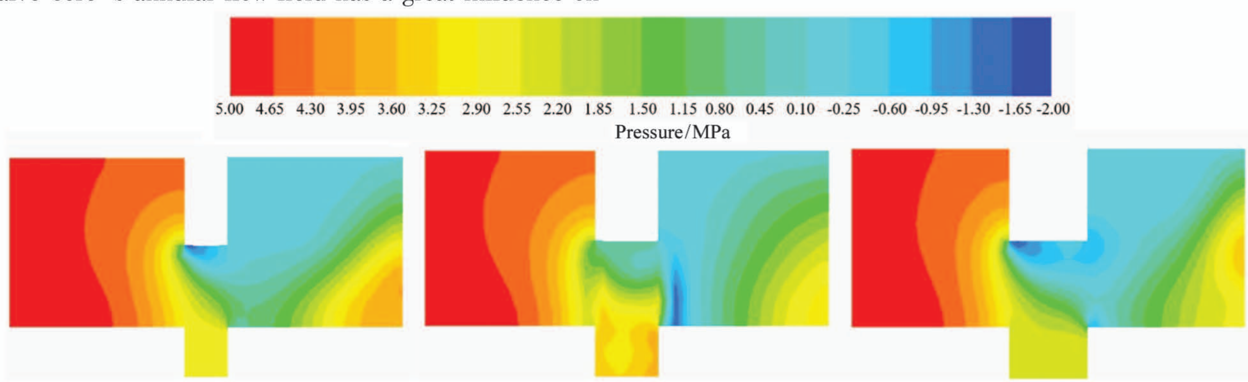

Fig. 13 The pressure change when the opening of the rotary valve is 35 ° and the width of the annular flow field is 1 mm, 1.5 mm and 2 mm

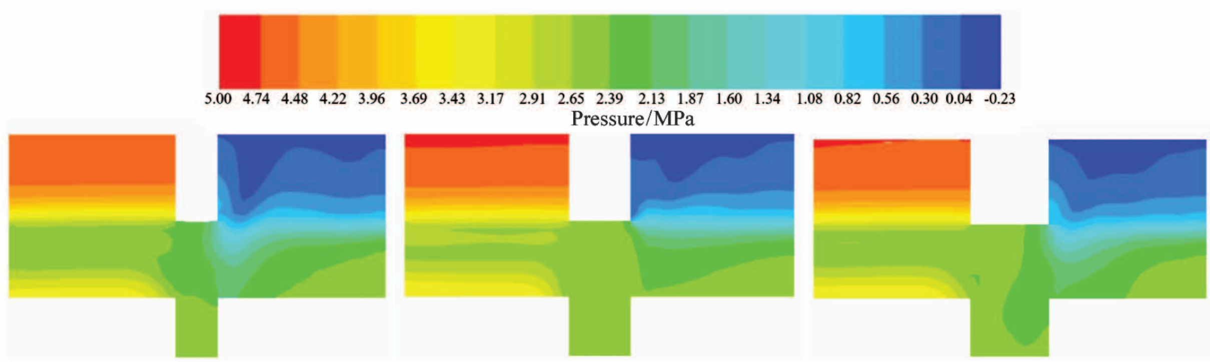

Fig. 14 The pressure change when the opening of the rotary valve is 5 ° and the width of the annular flow field is 1 mm, 1.5 mm and 2 mm

It can be seen from Fig. 13 and Fig. 14 that the width of the valve core's annular flow field has significant influence on the internal pressure change when the opening degree of the rotary valve is large, and no significant influence is observed when the opening degree is small. When the opening of the rotary valve is 35 ° and the width of the annular flow field is 1.5 mm, the internal flow field has pressure changes at the two groove ports of valve core. The rotary valve presents two-step throttle characteristics and better anti-cavitation ability. At the same opening degree, when the annular flow field's width is 1 mm and 2 mm, the internal flow field has pressure change only at the one groove port of the valve core, and the rotary valve exhibits one-step throttle characteristic. Although both cases are one-step throttle, the cavitation index of the annular flow field with a width of 1 mm is 0.820 at the inlet, which is higher than 0.807 with a width of 2 mm, which provides some references for the subsequent structural dimension design.

5 Conclusions

Through the simulation, the position of the pressure change of the rotary valve with double-rotation valve port during the working process is confirmed, and the changing rules of the throttle position are obtained. When the opening of the valve port is large, the position of the pressure change is mainly at the two groove ports of the valve core. With the decrease of the opening of the valve port, the position of the pressure change will appear at groove ports of the valve core and the rotary valve port. When the opening of the valve port is small, the position of the pressure change is mainly at the two rotary valve ports. It is verified that the rotary valve with double-rotation valve ports keeps the two-step throttle characteristics in the whole process of valve opening change. Comparison of the throttle characteristic and table of cavitation index between structure of double-rotation valve port and single-rotation valve port shows that the structure of double-rotation valve port'stwo-step throttle characteristics is less affected by the change of the valve opening degree, and has a better two-step throttle characteristics and cavitation resistance, also it can reduce the impact of cavitation on the joint output accuracy.

Besides, the effects of oil supply pressure, the valve core's rotation speed and the annular flow field's width on the two-step throttle characteristics of the rotary valve with double-rotation valve port are also studied. It is found that the two-step throttle characteristics of the rotary valve is not affected by the change of the valve core's speed, but the frequency of the pressure change at the throttle port will increase with the increase of the speed. The change of the oil supply pressure will not change the two-step throttle characteristics of the rotary valve, but it will affect the range of the pressure change at the throttle port, and the flow at the rotary valve port will increase with the increase of the oil supply pressure. When the opening of the rotary valve is large, the annular flow field's width of the valve core has a great influence on the two-step throttle characteristics. If the size is too large or too small, the rotary valve will show the one-step throttle characteristic in the working process, and the possibility of cavitation at the inlet is higher when the size is smaller. The conclusions obtained in this work will provide a theoretical basis for the design and control of the rotary valve.

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