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Design and Numerical Study of Hybrid Magnetic Source Disc-type Magnetorheological Valve

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Magnetorheological valves are important components in hydraulic systems that provide precise position control. At present, the low-pressure drop performance of magnetorheological valves is the main problem limiting their application. To improve the pressure drop performance of magnetorheological valves, a hybrid magnetic source disc magnetorheological valve is proposed. The magnetic pressure drop model and viscous pressure drop model of the hybrid magnet source disc type magnetorheological valve based on the Bingham model are Derived. Magnetic field distributions in the damping channel of the hybrid magnet source disc type magnetorheological valve are obtained by using ANSYS finite element analysis software. The mathematical model of the relationship between pressure drop and magnetic induction intensity was established using Matlab software, and the effects of parameters such as effective current, axial damping gap, radial damping gap, and coil width on the pressure drop performance of disc-type magnetorheological valves with hybrid magnetic sources were numerically analyzed. The results show that the pressure drop of the disc magnetorheological valve with a hybrid magnetic source can reach 10.9935 MPa at the current I=3A, axial damping gap ga=1 mm, and radial damping gap gr=1.5 mm. Compared with the conventional disc magnetorheological valve, the pressure drop performance of the hybrid magnetic source disc magnetorheological valve is improved by 28 %, which provides ideas on how to improve the pressure drop performance of the magnetorheological valve.

Keywords : magnetorheological valve, hybrid magnetic source, disc, pressure drop, performance analysis

1. Introduction

In the process of long-term relative movement, the mutual abrasion among traditional hydraulic control valve spare parts leads to the leakage of hydraulic oil, which affects the stability and reliability of the hydraulic system. A magnetorheological valve is a new type of hydraulic control valve and uses a new type of intelligent material magnetorheological fluid (MRF) [1, 2] as the working medium, providing a better solution to the problems caused by traditional hydraulic valves. The structure of magnetorheological valves is easier and more stable in movement than traditional hydraulic control valves with no mutual movement among the parts. Merely controlling the effective current can change the magnetic field strength, and the simple operation with a quick response can ameliorate the defects of traditional control valves in a better way, thereby improving the performance of the hydraulic system to meet the needs of a wider range of applications.

Domestic and foreign researches on magnetorheological valves mainly focus on structural design and optimized design. In terms of structural design, a two-stage disc-type damping gap magnetorheological valve designed by Aydar [3] of the University of Nevada can produce a pressure difference of more than 9.6 MPa when the input current is 5A. A two-stage radial serpentine magnetorheological valve designed by Hu Guoliang [4] is a radial flow magnetorheological valve, compared with the axial flow magnetorheological valve, the radial flow magnetorheological valve has a more reasonable structure. Malaysia Abd Fatah *et al.* [5] proposed a serpentine magnetic flux path method for designing magnetorheological valves, and the results show that the serpentine magnetic flux path method can enlarge the effective working area of the magnetorheological fluid and the addition and thickness of non-magnetic materials contribute to further increase the pressure drop in the valve. Sahin [6] and his team

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studied the responding time of magnetorheological fluids and magnetorheological valves under different flow patterns, and the results show that the pressure responding time of magnetorheological fluid and the magnetorheological valve is determined by the electrical parameters and the valve geometry design. Kubik *et al.* [7] proposed a toroidal magnetorheological valve with three excitation coils, which is also used as a bypass valve for the magnetorheological damper. The valve can achieve a shorter response time and a larger range of dynamic force. Imaduddin and Hu *et al.* [8, 9] studied the meandering flow path formed by the combination of annular and radial gaps to investigate the pressure drop variation law of magnetorheological valves. Hu Guoliang *et al.* [10] proposed a new damping gap adjustable magnetorheological valve structure, which can change the damping gap by rotating the spool to change the relative position with the valve body. Imaduddin [11] and Hu *et al*. [12] studied compact magnetorheological valves, where the clearance has a significant effect on their performance. Kubík *et al.* [13] designed, simulated, and experimentally tested the valve and showed that an average response time of 4.1 ms and a maximum dynamic range of 8 can be achieved. In terms of optimization, the study result of Hu Guoliang [14] and his team, the magnetic line of induction can be altered by adding magnetic isolation materials, resulting in improving the magnetic circuit of the magnetorheological valve. By optimizing, and analyzing four magnetorheological valves with different structural parameters and comparing the study results, Nguyen [15-18] of Inha University in South Korea found that the ring-disk combined structure possesses the best pressure drop performance under the circumstance of the same shape and volume of the magnetorheological valve. Presently, the single-flow magnetorheological valve, as a form of most magnetorheological valves, still presents various defects which makes it inconvenient to apply magnetorheological valves and difficult to meet some special requirements.

This paper proposes a hybrid-flow magnetorheological valve with a coil-permanent magnet combination, its name is a hybrid magnetic source disc-type magnetorheological valve. Based on the Bingham plastic model, the pressure drop teaching model of the hybrid magnetic source disc-type magnetorheological valve is deduced. The simulation and analysis for the magnetic field intensity in the flow channel of the magnetorheological valve are conducted by using the finite element method. And the key parameters such as effective current, axial damping clearance, radial damping clearance, and coil width influence the pressure drop performance of the hybrid magnetorheological valve and are numerically studied.

2. Structure and Working Principle

The working principle of the magnetorheological valve is based on the magnetorheological effect of magnetorheological fluid, the magnetorheological fluid transforms into a semi-solid under the magnetic field. The magnetic particles in the magnetorheological fluid swiftly form a chain structure arranged in the direction of the magnetic field, and a large number of chain-like structures produce a shear yield stress, which changes the flow rate of the magnetorheological fluid, thereby affecting the pressure drop at the inlet and outlet of the magnetorheological valve.

As shown in Fig. 1, the designed hybrid magnetic source disc-type magnetorheological valve structure model is composed of an end cover, valve sleeve, magnetic isolation ring, magnetic guide disc, support disc, coil holder, valve core, permanent magnet, sealing ring, and other elements. There are mainly three types of liquid flow channels in the structure as follows: the hole-shaped damping gap formed by the 4 orifice liquid flow channels, the round ring-shaped damping gap formed by the 3 axial liquid flow channels, and the disc-shaped damping gap

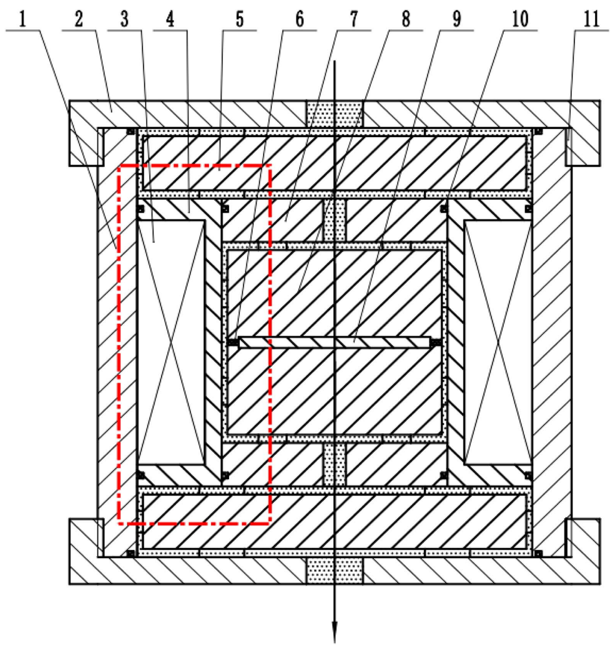


Fig. 1. (Color online) Structure model of hybrid magnetic source disc magnetorheological valve.
(1. Valve sleeve 2. End cover 3. Excitation coil 4. Coil holder 5. Magnetic guide disc 6. Magnetic isolation ring 7. Support disk 8. Valve core 9. Permanent magnet 10. Sealing ring 11. Threaded connection)

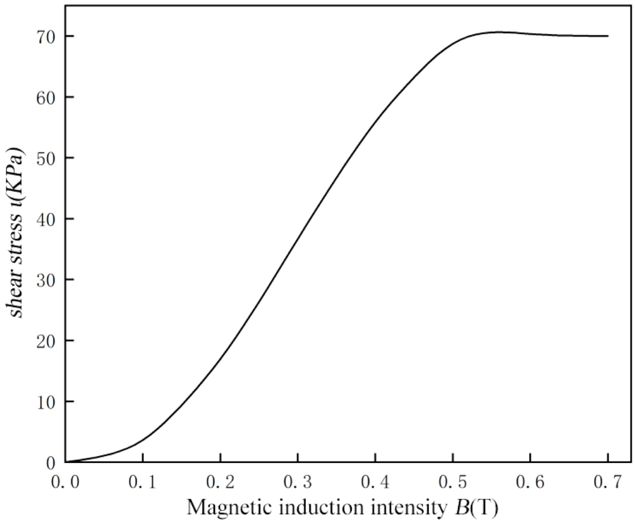


Fig. 2. The τ-B relationship curve between MRF-J25T.

Table 1. Related parameters of MRF-J25T.

Project	Parameter
density	2.65 g/cm^3
Zero field viscosity (γ = 10/s, 20 °C)	1 Pa·s
Shear stress (B=5000Gs)	≥ 45 kpa
Magnetization performance (Ms)	380 kA/m
Temperature range	–40~130 °C

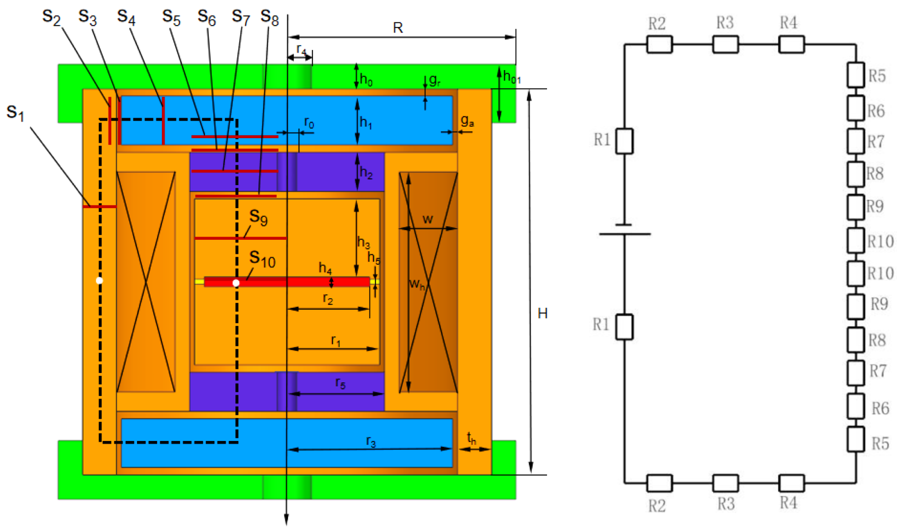
formed by the 6 radial liquid flow channels. When an effective current is applied to the excitation coil, the ideal magnetic field line is shown as the red dashed line in Fig. 1, the damping gap through which the magnetic field line passes perpendicularly is the effective damping gap. In addition, a permanent magnet is placed into the middle of the valve core, making the magnetorheological fluid in a more saturated state, thus also increasing the pressure drop at the inlet and outlet of the magnetorheological valve.

This article selects MRF-J25T magnetorheological fluid as the working medium of the magnetorheological valve. In Fig. 2, the τ-B relationship curve between MRF-J25T magnetorheological fluid magnetic induction intensity and shear stress is fitted by a smooth spline curve with a degree of smoothness of 0.999321. Its basic parameters are shown in Table 1.

3. Magnetic Circuit Design

Figure 3(a) shows a simple magnetic circuit model of a hybrid disc magnetorheological valve. The dashed line in the figure represents an ideal closed magnetic circuit, which is a superimposed magnetic field generated by the simultaneous action of a permanent magnet and an energized excitation coil. The magnetic induction lines pass through the magnetic materials such as valve sleeve, conductive disc, support disc, spool, and permanent magnets to form a complete closed circuit. As shown in Fig. 3(b), the magnetic circuit can be divided into ten segments R1-R10 due to the symmetrical structure, and the magnetoresistance of these ten segments needs to be calculated numerically to obtain the saturation magneto-dynamic potential of the magnetic circuit.

According to Kirchhoff's law, the corresponding mag-



(a) (b)

Fig. 3. (Color online) The hybrid magnetic source disc-type magnetorheological valve: (a) magnetic circuit diagram and (b) equivalent magnetic circuit diagram.

netic circuit can be determined by the following formula:

$$N_c I = \oint_c h dl = \sum_{i=1}^{m} H_i l_i \quad (1)$$

Where: N_c is the number of turns of the excitation coil, I is the current applied to the excitation coil, H_i l_i and respectively represents the magnetic field intensity and effective length of the part of the magnetic circuit.

On the other hand, the magnetic flux in the coil can be represented as follows:

$$\varphi = \oint_c BdS = B_i S_i \quad (2)$$

Where: B_i and S_i respectively represent the flux density and cross-sectional area of the middle part of the magnetic circuit.

According to electromagnetic theory, the relationship between magnetic flux density B and magnetic field intensity H can be expressed by the following formula:

$$B_i = \mu_0 \mu_i H_i \quad (3)$$

Where: μ_0 is the absolute permeability of vacuum, which is $4\pi\times10^7$ H/m; μ_i is the relative permeability of each part of the magnetic material. The reluctance of each part of the magnetic circuit can be expressed as:

$$R_i = \frac{l_i}{\mu_0 \mu_i B_i} \quad (4)$$

Therefore, it can be further expressed as:

$$N_c I = \sum_{i=1}^{m} H_i l_i = \sum_{i=1}^{m} \frac{B_i}{\mu_0 \mu_i} l_i = \sum_{i=1}^{m} \frac{l_i}{\mu_0 \mu_i B_i} \phi = \sum_{i=1}^{m} R_i \phi \quad (5)$$

The flux density B of each part of the magnetic circuit can be written as the following formula, but does not exceed the saturation flux density of the magnetic material:

$$B_i = \frac{\phi}{S_i} = \frac{N_c I}{S_i \sum_{i=1}^{m} R_i} \leq B_{iset} \quad (6)$$

Where: B_i represents B_{iset} the saturated flux density of the corresponding material in the chain.

After calculation, the main structural parameters of Valves are shown in Table 2.

Table 2. The dimensional Parameters of the hybrid magnetic source disc-type magnetorheological valve.

Parameter	Explain	Numerical value (mm)
R	Body radius	47
H	Valve sleeve width	79
t_h	Valve sleeve thickness	7
h_0	End cap thickness	5
h_{01}	End cap thickness	12
h_1	Guide disk thickness	10
h_2	Supporting plate thickness	8
h_3	Valve core thickness	16
h_4	Permanent magnet thickness	2
h_5	The thickness of the magnetic separator ring	1
r_0	The damping gap size of the circular tube	2
r_1	Spool radius	19
r_2	Permanent magnet radius	17
r_3	Guide disk radius	34
r_4	Size of circular tube damping gap	5
r_5	The radius of the support plate	20
g_a	Axial damping gap size	1
g_r	Radial damping gap size	1.5
w	Winding groove depth	12
w_h	Width of winding groove	45

4. Mathematical Model of Pressure Drop

The adjustable range of pressure drop of the magnetorheological valve determines the performance of the magnetorheological valve, therefore, the key factor to evaluate its performance is the pressure drop model of the constructed hybrid magnet source disc magnetorheological valve. Although the designed hybrid disc magnetorheological valve has a regular axisymmetric structure, the corresponding pressure drop pressure model is different considering the different magnetic field strengths and damping gap types in each region of the magnetorheological valve. Fig. 4 shows a simplified diagram of the drop

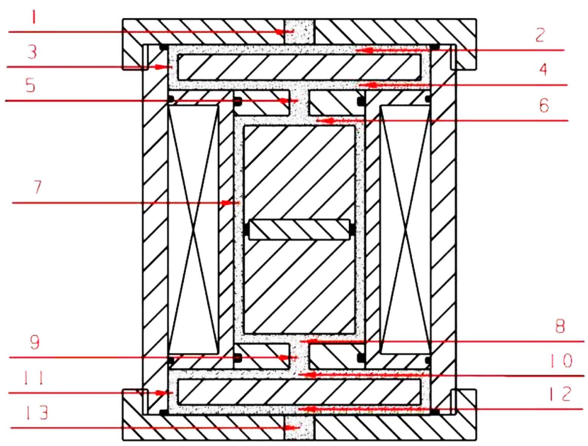


Fig. 4. (Color online) A simplified diagram of the area of dropping pressure of the hybrid magnetic source disc-type magnetorheological valve.

pressure region of the hybrid magnetically-sourced disc-type magnetorheological valve. Considering various shapes, the liquid flow channel is divided into 13 liquid flow channels, which can be divided into three different regions, i.e., orifice region, circular region, and disk region. In the flow mode, the magnetorheological valve is usually described by the Bingham plasticity model, where the total pressure drop at the inlet and outlet consists of the viscous pressure drop Δpη out and the magnetic pressure drop Δpτ. From Fig. 4, it is known that all 13 liquid flow channels generate viscous pressure drop, among which only six liquid flow channels, 3, 4, 6, 8, 10, and 11, generate magnetic pressure drop.

4.1. Pressure Drop Model at The Hole-shaped Area

As shown in the figure, the hole-shaped area liquid flow channel is mainly composed of 1,13 and 5,9. Because the flow direction of the magnetorheological fluid is parallel to the magnetic line of induction. So only the viscous pressure drop Δp_η is generated in these four liquid flow channels. According to the formula for calculating the pressure loss along the path can be considered as the liquid flowing in the hole gap, Therefore, the calculation formula of the viscous pressure drop is [19]:

$$\Delta p_\eta = \frac{8l}{\pi R^4}\mu q \tag{7}$$

Where: μ means zero field viscosity; R means the half diameter of the liquid flow channel; l means the liquid flow channel length; q means the liquid flow rate.

For flow channels 1 and 13, bringing ($\Delta l = h_0$, $R = r_4$) into equation (7) simplifies to:

$$\Delta p_{\eta-1} = \Delta p_{\eta-13} = \frac{8h_0}{\pi r_4^4}\mu q \tag{8}$$

For Flow channels 5 and 9, bringing ($\Delta l = h_2$, $R = r_0$) into equation (7) simplifies to:

$$\Delta p_{\eta-5} = \Delta p_{\eta-9} = \frac{8h_2}{\pi r_0^4}\mu q \tag{9}$$

4.2. Pressure Drop Model at The round ring-shaped Area

As can be seen from the figure, the liquid flow channels 3, 11, and 7 are all-around ring-shaped areas. When the magnetic lines of force pass vertically through the liquid flow channel, the liquid flow channel can generate a magneto-induced pressure drop Δp_τ, it is called an effective liquid flow channel. Therefore, channels 3 and 11 are effective liquid flow channels, while generating two pressure drops, a magneto-induced pressure Δp_τ drop and a viscous pressure drop Δp_η. Only a viscous pressure drop Δp_η occurs in channel 7. Which can be regarded as a liquid flowing in the annular gap of concentric cylinders according to the calculation formula of pressure loss along the path. Equation (10) is the simplified viscous pressure drop and equation (11) is the simplified magneto-induced pressure drop [11].

$$\Delta p_\eta = \frac{6l}{\pi r h^3}uq \tag{10}$$

Where: l means the length of the round ring-shaped; h means width of the effective liquid flow channel; r means the inner radius of the round ring-shaped; q means the liquid flow rate; μ means zero field viscosity.

$$\Delta p_\tau = C\frac{\Delta l}{h}\tau_y(B) \tag{11}$$

Where: C means correction coefficient, The coefficient c is obtained by calculating the ratio between field-dependent pressure drop and viscous pressure drop using the approximation function as defined by Nguyen et. al[17] in the following equation; $\tau_y(B)$ means shear stress generated at the liquid flow channel; Δl means the length of the effective liquid flow channel; h means the width of the effective liquid flow channel.

For Flow channels 7, bringing ($l = 2h_3 + h_4$, $r = r_1$, $h = ga$) into equation (10) simplifies to:

$$\Delta p_{\eta-7} = \frac{6u(2h_3+h_4)q}{\pi r_1 g_a^3} \tag{12}$$

For Flow channels 3 and 11, bringing ($l = h_1, r = r_3$, $h = ga$) into equation (10) simplifies to:

$$\Delta p_{\eta-3} = \Delta p_{\eta-11} = \frac{6uh_1 q}{\pi r_3 g_a^3} \tag{13}$$

Bringing ($\Delta l = h_1$, $h = ga$, $\tau_y(B) = \tau_3(B)$, $\tau_{11}(B)$) into equation (11) simplifies to:

$$\Delta p_{\tau-3} = \frac{Ch_1}{g_a}\tau_3(B) \tag{14}$$

$$\Delta p_{\tau-11} = \frac{Ch_1}{g_a}\tau_{11}(B) \tag{15}$$

4.3. Pressure Drop Model at The Disk Area

The liquid flow channels 2, 4, 6, 8, 10, and 12 are all disk areas, and these channels will produce a viscous pressure drop Δp_η in which the magnetorheological fluid can be calculated as a flat plate model with gradually increasing fluid flow channels, and the calculation formula for viscous pressure drop is obtained as follows [20]:

$$\Delta p_{\eta} = \frac{6uq}{\pi h^3}\ln(\frac{R}{r}) \tag{16}$$

Where: R means the outer radius at the disc area; r means the inner radius of the disk area; h means disc width; μ means zero field viscosity; q means the liquid flow rate.

For Flow channels 2 and 12, bringing ($R = r_3$, $r = r_4$, $h = gr$) into equation (16) simplifies to:

$$\Delta p_{\eta-2} = \Delta p_{\eta-12} = \frac{6uq}{\pi g_r{}^3}\ln(\frac{r_3}{r_4}) \tag{17}$$

For Flow channels 4 and 10, bringing ($R = r_3$, $r = r_0$, $h = gr$) into equation (16) simplifies to:

$$\Delta p_{\eta-4} = \Delta p_{\eta-10} = \frac{6uq}{\pi g_r{}^3}\ln(\frac{r_3}{r_0}) \tag{18}$$

For Flow channels 6 and 8, bringing ($R = r_1$, $r = r_0$, $h = gr$) into equation (16) simplifies to:

$$\Delta p_{\eta-4} = \Delta p_{\eta-8} = \frac{6uq}{\pi g_r{}^3}\ln(\frac{r_1}{r_0}) \tag{19}$$

Moreover, the liquid flow channels 4, 6, 8, and 10 will also produce a magnetically induced pressure drop Δp_τ under the action of a magnetic field. The calculation formula is [20]:

$$\Delta p = \frac{C(R-r)}{h}\tau_y(B) \tag{20}$$

Where: R means the outer radius at the disc area; r means the inner radius of the disk area; h means disc width; $\tau_y(B)$ means shear stress generated at the liquid flow channel.

For Flow channels 3 and 11, bringing ($R = r_3$, $r = r_3$, $h = ga$, $\tau_y(B) = \tau_4(B)$, $\tau_{10}(B)$) into equation (20) simplifies to:

$$\Delta p_{\tau-4} = \frac{C(r_3 - r_0)}{g_r}\tau_4(B) \tag{21}$$

$$\Delta p_{\tau-10} = \frac{C(r_3 - r_0)}{g_r}\tau_{10}(B) \tag{22}$$

For Flow channels 6 and 8, bringing ($R = r_1$, $r = r_0$, $h = ga$, $\tau_y(B) = \tau_6(B)$, $\tau_8(B)$) into equation (20) simplifies to:

$$\Delta p_{\tau-6} = \frac{C(r_1 - r_0)}{g_r}\tau_6(B) \tag{23}$$

$$\Delta p_{\tau-8} = \frac{C(r_1 - r_0)}{g_r}\tau_8(B) \tag{24}$$

By establishing three regional pressure drop mathematical models, we can get the total pressure drop mathematical model of the magnetorheological valve as follows:

$$\begin{aligned}\Delta p &= \Delta p_\eta + \Delta p_\tau \\ &= 2(\Delta p_{\eta-1} + \Delta p_{\eta-5} + \Delta p_{\eta-3} + \Delta p_{\eta-2} + \Delta p_{\eta-4} + \Delta p_{\eta-6}) + \Delta p_{\eta-7} \\ &+ \Delta p_{\tau-3} + \Delta p_{\tau-4} + \Delta p_{\tau-6} + \Delta p_{\tau-8} + \Delta p_{\tau-10} + \Delta p_{\tau-11}\end{aligned} \tag{25}$$

5. Results Analysis and Discussion

5.1. Simulation process

To verify the feasibility of the design of the hybrid magnetic source disc-type magnetorheological valve, the

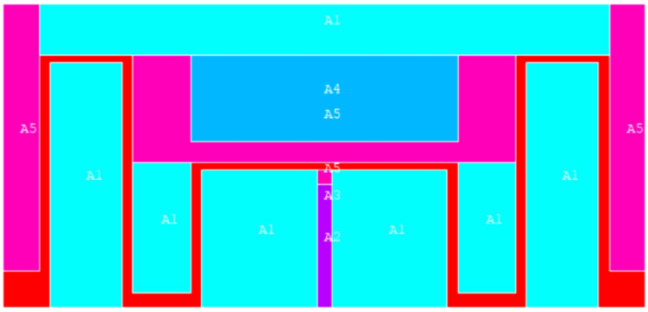


Fig. 5. (Color online) Simulation model diagram of hybrid magnetic source disc-type magnetorheological valve.

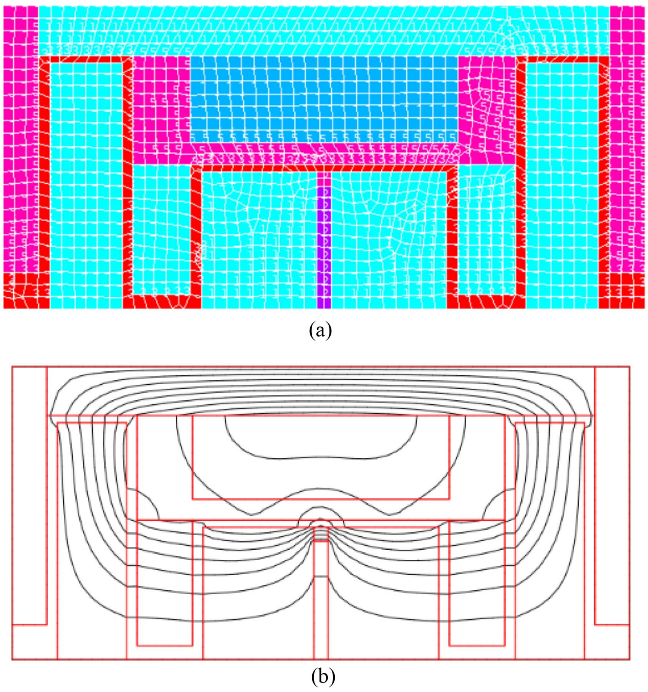


Fig. 6. (Color online) (a) Finite Element Model of the hybrid magnetic source disc-type magnetorheological valve. (b) Magnetic flux density distribution of the hybrid magnetic source disc-type magnetorheological valve.

electromagnetic field in the hybrid magnetic source disc-type magnetorheological valve is simulated and analyzed by the finite element method. According to the symmetry of the structure, the three-dimensional entity is transformed into a two-dimensional plane. Considering that its section is a regular axisymmetric figure, the 1/2 section is selected as the simulation object without affecting the accuracy of the model solution. Fig. 5 shows the two-dimensional simulation entity model of a hybrid magnetic source disc-type magnetorheological valve.

By adopting the intelligent meshing division method at the division accuracy 1, the physical model is meshed as shown in Fig. 6. A boundary condition of parallel magnetic lines of force without side leakage is imposed, and a current density is added to the coil unit to input the excitation load.

5.2. Reliability of Hybrid Magnetic Source Disc-type Magnetorheological Valve Designed by Magnetic Circuit Method

To verify the reliability of the hybrid magnetic source disc magnetorheological valve designed by the magnetic circuit method, the flow rate of the hybrid magnetic source disc magnetorheological valve is set to 4 L/min, the axial damping gap ga=1 mm, the radial damping gap gr=1.5 mm, the coil width w=12 mm, the effective current (excitation current) I=3A, the number of turns N=600, and the magnetic induction intensity distribution in the magnetorheological valve flow channel is shown in Fig. 7. From Fig. 7, it can be seen that when the magnetic induction strength of the effective axial damping gap is 0.2-0.3 T, the magnetic induction strength of the effective radial damping gap is 0.4-0.55 T. The reason why the magnetic induction strength of the radial damping gap is greater than that of the axial damping gap is that there is a permanent magnet designed in the middle of the radial damping channel 7, which provides the magnetic field for the radial damping gap, so it increases the radial gap The magnetic induction strength of the radial gap is increased. The purpose of designing the permanent magnet at radial channel 7 is that, as can be seen from Fig. 6, the magnetic field generated by the coil has very little effect on radial channel 7. To compensate for this problem, the permanent magnet is designed here, and by using the magnetic field

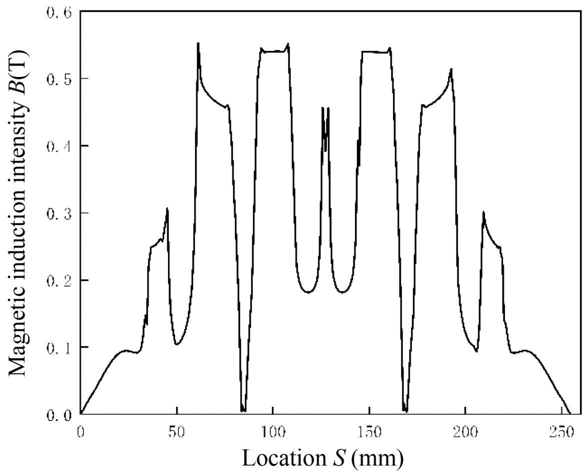


Fig. 7. Distribution diagram of the magnetic induction intensity B along the path S.

generated by the permanent magnet, the magnetorheological effect occurs in the magnetorheological fluid out of the radial channel 7, so that the designed damping channel can be effectively used to achieve the purpose of enhancing the pressure drop performance of the magnetorheological valve.

According to the magnetic field distribution and the mathematical model of the pressure drop of the magnetorheological valve in Fig. 7. The pressure drop values of the hybrid magnetic source disc-type magnetorheological valve shown in Table 3 can be obtained. Table 3 also shows the pressure drop of the conventional disc-type magnetorheological valve. From the table, it is found that the pressure drop of the hybrid magnetic source disc-type magnetorheological valve can reach about 10.9935 MPa, which is 20 % higher than the pressure drop of the conventional disc-type magnetorheological valve, which verifies the good performance of the magnetorheological valve designed in this paper.

5.3. The Effect of Effective Current on The Pressure Drop Performance of Hybrid Magnetic Source Disc-type Magnetorheological Valve

Under different effective currents, the magnetic field distribution in the flow channel of the hybrid magnetic

Table 3. The Pressure drop value of the hybrid magnetic source disc-type magnetorheological valve.

	Viscous Pressure Drop Δp_η (MPa)	Magnetic Pressure Drop Δp_τ (MPa)	Total Pressure Drop Δp (MPa)
Hybrid magnetic source disc type magnetorheological valve	1.0035	9.99	10.9935
Conventional disc-type magnetorheological valve	0.9852	7.568	8.5532

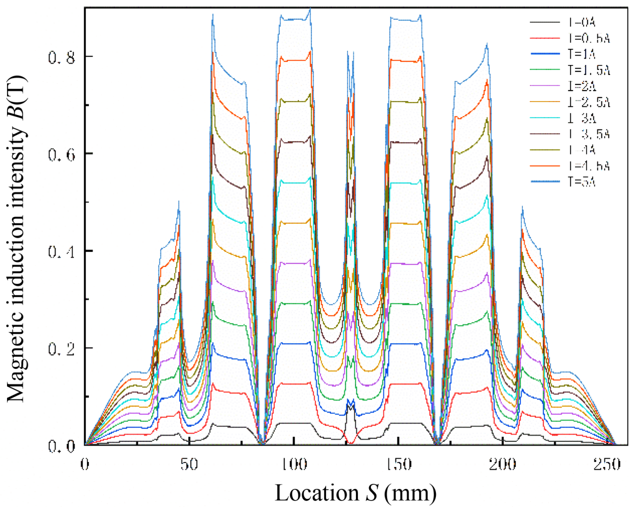


Fig. 8. (Color online) Magnetic flux density of different finite currents along the flow path.

source disc-type magnetorheological valve is shown in Fig. 8. It can be seen from the Figure that the magnetic flux density in the liquid flow channel increases as the effective current enhances. Under the same current, the magnetic induction intensity at the effective radial damping gap is greater than the magnetic induction intensity at the effective axial damping gap, and the closer to the permanent magnet, the greater the magnetic induction intensity at the effective radial damping gap.

The relationship between the dropping pressure performance of the hybrid magnetic disk magnetorheological valve and the effective current curve is shown in Fig. 9. It can be seen from Figure that the performance of dropping pressure of the hybrid magnetic disc magnetorheological valve increases with the enhancement of the effective current I. Since the magnitude of the viscous pressure drop of the magnetorheological valve has nothing to do with the effective current, its viscous dropping pressure remains unchanged. The magnetic voltage drop increases with the amplification of effective current with slowing-down tendency. The principle is that the increase of current will amplify the magnetic induction intensity and make the magnetorheological fluid nearly saturated. Therefore, the increase of pressure drop performance of the hybrid magnetic source disc magnetorheological valve slows down.

5.4. Influence of Axial Damping Gap on Performance of Dropping Pressure of Hybrid Magnetic Source Disc-type Magnetorheological Valve

Figure 10 shows the magnetic induction intensity inside the flow channel of the hybrid magnet source disc-type magnetorheological valve under different axial damping gap conditions. From the figure, it can be seen that the magnetic induction intensity at the effective axial and radial damping gaps within the hybrid magnet source disc-type magnetorheological valve is smaller when the axial damping gap is larger. The reason is that when the damping gap is larger, the magnetic resistance of the damping channel becomes larger, and the magnetic induction intensity within the effective gap of the hybrid magnet source disc-type magnetorheological valve decreases when the total magnetic flux in the magnetic circuit does not change.

The pressure drop performance of the hybrid magnetic source disc-type magnetorheological valve changes with

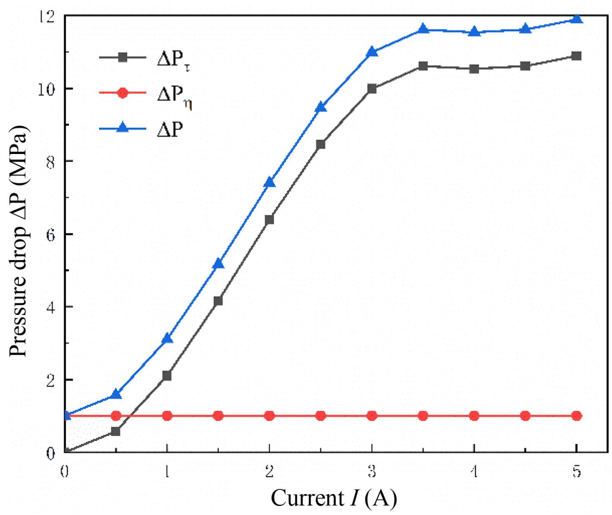


Fig. 9. (Color online) Pressure drop under different applied current.

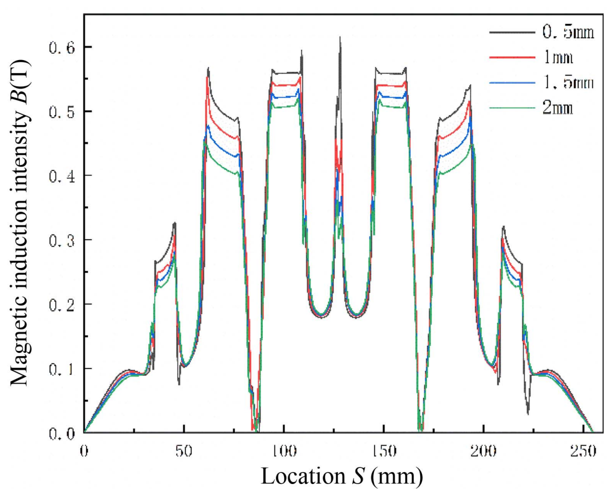


Fig. 10. (Color online) Magnetic flux density of different axial damping gaps along the flow path.

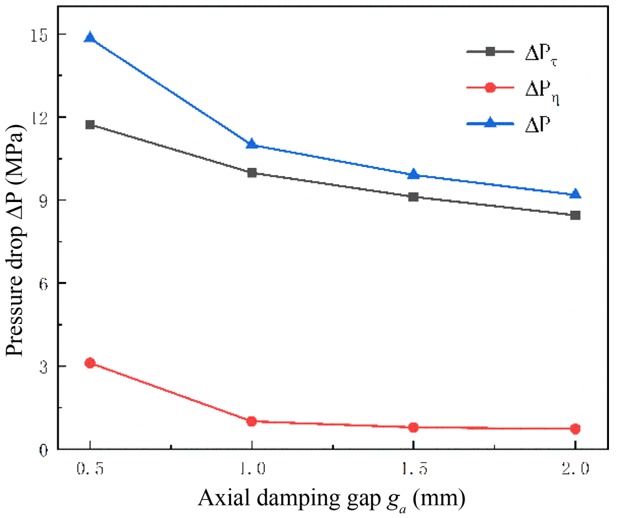


Fig. 11. (Color online) Pressure drop under different axial damping gap.

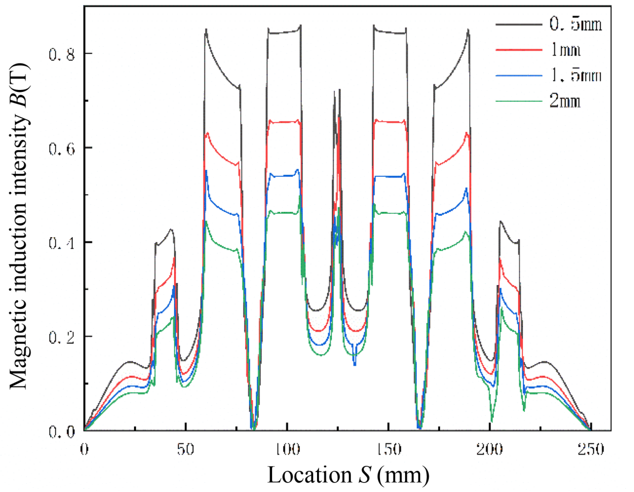


Fig. 12. (Color online) Magnetic flux density of different radial damping gaps along the flow path.

the axial damping gap shown in Fig. 11. It can be seen that as the axial damping gap increases, the values of dropping pressure are decreasing. In terms of viscous pressure drop, when the magnetorheological fluid flows, the axial damping gap is getting smaller, and the pressure loss along the path is higher. Therefore, a larger value of dropping pressure can be produced within 0.5-1 mm, and once the axial damping gap increases to reach a certain level, the pressure drop caused by the pressure loss along the path becomes more stable. Concerning the magneto-induced pressure drop, the smaller the axial damping gap is the better the magnetorheological effect of the magnetorheological fluid can be achieved with the greater pressure drop floating within 0.5-1 mm. But with the increase of the axial damping gap, the magnetorheological effect of the magnetorheological fluid will be weakened, subsequently, the pressure drop value produced will also decrease.

5.5. The Influence of The Radial Damping Gap on The Performance of Dropping Pressure of The Hybrid Magnetic Source Disc-type Magnetorheological Valve

The magnetic field distribution in the flow channel of the hybrid magnetic source disc-type magnetorheological valve under different radial damping gap conditions is shown in Fig. 12. Judging from the Figure, it can be seen that the radial damping gap g_r figure is rising, and the magnetic induction intensity at the effective axial and radial damping gaps becomes smaller in the magnetic field distribution in the flow channel of the hybrid magnetic source disc-type magnetorheological valve under different radial damping gap conditions. The reason is that the magnetic resistance of the radial damping gap in the magnetic circuit becomes larger with the enhancement of the radial damping gap, resulting in a decrease in the performance of dropping pressure of the hybrid magnetic source disk-type magnetorheological valve.

The pressure drop performance of the hybrid magnetic source disc-type magnetorheological valve changes with the radial damping gap is shown in Fig. 13. It can be seen from Figure that the pressure drop of the magnetorheological valve shows a downward trend as the radial damping gap increases. The same as the effect of the axial damping gap on the pressure drop performance of the magnetorheological valve, the degree of pressure drop is larger within 1-1.5 mm, and then the degree of decline is slowed down, and the difference is that the radial damping gap has a greater impact on the pressure drop performance of the magnetorheological valve than the axial damping gap. The reason why the viscous pressure drop reaches 2.25 MPa at 1 mm is that the liquid flow channel of the entire magnetorheological valve is mainly composed of radial damping gaps, and once the radial damping gap becomes too small, the pressure loss along the path will be increased in the period of the magnetorheological fluid flowing through the channel, resulting in a large viscous pressure drop and the higher risk of magnetorheological valve blockage. Meanwhile, the magnetically induced voltage drop has also reached a very high value at 1-1.5 mm. The cause is that as the radial damping gap is small, the magnetorheological effect of the magnetorheological fluid will be optimal, and greater shear yield stress and greater pressure drop will appear. However, for more complicated liquid flow channels, a slightly larger radial damping gap can be applied to avoid

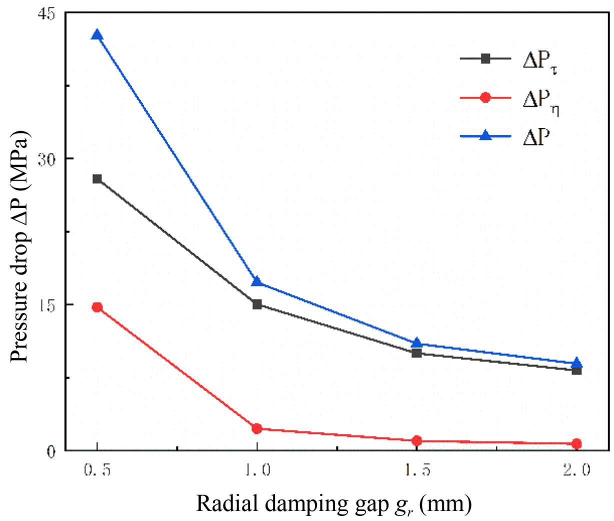


Fig. 13. (Color online) Pressure drop under different radial damping gap.

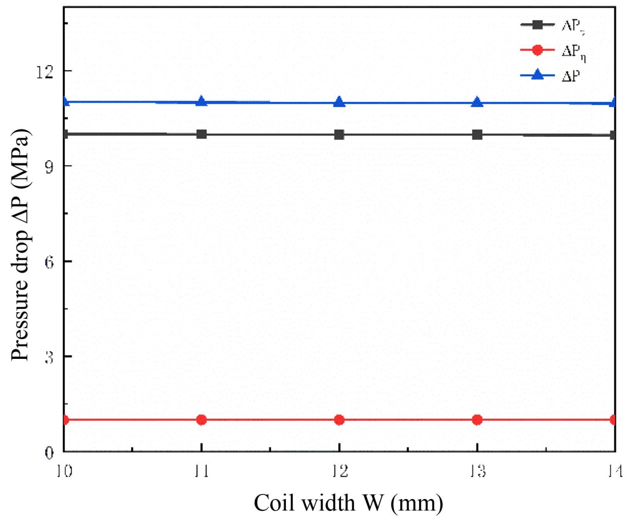


Fig. 15. (Color online) Pressure drop under different coil width.

clogging.

5.6. Influence of Coil Width on Performance of Dropping Pressure of The Hybrid Magnetic Source Disc-type Magnetorheological Valve

Also under the basic parameter setting, only the size of the coil width w is changed. A distribution diagram of the magnetic induction intensity of different coil widths in the liquid flow channel path S is illustrated in Fig. 14. It can be seen from the figure that the influence of the width of the coil on the magnetic induction intensity in the liquid flow channel is not obvious, only a few parts have changed, and most of the curves are coincident. The region of the change mainly occurs at the effective radial damping clearance. At the first effective radial damping gap, when the coil width is 12 mm, there will be an obvious sudden change in the magnetic induction intensity.

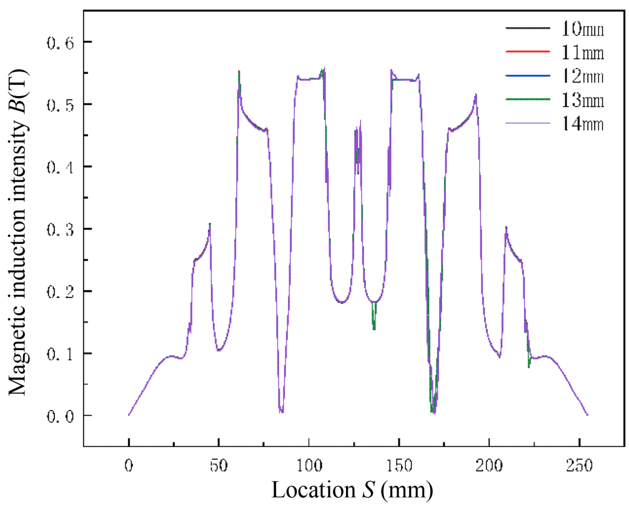


Fig. 14. (Color online) Magnetic flux density of different coil widths along the flow path.

The pressure drop performance of the hybrid magnetic disc magnetorheological valve changes with the width of the coil shown in Fig. 15. It can be seen from the figure that the width of the coil has only an effect on the magnetic pressure drop instead of the viscous pressure drop of the magnetorheological valve. The magnetic pressure drop is getting smaller as the coil width is larger, however, the effect is rather little. The factors of above - the mentioned phenomenon is that alteration of the coil width will only affect the current density of the coil, and the current density of the coil will affect the magnetic induction intensity of the coil.

6. Conclusion

1. Under the basic parameters of current I=3A, axial damping gap ga=1 mm, radial damping gap gr=1.5 mm, coil width W=12 mm, coil turns N=600, etc, the dropping pressure of the hybrid magnetic disc magnetorheological valve reaches 10.9935 MPa, and meets the design requirements.

2. The performance of dropping pressure of the hybrid magnetic source disc-type magnetorheological valve increases with the amplification of the effective current. Under the same current, the radial damping gap has a greater impact on the pressure drop performance of the hybrid magnetic source disc than the axial damping gap.

3. The performance of dropping pressure of the hybrid magnetic source disc-type magnetorheological valve

decreases with the increase of the axial damping gap. Under the same current, the radial damping gap has a greater impact on the pressure drop of the hybrid magnetic source disc magnetorheological valve than the axial damping gap, and the closer to the radial damping gap the permanent magnet is, the greater the pressure drop becomes. With the axial damping gap ranging within 0.5-1 mm and the radial damping gap within 1-1.5 mm, the pressure drop of the hybrid magnetic disc magnetorheological valve has a more significant effect.

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