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Design and Modeling of a Magnetorheological Valve with Both Annular and Radial Flow Paths

H. X. Ai,[1] D. H. Wang[1,2,]* and W. H. Liao[2]

[1]Key Laboratory of Optoelectronic Technology and Systems of the Ministry of Education of China
Chongqing University, Chongqing, China 400044

[2]Smart Materials and Structures Laboratory, Department of Automation and Computer-Aided Engineering
The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China

ABSTRACT: In this article, an MR valve possessing simultaneously annular fluid flow resistance channels and radial fluid flow resistance channels is designed, and its structure and working principle are described. In addition, a mathematical model for the MR valve with both annular and radial flow paths is developed and the simulation is carried out to evaluate the newly developed MR valve. The simulation results based on the proposed model indicate that the efficiency of the MR valve with circular disk-type fluid resistance channels is superior to that with annular fluid resistance channels under the same magnetic flux density and outer radius of the valve. Furthermore, the results also show that the efficiency of the MR valve can be improved significantly with two types of fluid flow resistance gaps, viz. annular fluid flow resistance gaps and circular disk-type fluid flow resistance gaps simultaneously.

Key Words: magnetorheological valve, annular channel, circular disk-type channel, magnetorheological fluid flow, fluid flow resistance gap.

INTRODUCTION

Magnetorheological (MR) fluid is one kind of smart fluid whose rheological properties can be rapidly varied by a magnetic field. With the controllable rheological properties, the MR fluid can be used to make various smart devices and systems (Carlson et al., 1996). Recently, designs, modeling, and applications of MR valves have been explored by several researchers due to the development of MR dampers (Wang and Gordaninejad, 1999, 2005) and MR hydraulic actuation systems (Kordonsky, 1993; Kordonsky et al., 1994, 1996; Gorodkin et al., 1998; Yoo and Wereley, 2002, 2004).

Magnetorheological fluid dampers, which utilize the advantages of MR fluids, are semiactive control devices that are capable of generating the magnitude of force sufficient for large-scale applications, while requiring only a battery for power (Dyke et al., 1996; Spencer et al., 1997). Figure 1 shows the schematic of an MR fluid damper, whose key feature lies in a controllable MR valve.

On the other hand, several researchers have focused on the development of devices, such as hydraulic actuation systems, utilizing MR fluids (Kordonsky, 1993; Kordonsky et al., 1994, 1996; Gorodkin et al., 1998; Yoo and Wereley, 2002, 2004). In the development of these systems, MR valves are the key components that are used to change directions, velocities, and output forces of the cylinders. One of the possible layouts of the MR valves for the hydraulic cylinder piston movement control presented by Kordonsky (1993) is shown in Figure 2. When the current transmits through the windings of diagonally located MR valves (1, 4 or 2, 3), the resistance changes of MR fluids lead to a pressure drop in the cylinder chambers and then an appropriate displacement of the piston. This actuator can execute complicated motions by controlling the current in the MR valve windings. Yoo and Wereley also studied the performance of an MR hydraulic power actuation system based on the layout of the MR valves shown in Figure 2 (Yoo and Wereley, 2004).

Kordonsky et al. (1994, 1996) presented several MR valves with compact structures and optimal channels. Yoo and Wereley (2002) designed and modeled a high-efficiency MR valve. According to their results, an MR valve is actually a proportional throttle valve without moving parts. In general, an MR valve comprises a magnetic body and a magnetic core that houses an induction coil winding and a hydraulic channel located between the outside of the core and the inside of the body connected to a fluid inlet port and an outlet port. As MR fluids flow through such valves,

*Author to whom correspondence should be addressed.
E-mail: dhwang@cqu.edu.cn

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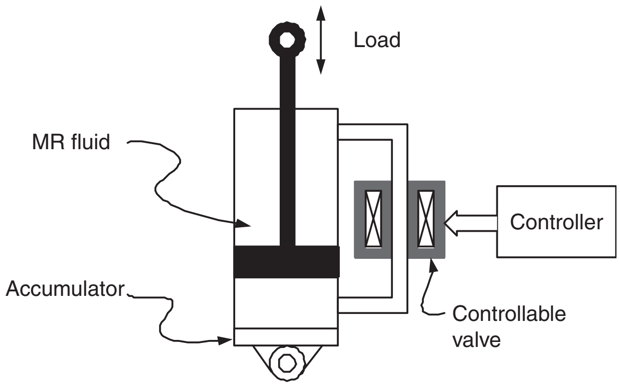


Figure 1. Schematic of an MR fluid damper.

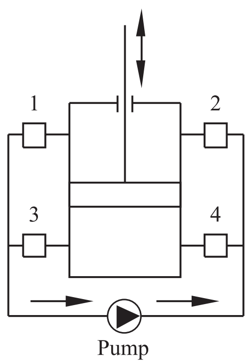


Figure 2. Layout of MR valves for an MR hydraulic actuation system.

a magnetic field is applied to the fluids to increase their viscosity. This change in viscosity increases the resistance of the fluid flowing through the valve, which causes the inlet pressure to increase, thereby slowing or stopping the fluid flow.

Many advantages of using the MR valves in hydraulic actuators can be achieved. On the one hand, the MR valves can be easily controlled by electrical currents at high speed. On the other hand, to avoid the use of moving mechanical parts, the structures of MR valves can be simplified and the reliability can be increased.

Till now, almost all the MR valves have only one type of fluid flow resistance channels – annular fluid flow resistance channels – and hence their fluid flow block forces are relatively low. Generally, to increase the fluid flow resistance force, the volume size and energy consumption for the MR valve are increased, which makes the miniaturization of the MR valve difficult.

Recently, Wang and Gordaninejad (1999, 2005) studied the MR fluid dampers with the radial flow paths of MR fluids, which are not used to compose the MR valves. In this study, an MR valve possessing simultaneously annular fluid flow resistance channels (Kordonsky, 1993; Kordonsky et al., 1994, 1996; Gorodkin et al., 1998; Wereley and Pang, 1998; Yoo and Wereley, 2002, 2004) and radial (circular disk-type) fluid flow resistance channels (Wang and Gordaninejad, 1999, 2005) is designed, and its structure and working principle are introduced. In addition, the mathematical model for the MR valve with both annular and radial flow paths is developed and the simulation is carried out to investigate the newly developed MR valve.

STRUCTURE AND WORKING PRINCIPLE OF THE MR VALVE

Problem Formulation

There are two main operational modes for the controllable devices based on the MR fluids, which include the valve mode (fixed poles) and the shear mode (Carlson et al., 1996). In the valve mode, the MR fluids flow between fixed plates by a pressure drop, and the flow resistance can be controlled by the magnetic field which runs normal to the flow direction. Figure 3 can be used to depict the working principle, which can be realized by an annular fluid resistance channel formulated between the outside of a bobbin and the inside of a hydraulic cylinder as shown in Figure 4.

For the MR valve proposed by Kordonsky (1993) and Kordonsky et al. (1994, 1996) as shown in Figure 4(a), it comprises two flat annular throttling hydraulic channels 1 connected by internal channel 2, and the hydraulic channels are magnetic circuit gaps between the body and the core. Figure 4(b) illustrates the principle of the MR valve studied by Yoo and Wereley (2002), which includes three segments of annular fluid resistance channels. However, both the valves have only one type of fluid flow resistance channels – annular fluid flow resistance channels – and hence their fluid flow block forces are relatively low. To increase the fluid flow block force, it is usual to increase the volume size and energy consumption for the MR valve, which makes the miniaturization of the MR valves difficult. Although the optimization of the magnetic flux and the structure may be able to increase the valve's efficacy.

According to the above analysis, the MR valve slows or stops the fluid flow by increasing the fluid viscosity in the fluid flow gap under the magnetic field. To improve the efficacy of the MR valve, an appropriate way is considered for increasing the fluid resistance gap area without increasing its volume size and magnetic flux density. In this case, two circular disk fluid resistance gaps are designed on the structure of an MR valve, which also possesses annular fluid resistance channels to improve the efficacy.

Structure of the MR Valve with Both Annular and Radial Flow Paths

Figure 5 depicts the structure of the MR valve with annular and radial fluid flow resistance gaps simultaneously and its drawing and exploded photo are shown in Figure 6(a) and (b), respectively. Observing Figures 5 and 6, the MR valve with both annular and radial flow paths comprises two main units: the valve core unit and the magnetic hydraulic cylinder. The valve core unit consists of a magnetic valve core, a nonmagnetic bobbin, two magnetic circular disks, etc. The valve core with a central hole is covered with a nonmagnetic bobbin, which is used to wind the induction coil. Two circular plates are connected to the two ends of the valve core through positioning pins, which are used to constitute the circular disk-type fluid flow resistance gaps. The positioning pins are nonmagnetic and are used to ensure the concentricity of the connected parts. Each pin is installed coaxially with a nonmagnetic washer, which warrants the thickness of the circular disk-type fluid flow resistance gaps. When the valve core unit is coaxially positioned in the hydraulic cylinder, the annular fluid flow resistance channels are formulated between the inside of the hydraulic cylinder and the outside of the circular disks.

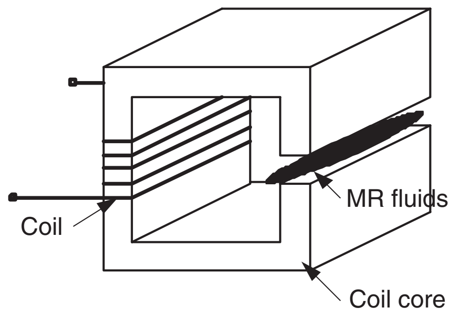


Figure 3. *Working principle of an MR valve.*

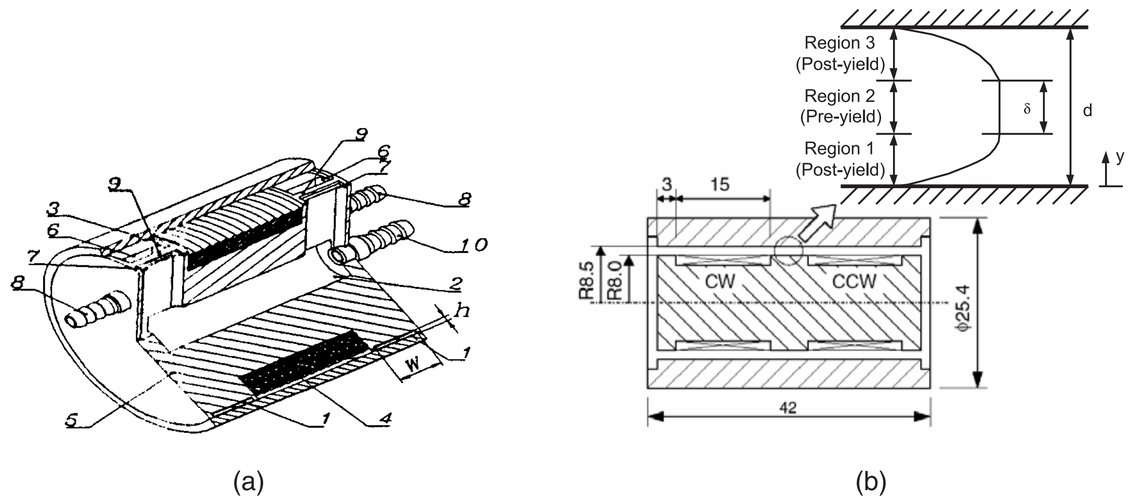


Figure 4. *MR valves with annular flow resistance channels: (a) Gorodkin et al. (1998) and (b) Yoo and Wereley (2002, 2004).*

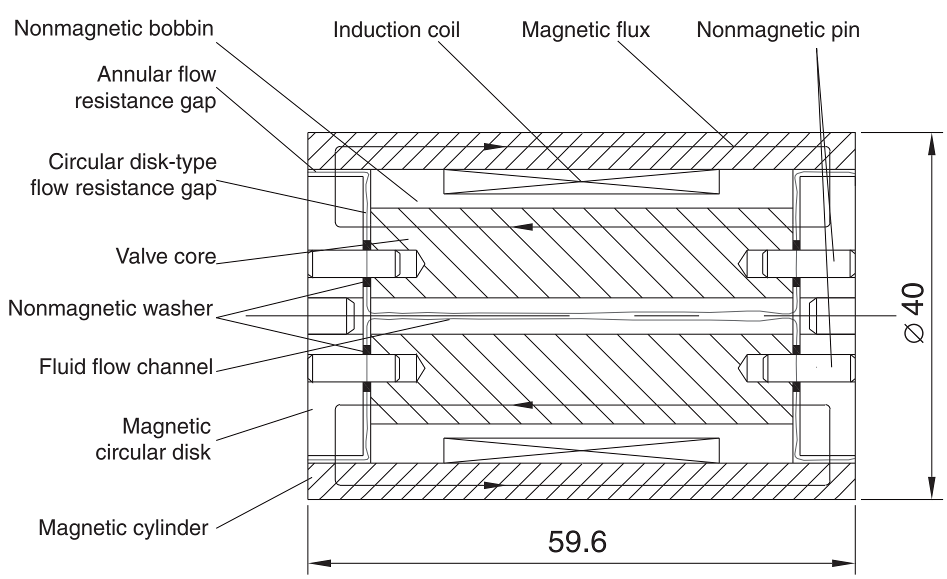
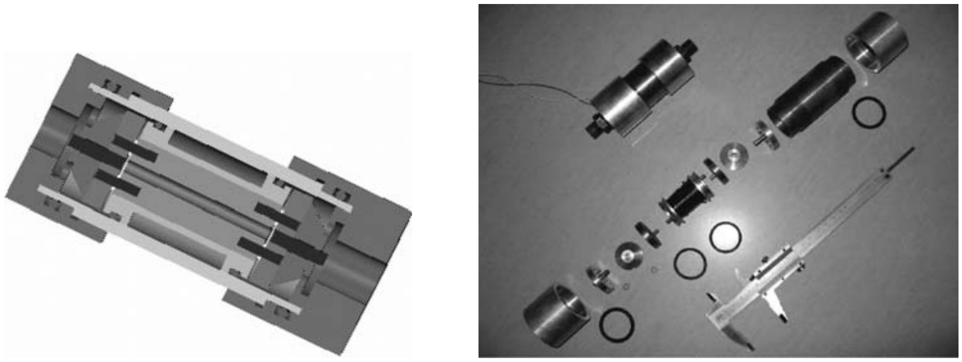


Figure 5. *The structure and principle of an MR valve with annular and circular disk-type fluid flow resistance gaps simultaneously.*



(a) (b)

Figure 6. *An MR valve with annular and circular disk-type fluid flow resistance gaps simultaneously: (a) drawing and (b) exploded photo.*

In this design, the MR fluids flow into the left-hand (right-hand) radial flow gap of the valve through the left-hand (right-hand) annular gap. Then the MR fluids flow into the right-hand (left-hand) radial flow gap through the central hole of the valve core. At last, the MR fluids flow out of the valve through the right-hand (left-hand) annular fluid flow resistance gap. The MR fluids are filled in to flow between the channels by a pressure drop, which is controlled by the magnetic field.

Magnetic Flux Path of the MR Valve with Both the Annular and Radial Flow Paths

To adjust the flow resistance of the MR fluids by applying the magnetic field, the appropriate magnetic flux path should be considered through the structure design. Due to the existence of the nonmagnetic bobbin, the magnetic flux induced by the induction coil under the electric current forms a loop along the valve core, the circular disks, and the hydraulic cylinder as shown in Figure 5. In this design, the magnetic flux is perpendicular to the circular disk-type flow resistance gaps and the annular gaps simultaneously to ensure the maximum flow resistance due to the magnetic field.

When applying a magnetic field, the MR fluids flowing into the fluid flow resistance gaps will immediately become semisolids from Newtonian fluids, which increases the yield stress of the MR fluids. The yield stress continuously increases with the increase of the driving current in the induction coil before the magnetic field strength for the MR fluids is saturated. In this way, the volume flux and the pressure drop of the MR valve can be controlled continually by the coil electric current.

MODELING OF THE MR VALVE

The mathematical modeling of the MR valves is the foundation for simulations. The modeling of the newly developed MR valve is based on the assumption that the fluid flow resistance induced by the valve is the summation of the fluid flow resistances induced by the annular channels and the circular disk channels.

Modeling of MR Fluid Flow in an Annular Channel

Figure 7(a) depicts the annular fluid flow resistance channel between the inner face of the cylinder and the outer annular face of the circular disk with a radius of R. In general, the annular fluid flow resistance channel of the valve containing MR fluids is modeled as an approximate rectangular duct containing MR fluids (Phillips, 1969; Wereley and Pang, 1998). As shown in Figure 7(b), the width, the length, and the thickness of the equivalent rectangular duct are $2\pi R$, L_a, and d (which is the thickness of the annular flow resistance gap between the fixed poles), respectively. The pressure drop developed in an MR valve with the annular fluid flow resistance channel is commonly assumed to result from the sum of a viscous component ΔP_η and a field-dependent induced yield stress component ΔP_τ, which can be expressed as (Phillips, 1969)

$$\frac{dP_1}{dx} = \frac{dP_\eta}{dx} + \frac{dP_\tau}{dx} = \frac{6\eta Q}{\pi d^3 R} + \frac{c\tau_y}{d} \tag{1}$$

where Q is the volumetric flow rate, η is the fluid viscosity without applied magnetic field, and τ_y is the dynamic yield stress in response to an applied magnetic field, c is a function of the flow velocity profile which ranges between a minimum value of 2 (when $\Delta P_\tau/\Delta P_\eta < 1$) and a maximum value of 3 (when $\Delta P_\tau/\Delta P_\eta > 1$). By integrating Equation (1) over the length of the rectangular duct (0 to L_a), the following equation can be obtained

$$\Delta P_1 = \Delta P_\eta + \Delta P_\tau = \frac{6\eta Q L_a}{\pi d^3 R} + \frac{c\tau_y L_a}{d} \tag{2}$$

where R is the inner radius of the annular flow resistance channel, which equals the radius of the circular disks as shown in Figure 7.

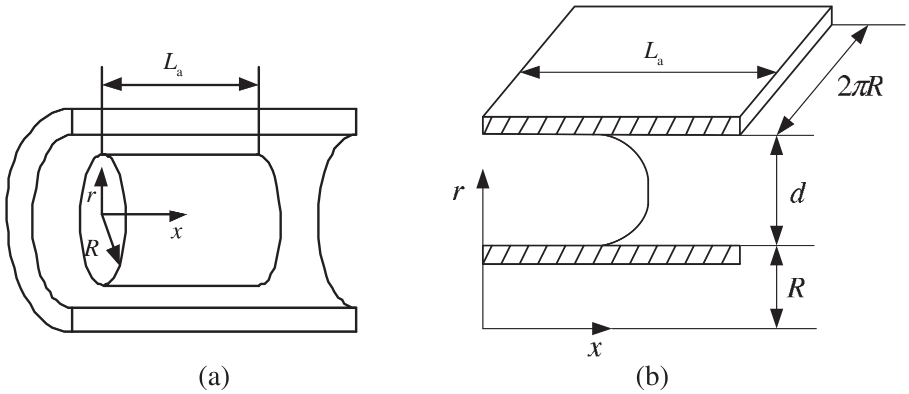


Figure 7. *Modeling of the MR fluid flow in an annular flow resistance channel: (a) an annular model and (b) an approximation by a rectangular model.*

Modeling of MR Fluid Flow in a Circular Disk Channel

Figure 8 shows the working model of the MR fluids in the radial fluid flow resistance channels. The radial flow resistance channel, whose thickness also equals d between the planes A and B. The MR fluids flow into the radial resistance gap from the left-hand (right-hand) outer annular face of the magnetic circular disk, then flow into the left-hand (right-hand) radial fluid flow resistance channel through the central hole of the valve core. We also consider the model of the radial flow resistance gap of the MR valve as the approximate rectangular duct. According to the flowing direction of the MR fluids in the radial flow resistance gap, the pressure drop of the MR fluids in the MR valve changes along the radial direction of the circular disk. In the approximation, the width of the rectangular duct changes from $2\pi R_0$ to $2\pi r_0$, where R_0 and r_0 are the radii of the radial flow resistance channel and the central hole of the valve core, respectively. The pressure drop ΔP_2 of the MR fluids in the radial flow resistance gap along the radial direction comprises a viscous component and a field-dependent induced yield stress component. The pressure drop in the radial flow resistance gap can be expressed as (Phillips, 1969)

$$\frac{\mathrm{d}P_2}{\mathrm{d}r} = \frac{\mathrm{d}P_\eta}{\mathrm{d}r} + \frac{\mathrm{d}P_\tau}{\mathrm{d}r} = \frac{6\eta Q}{\pi r d^3} + \frac{c\tau_y}{d} \tag{3}$$

where the symbols are identical to those given in Equations (1) and (2). Through integrating Equation (3) from r_0 to R_0, the following equation is derived:

$$\Delta P_2 = \Delta P_\eta + \Delta P_\tau = \frac{6\eta Q}{\pi d^3}\ln\frac{R_0}{r_0} + \frac{c\tau_y}{d}(R_0 - r_0) \tag{4}$$

Modeling of an MR Valve with Both the Annular and the Circular Disk Resistance Channels

Figure 9 shows the flow of the MR fluids in the fluid flow resistance channels of the MR valve with both

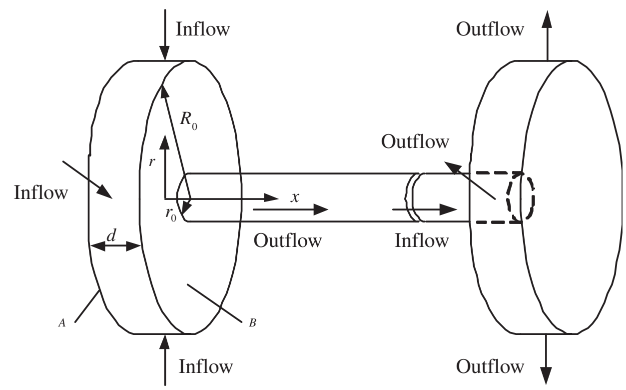


Figure 8. *Modeling of MR fluid flow in radial flow gaps.*

annular and radial flow paths. So the flow resistance of the MR valve can be considered as the summation of the flow resistances of the MR valve with annular fluid flow resistance channels and the MR valve with circular disk-type fluid flow resistance channels. According to Equations (2) and (4), the pressure drop ΔP of the MR fluids passing the MR valve can be expressed as

$$\Delta P = 2\Delta P_1 + 2\Delta P_2 = 2\left[\frac{6\eta Q L_a}{\pi d^3 R} + \frac{c\tau_y L_a}{d}\right] + 2\left[\frac{6\eta Q}{\pi d^3}\ln\frac{R_0}{r_0} + \frac{c\tau_y}{d}(R_0 - r_0)\right] \tag{5}$$

where the symbols are given in Equations (1)–(4), d is the thickness of the annular and circular disk-type flow resistance channels.

SIMULATION RESULTS AND ANALYSIS

The valve dimensions are given in Table 1. In the simulation, the MR fluid 132LD by Lord Corporation is used, whose dynamic yield stress is approximated by

$$\tau_y = a_3 B^3 + a_2 B^2 + a_1 B^1 + a_0 \tag{6}$$

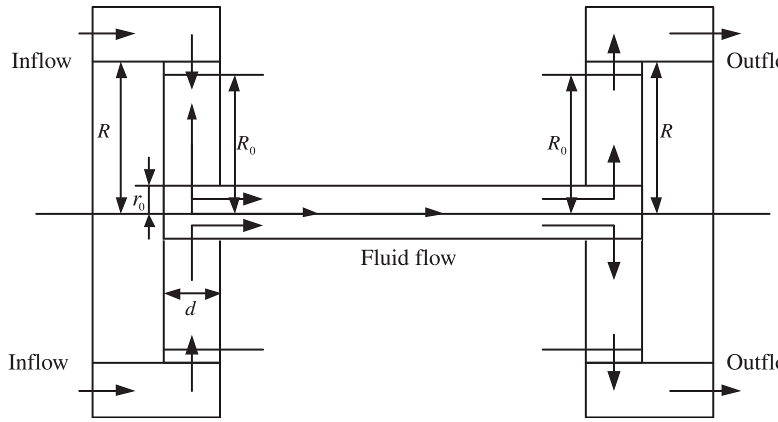


Figure 9. *Modeling of the MR valve with both annular and radial flow paths.*

Table 1. Valve dimensions.

Parameter	Value	Parameter	Value
Outer diameter of valve	40 mm	Annular gap length	4 mm
Bobbin diameter	25.4 mm	Air gap thickness	0.8 mm
Circular disk diameter	30.4 mm	Outer diameter of valve core	22.4 mm
Central hole diameter	4 mm	Maximum magnetic flux density	0.8 T

where the polynomial coefficients are determined by least squares fitting of the dynamic yield stress data as a function of the magnetic flux density from the data supplied by Lord Corporation and $a_0 = -0.877\,\text{kPa}$, $a_1 = 17.42\,\text{kPa/T}$, $a_2 = 122.56\,\text{kPa/T}^2$, and $a_3 = -86.51\,\text{kPa/T}^3$ and the nominal plastic viscosity η is assumed to be 0.25 Pa s. The simulation results for the MR valves are shown in Figures 10 and 11.

In Figure 10(a), the pressure drops induced by different MR valves as a function of the magnetic flux density are shown when $d = 0.8\,\text{mm}$ and $Q = 15\,\text{cc/s}$. Observing Figure 10(a), all pressure drops through different MR valves increase with the increase of the magnetic flux density. However, the pressure drops for all the MR valves increase slowly when $B \geq 0.8\,\text{T}$, which indicates that the magnetic saturation of the MR fluid appears. To sufficiently use the controllability of the magnetic field, the design of valves should assure that the maximum magnetic field does not exceed the saturation magnetic field strength of the MR fluids.

On the other hand, it can be seen that the pressure drop through the MR valve with circular disk-type flow resistance gaps is much larger than that through the valve with annular flow resistance gaps with the same radius of the hydraulic cylinder and magnetic flux density. In this case, using the MR valve with the circular disk-type flow resistance gaps can get larger controllable range for the MR fluid than that with annular flow resistance gaps. Furthermore, from Figure 10(a), the MR valve with two types of fluid flow resistance channels is the most significant in pressure drop among the MR valves considered in this study.

The relationships of the pressure drops of the MR valves with the flow resistance gap thickness are shown in Figure 10(b) when $B = 0.8\,\text{T}$ and $Q = 15\,\text{cc/s}$. The pressure drops induced by all the MR valves decrease with the increase in the flow resistance gap thickness. However, the decreases of the pressure drops will be slowed down when the fluid flow resistance gap thickness d ranges from 0.8 to 1.0 mm. Theoretically speaking, the smaller the flow resistance gap thickness is, the larger the pressure drop is produced. But by decreasing the flow resistance gap thickness infinitely, it becomes hard to manufacture and assemble the MR valve and the MR fluid flow flux through the flow resistance channels will be limited even without the magnetic field. Observing Figure 10(b), the feasible gap thickness ranges between 0.8 and 1.0 mm. In addition, it can also be seen that the pressure drop induced by the MR valve with the circular disk-type flow resistance gaps will be larger than that induced by the MR valve with the annular flow resistance gaps when the gap thickness changes.

Figure 10(c) shows the variation of the pressure drops induced by the MR valves with the flow rate when $d = 0.8\,\text{mm}$ and $B = 0.8\,\text{T}$. The pressure drops by the MR valve with the circular disk-type flow resistance gaps is significantly larger than that by the MR valve with the annular flow resistance gaps when the flow rate of the MR fluids ranges between 10 and 100 cc/s. Observing Figure 10(c), the pressure drops induced by the MR valves are almost invariable with the increase in the flow rate, which indicates that the pressure drops of the MR valves are induced mainly by magnetorheological effect in the magnetic field.

Figure 10(d) shows that the pressure drops of the MR valves vary with the outer radius of the radial gap R_0 (for the MR valve with annular flow resistance channel, $R = R_0 + 4\,\text{mm}$) when $B = 0.8\,\text{T}$, $d = 0.8\,\text{mm}$, and $Q = 15\,\text{cc/s}$. From Figure 10(d), when R_0 exceeds 6 mm,

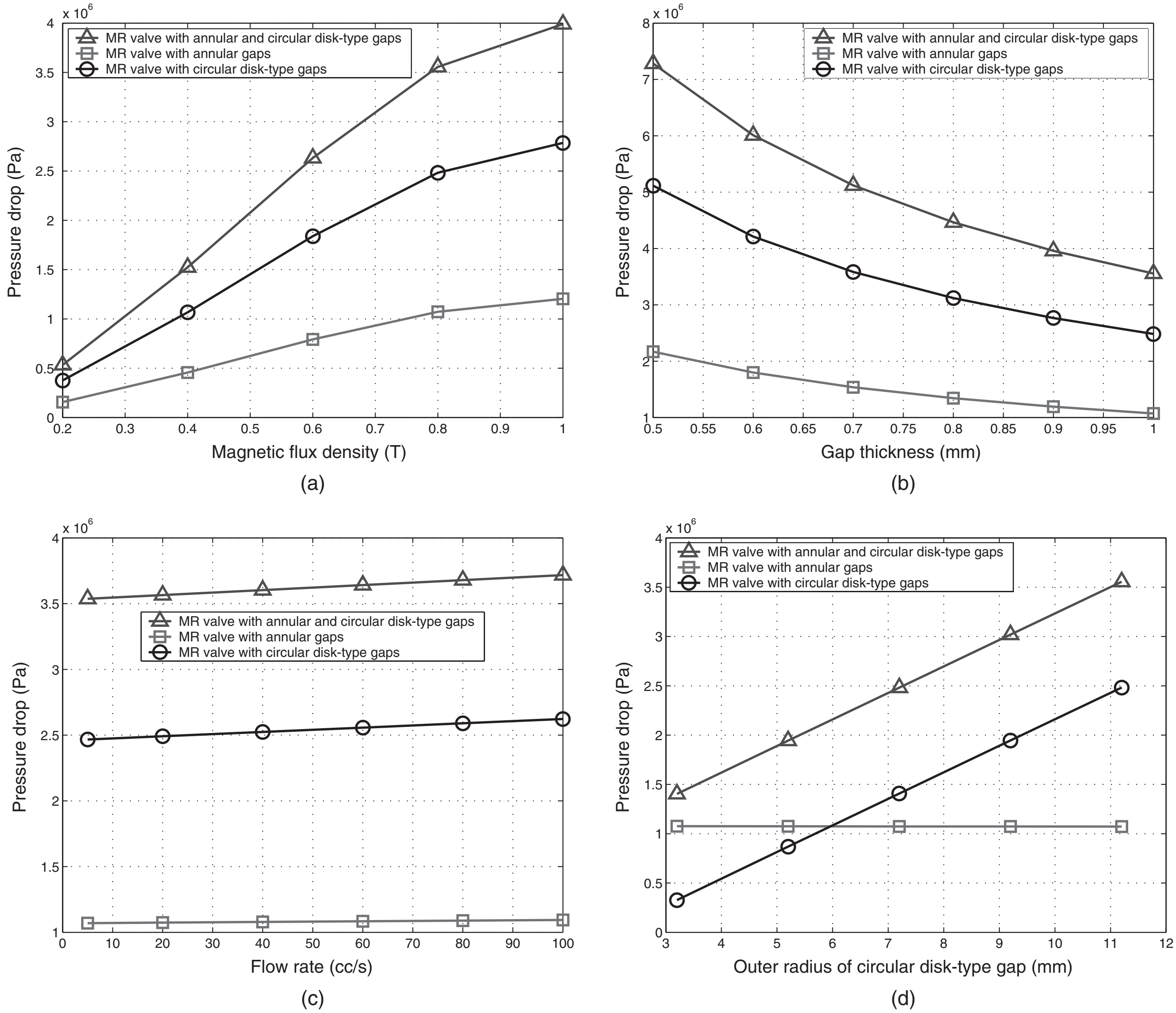


Figure 10. *Pressure drops of the MR valves vs the parameters of the MR valves: (a) pressure drop vs magnetic flux density ($d = 0.8$ mm, $Q = 15$ cc/s, $R = 15.2$ mm); (b) pressure drop vs channel gap ($B = 0.8$ T, $Q = 15$ cc/s, $R = 15.2$ mm); (c) pressure drop vs flow rate ($B = 0.8$ T, $d = 0.8$ mm, $R = 15.2$ mm), and (d) pressure drop vs outside radius of circular disk-type gap ($B = 0.8$ T, $Q = 15$ cc/s, $d = 0.8$ mm, $R = R_0 + 4$ mm).*

the pressure drop produced by the valve with circular disk-type flow resistance gaps is larger than that produced by the valve with annular flow resistance gaps. It is worth noting that the pressure drop induced by the MR valve with annular flow resistance gaps decreases with the increase of the outer radius of the circular disk-type gap R_0, which is shown in Figure 11. However, the effect of the outer radius of the circular disk-type gap R_0 on the pressure drop is too small to be identified from Figure 10(d). Notwithstanding this, the pressure drop through the MR valve with annular and radial flow paths is still larger than those through the other two valves. In this case, the radius of the MR valve core should be carefully considered while designing a practical MR valve.

CONCLUSIONS

The simulation results based on the proposed models show that the efficiency of the MR valve with circular disk-type fluid resistance gaps is superior to that with annular fluid resistance gaps with the same magnetic flux and outer circular radius of the cylinder. The results also show that the efficiency of the MR valve possessing annular fluid flow resistance channels and circular disk-type fluid resistance channels simultaneously can surpass those with the MR valves possessing only one type of flow resistance channels, which attributes to the larger fluid flow yield area with the MR valve without increasing the volume size and energy consumption. The larger fluid flow block force can be produced with the

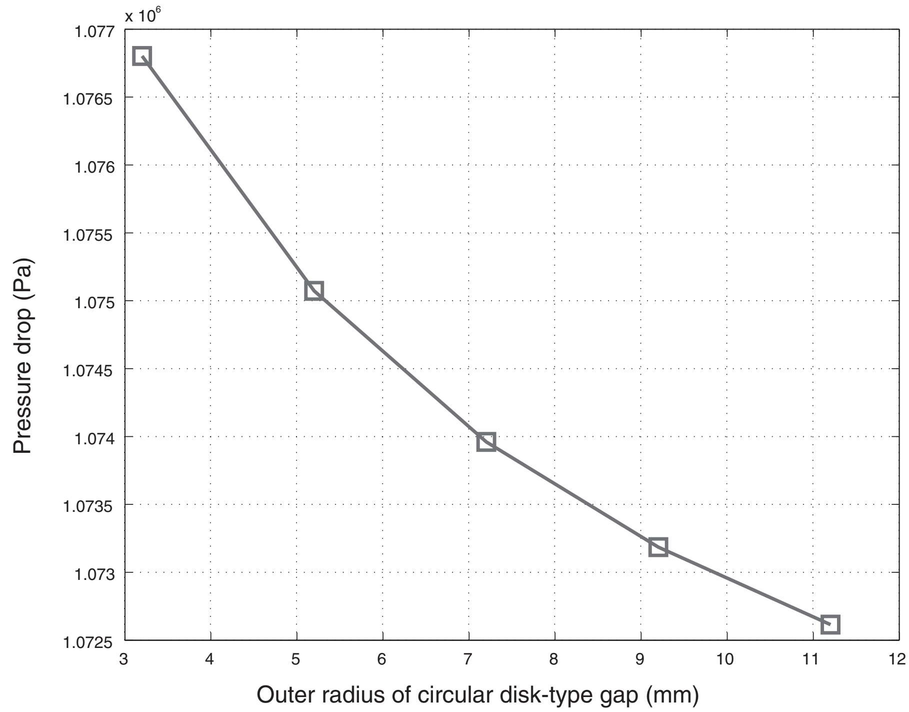


Figure 11. *Pressure drop of the MR value with annular flow resistance channels with the outer radius of the circular disk-type gap R_0.*

newly developed MR valve than those with the MR valves possessing only one type of fluid flow resistance channels.

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