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ORIGINAL ARTICLE

Finite element modeling and simulation of proposed design magneto-rheological valve

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Abstract Magneto-rheological (MR) valve is one of the devices generally used to control the speed of Hydraulic actuator of MR fluid. The performance of valve depends on the magnetic circuit design. Present study deals with a new design of MR valve. A mathematical model for the MR valve is developed and the simulation is carried out to evaluate the newly developed MR valve. The design of the magnetic circuit is accomplished by magnetic finite element software such as Finite Element Method Magnetic (FEMMR). The model dimensions of MR valve, material properties are taken into account. The results of analysis are presented in terms of magnetic strength H and magnetic flux density B. The simulation results based on the proposed model indicate that the efficiency of the proposed MR valve is superior to two other types of MR valves, under the same magnetic flux density. As a conclusion, the new valve design has improved the efficiency of MR valve significantly.

Keywords Magneto-rheological (MR) fluid · (MR) valve design · Magnetic field · FEMM software

1 Introduction

Magneto-rheological (MR) fluid is fascinating material, composed of micro-sized magnetic particles suspended in liquid, such as hydrocarbon oil or silicon oil. The rheological properties of MR fluid are rapidly and reversibly altered when an external magnetic field is applied. The suspended particles in the MR fluid become magnetized and align themselves, like chains, with the direction of the magnetic field. The formulation of these particle chains restricts the movement of the MR fluid, thereby increasing the yield stress of the fluids.

Designs that take advantage of MR fluids are potentially simpler and more reliable than conventional electromechanical devices.

MR fluid is a controllable fluid. It is essential to know the work done by researchers in the study MR fluids and for the purpose of knowledge of the properties and specifications of this MR fluid and their possible use. Bossis et al. [1] have presented the basic phenomena related to the interplay between inter particle magnetic forces. Zipser et al. [2] has described the flow behavior of magneto-rheological fluids in narrow channels, influenced by variable magnetic fields and temperature. Olabi and Grundwald [3] have showed the excellent features like fast response. Laun et al. [4] has done the measurements of the first and second normal stress difference in steady shear of a 50% volume MR fluid. Brigadnov et al. [5] have presented the material constitutive relations for a non-Newtonian incompressible MR fluid.

Some researchers have developed new control systems are implicitly with MR fluid devices. Kim et al. [6] have developed semi-active nonlinear control of a building with a MR damper system, which used the same technology used by Cheng-Wu Chen [7]. Yu et al. [8] have developed a fuzzy neural network control system for vehicle stability utilizing MR suspension system, which used the same technology used by Liang et al. [9] and Chen et al. [10].

Hydraulic valves have complex construction and moving parts, thus the characteristics and life of hydraulic control valves are affected greatly by moving parts. Using the rheological property of MR fluid, the MR flow hydraulic control valve can be designed with absence of moving

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parts. MR valve has been studied by researchers like Yokota et al. [11]. They have proposed and fabricated a pressure control valve using MR fluid. The differential pressure and output power change of 0.68 MPa and 20 W were obtained with the input current and power change 710 A-turns and 1.9 W at the flow rate of 30 cm^3/s (1.8 L/min). Songjing et al. [12] have developed a new type MR fluid relief valve. The construction and working of new type valve were introduced. Yoo et al. [13] have designed the miniature MR valve with the maximum performance of the MR effect in fluid mechanics. Li et al. [14] have optimized the design of a high-efficiency MR valve using finite element analysis. Ai et al. [15] have designed an MR valve possessing simultaneously with annular fluid resistance channels and radial flow resistance channels. Nguyen et al. [16, 17] have presented the geometric optimal design of MR valves in order to improve valve performance, such as pressure drop.

In this research, the design and finite element of the new proposal MR valve are introduced.

The main objective of this paper is to evaluate the new design of MR flow control valve using FEMM^R software.

Finite element evaluation of three type MR valves is done. Two of them were studied by other researchers, the other one is proposed in this research.

2 Methodology

Devices that use MR fluids can be classified as pressure driven flow mode. Examples of pressure driven flow mode devices include valves, dampers, and shock absorbers. Another classification is direct-shear mode. Examples of direct-shear mode devices include clutches and brakes [18]. Figure 1 show these two classifications.

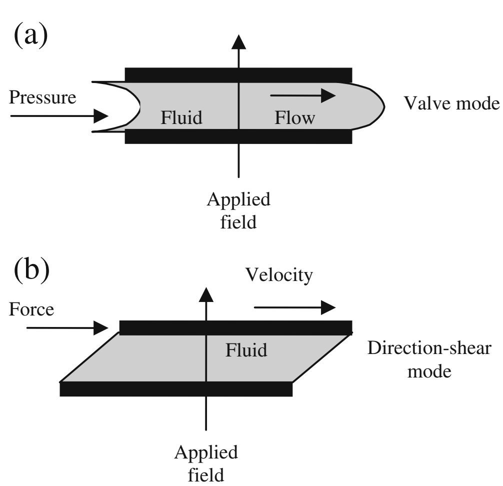


Fig. 1 Basic operational modes for controllable fluid devices: **a** pressure driven valve mode and **b** direct-shear mode

The valve design was done according to the following approach.

The mechanical energy required yielding the microstructure increases with increases in magnetic field resulting in a field, and this mechanical energy increases the yield shear stress as well. In the absence of magnetic field MR fluid behaves like Newtonian fluids. Hence, in the presence of magnetic, the MR fluid follows Bingham's plastic of flow, having variable yield strength. In this model, the Bingham equation is:

$$\tau = \eta\dot{\gamma} + \tau_y(\mathrm{H}) \qquad \tau > \tau_y \qquad (2-1)$$

τ is shear stresses, τ_y is field-dependent yield stress, H is the magnetic field, $\dot{\gamma}$, is the fluid shear rate, and η is the dynamic viscosity (i.e., viscosity at H=0). This equation is used to design device which works on the bases of MR fluid.

The pressure drop in a device is evaluated by summing the viscous component ΔP_η and yield stress component ΔP_τ. Pressure is approximated.

$$\Delta P = \Delta P_\eta + \Delta P_\tau = \frac{12\ \eta\ Q\ L}{g^3 W} + \frac{c\ \tau_y\ L}{g} \qquad (2-2)$$

Where L, g and w are the length, gap and width of the flow channel between the fixed poles, Q is the flow rate, η is the fluid viscosity with no applied field, and τ_y is the yield stress developed in response to an applied field. The parameter c has a value ranging from a minimum value of 2 (for $\Delta P_\tau/\Delta P_\eta$ less than ~1) to a maximum value of 3 (for $\Delta P_\tau/\Delta P_\eta$ greater than ~100).

The Eq. (2-2) is certainly useful in the design of MR fluid valve. In general, the annular channel considers ($w=\pi 2r$), where $2r$ is the mean diameter of annular gap.

In particular application for one coil annular flow resistance gaps valve the Eq. (2-2) becomes:

$$\Delta P = \Delta P_\eta + \Delta P_\tau = \frac{12\ \eta\ Q\ L_g}{\pi g^3 r} + \frac{2c\ \tau_y\ Lg}{g} \qquad (2-3)$$

Where L_g is annular gap length

And for two coils annular flow resistance gaps valve, it becomes:

$$\Delta P = \Delta P_\eta + \Delta P_\tau = \frac{6\ \eta\ Q\ L_T}{\pi g^3 r} + \frac{2c\ \tau_y\ L_1}{g} + \frac{c\ \tau_y\ L_2}{g} \qquad (2-4)$$

Where L_t is total gaps length, L_1 and L_2 are gaps length in the same valve.

If it applied to utilize for hollow disk gap, it becomes:-

$$\Delta P = \Delta P_\eta + \Delta P_\tau = \frac{6\ \eta\ Q}{\pi g^3} \ln \frac{R}{r} + \frac{c\ \tau_y (R - r)}{g} \ldots\ldots\ldots\ldots\ldots\ldots \quad (2-5)$$

Where R is outer radius and r is the inner radius of hollow disk gap.

When it is used to apply for hollow disk and annular gaps together, it becomes:-

$$\Delta P = 2\left(\frac{6\ \eta\ Q\ L_g}{\pi g^3 r} + \frac{c\ \tau_y\ L_g}{g}\right) + 2\left(\frac{6\ \eta\ Q}{\pi g^3} \ln \frac{R}{r} + \frac{c\ \tau_y (R - r)}{g}\right) \quad (2-6)$$

In order to calculate the pressure drop of the MR valve from the above equations, it is necessary to solve the magnetic circuit equations circuit solution. The yield shear stress τ_y is dependent on magnetic field H. It can be obtained from τ_y vs. H curve of MR fluid (MRF-132DG), as shown in Fig. 2.

It can also be obtained by using polynomial equation.

$$\tau_y = a_3 B^3 + a_2 B^2 + a_1 B + a_0 \quad (2-7)$$

W h e r e $a_0 = 0.877\text{kPa}, a_1 = 17.42\text{kPa/T}, a_2 = 122.56\text{kPa/T}^2, a_3 = -86.51/\text{T}^3\text{kPa}$

From the BH curve of MR fluid shown in Fig. 3, select the operating point (H, B) to give desired yield stress τ_y.

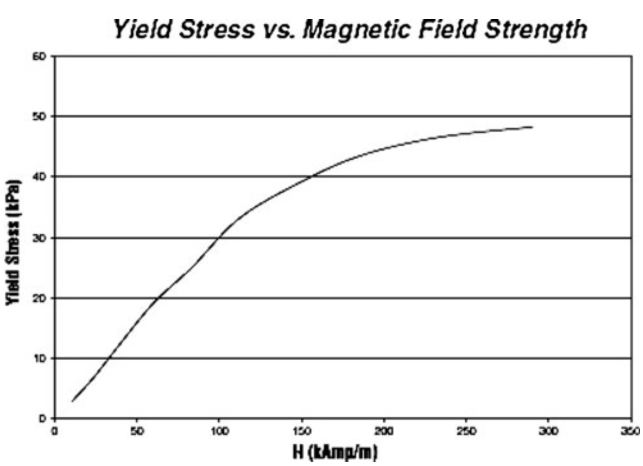


Fig. 2 Yield stress vs. magnetic field strength

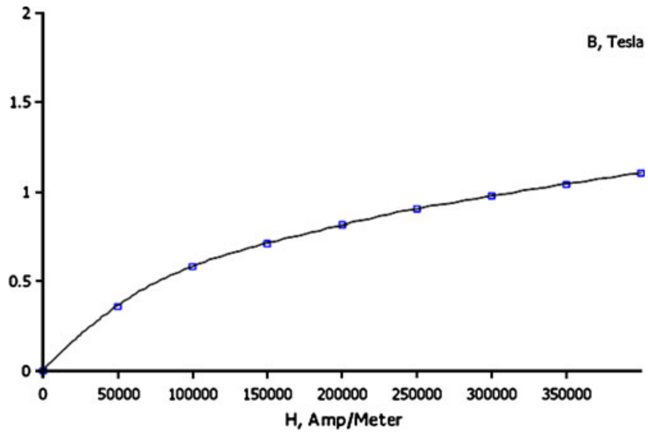


Fig. 3 Magnetic field B vs. magnetic field strength H

Magnetic flux is given by

$$\Phi = B_{fluid} \times A_{gap} \quad (2-8)$$

A_{gap} is the effective surface area of gap. Using the principal of Continuity of Magnetic Flux, it is used to determine flux density B_{steel} throughout flux.

$$\Phi_{fliud} = \Phi_{steel1} = \Phi_{steel2} = \Phi_{steel3} = \ldots.. \quad (2-9)$$

Then

$$B_{steel} = \frac{\Phi_{steel}}{A_{steel}} = \frac{B_{fluid} \times A_{gap}}{A_{steel}} \quad (2-10)$$

From the BH curve of the steel we can get $H_{steel.}$. This may not be the same at different places in flux conduit, if cross section varies. Determine the necessary amp-turns (NI) by using Kirchhoff's Law for magnetic circuits.

$$\begin{aligned} NI &= \oint H.dl \\ NI &= \sum H_i \times L_i \\ NI &= H_{fluid} \times g + H_{steel} \times L_{steel} \end{aligned} \quad (2-11)$$

L_{steel} is the total length of steel path through which magnetic flux goes through.

Cylindrical shape of MR valve has complex structure in magnetic analysis. Full optimization of the magnetic design can only be accomplished by assistance of magnetic finite element software capable of treating nonlinear materials. This research uses FEMM[R] software.

3 Finite element modeling of MR valve

The new design proposed MR valve consisting of a steel path and an annular gap with disk gap (hollow disk) as shown in Fig. 4. The steel path consists of bobbin, two cores and flux return. Mild steel 1006 is a material chosen for steel path, which has a high relative permeability of over 1,000. In the present study, the MR fluid property is selected according to the standard MRF-132DG. The current applied is 1.6 A.

This research was focused to design a new type of MR valve, easy to replace coil, because it is outside of effective area. The terminals of coil are easy to feed through. The overall body of valve length is short. It can be used in the next work.

At the design stage, many parameters, including fluid gap, bobbin diameter, flux length, the thickness of core and flux return as well as the number of wire turns, should be considered. To achieve an efficient MR valve, the flux density in the fluid gap should be maintained constant [19]. The relative permeability of the MR fluid is much smaller than that of low-carbon-steel-based bobbin, two cores and flux return; consequently, a smaller fluid gap will be better. Practical gaps typically range from 0.25 to 2 mm for ease of manufacture and assembly [20]. In this study, the gap is set to 0.5 mm. The analysis to calculate magnetic field will be determined by using finite method with the help of the FEMM^R software.

Due to structural symmetry, the MR valve will be analyzed as a 2-D axisymmetric model. The all dimensions of the valve were given. A finite element model of the magnetic circuit was developed. This was built using FEMM^R and the corresponding model is shown in Fig. 5.

At the same procedure and conditions, the analysis for two other types of MR valve was done. The dimensions of those MR valves were taken from literatures. The design

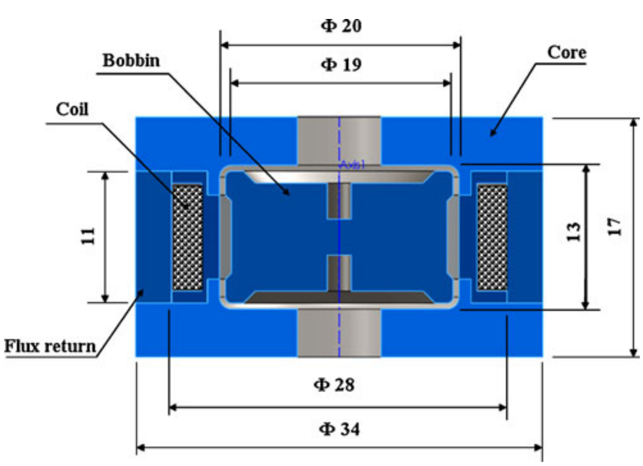


Fig. 4 Schematic shows the design and dimensions of MR valve

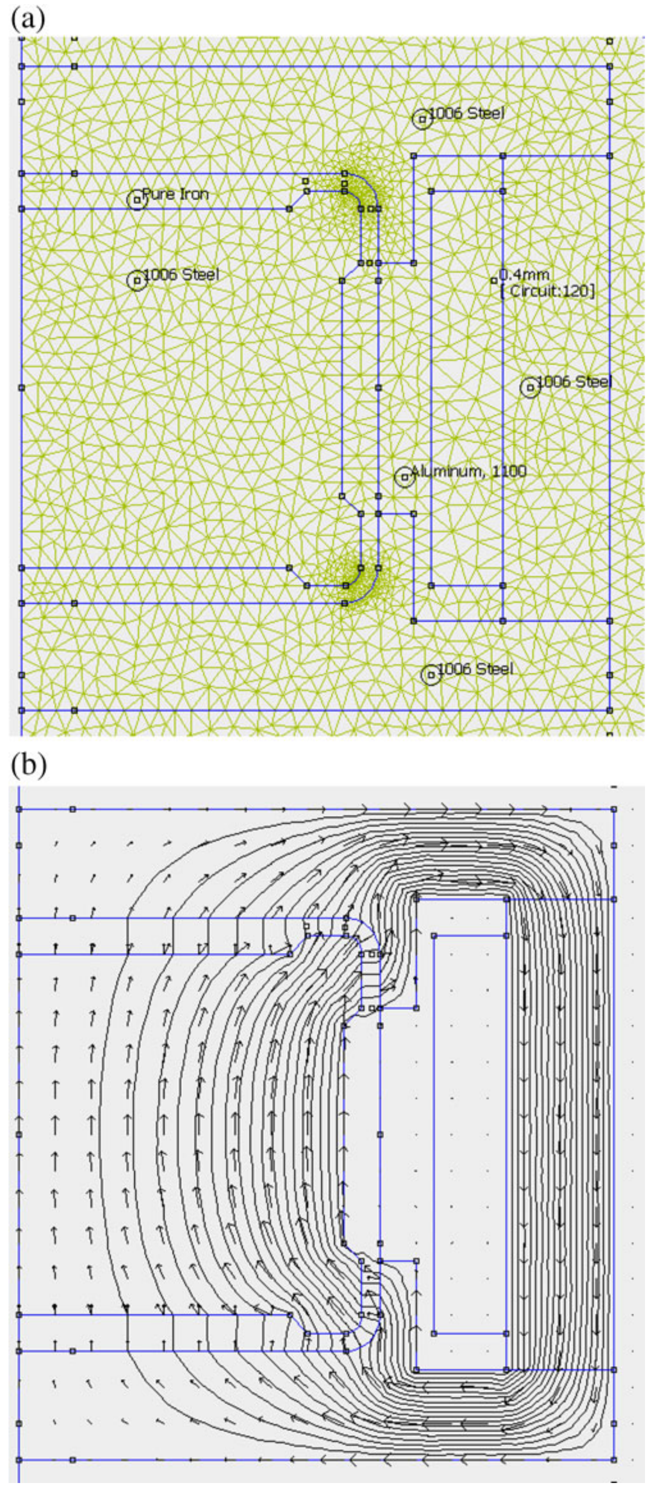


Fig. 5 Finite element model of the magnetic circuit for a new MR valve

idea of both of them was proposed by other researchers [14, 21, 22] (see Figs. 6 and 7).

The results of each MR valve design analysis are shown in Figs. 8, 9, and 10. The important thing of analysis is the

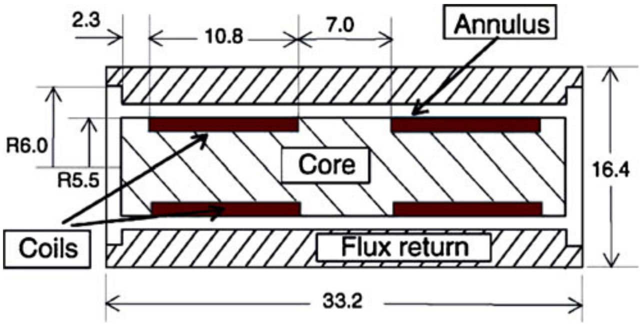


Fig. 6 Schematic shows the dimensions of two coils of MR valve [14]

magnetic strength *H* which is in effective gap of valve. It should be 200–250 kAmp/m. The yield shear stress is about 45 kPa.

Observing the FEMM results for previous works, such as MR valve shown in Fig. 8, it has two coils, the magnetic strength *H* in the valve gap is about 140 kAmp/m. The other MR valve shown in Fig. 9 has one coil, the magnetic field strength *H* in the valve gap is about 180 kAmp/m. In a new proposed design of MR valve shown in Fig. 10, which is proposed by this work, it is about 200 kAmp/m. The magnetic field strength *H* in the new MR valve is higher than the two other types. The valve shown in Fig. 9 has one coil. Its diameter larger of other one but the overall of body length is shorter. The valve shown in Fig. 8 has two coils, its diameter smaller than first one. The overall length of body length is longer. The disadvantage of two valves

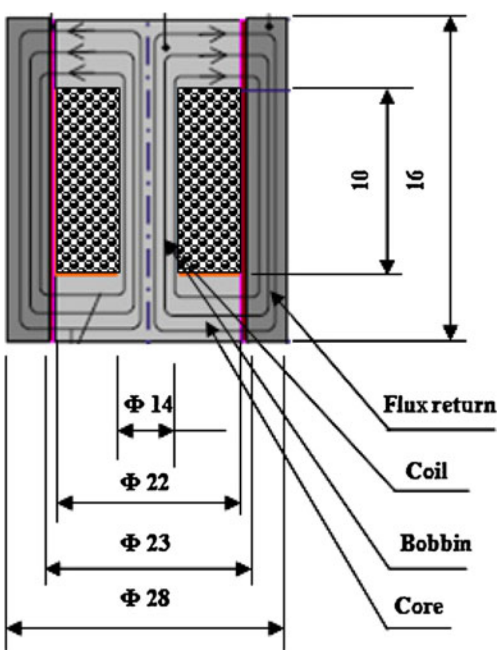
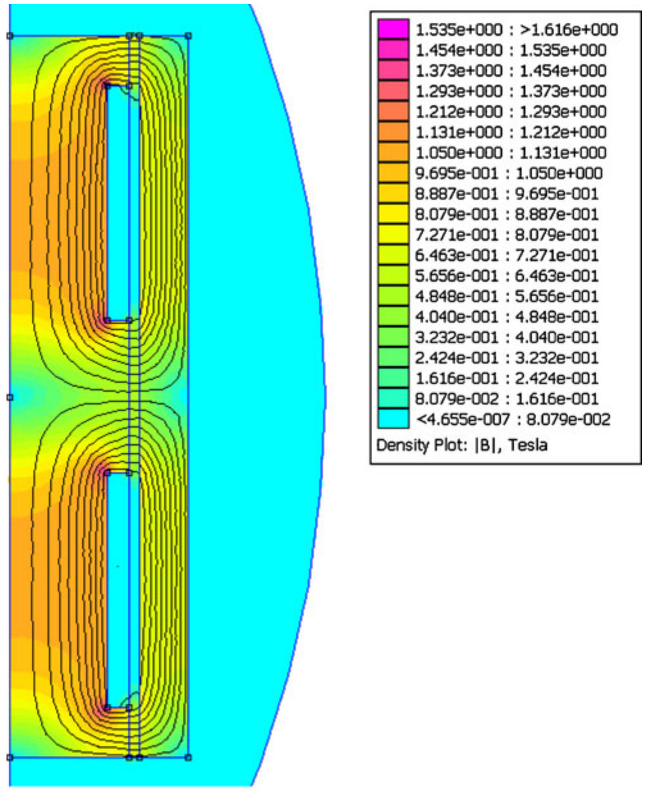
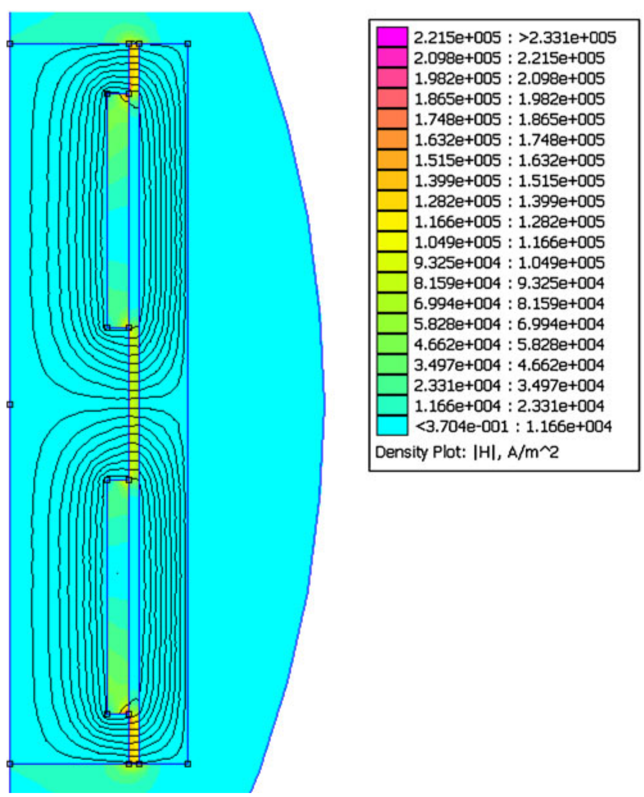


Fig. 7 Schematic shows the dimensions of one coil MR valve [17]



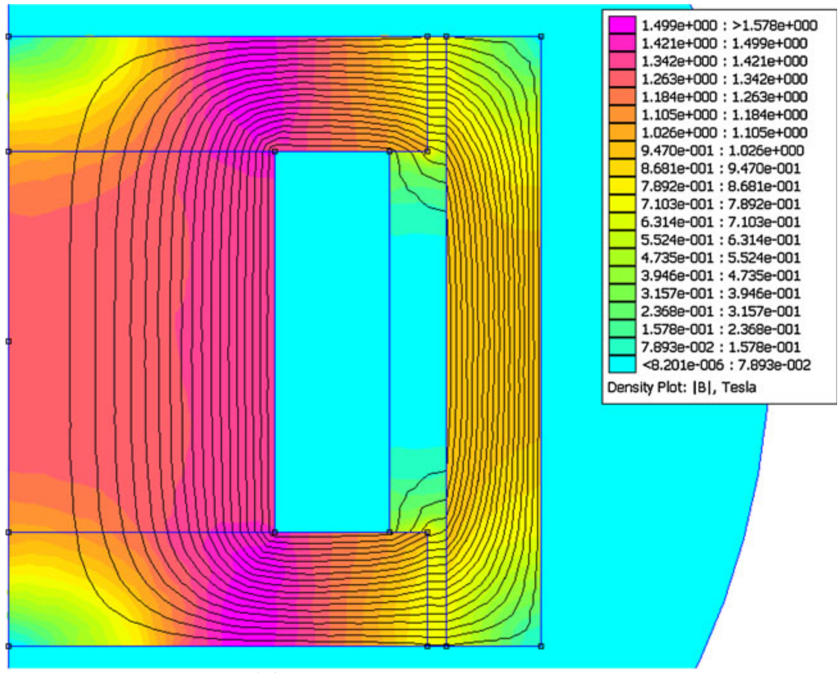
(a) Magnetic flux density



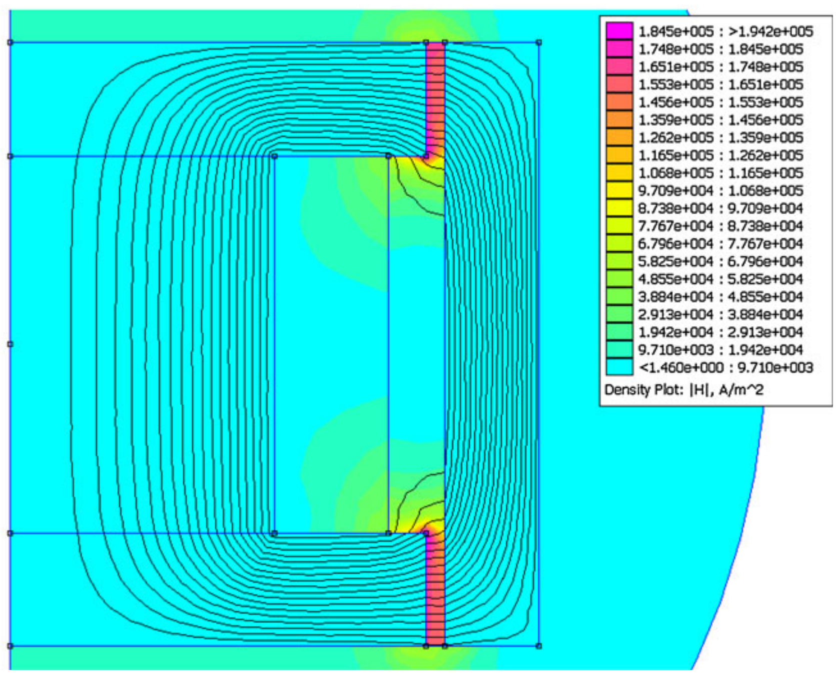
(b) Magnetic strength intensity

Fig. 8 Finite elements analysis for two coils annular MR valve **a** magnetic flux density, **b** magnetic strength intensity

Fig. 9 Finite elements analysis for one coil annular MR valve **a** Magnetic flux density, **b** Magnetic strength intensity



(a) Magnetic flux density



(b) Magnetic strength intensity

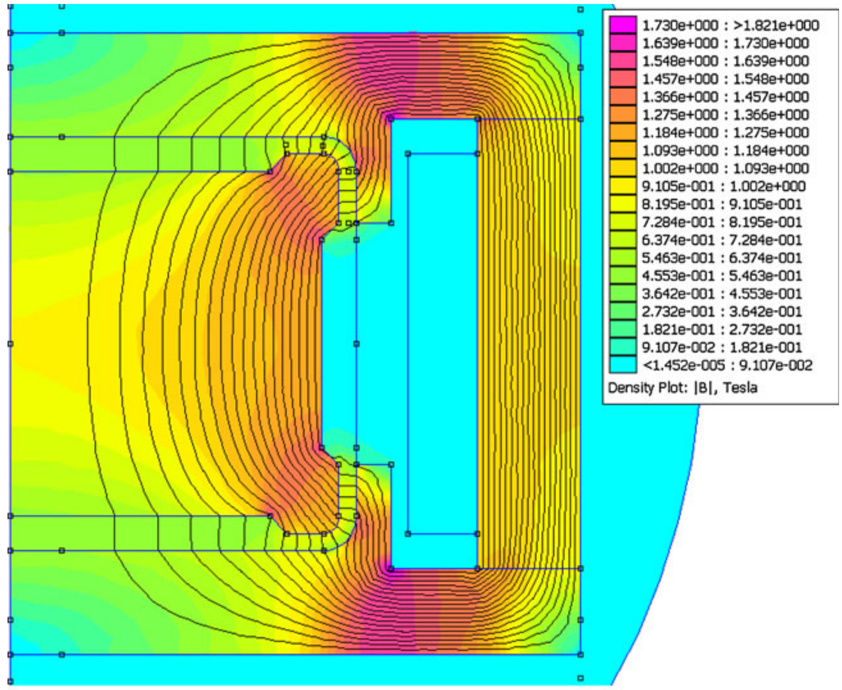
which are proposed by previous work is the terminals of coils could not feed through easily, because the coil is inside the effective area of magnetic field. It is in contact with MR fluid. That means if the coil is damaged, all valves should be replaced.

The new design of MR valve which is proposed by this work is developing the MR valve. The overall length is short and the coil is outside of the effective area of MR fluid, which means the terminals of coils, can be fed through easily.

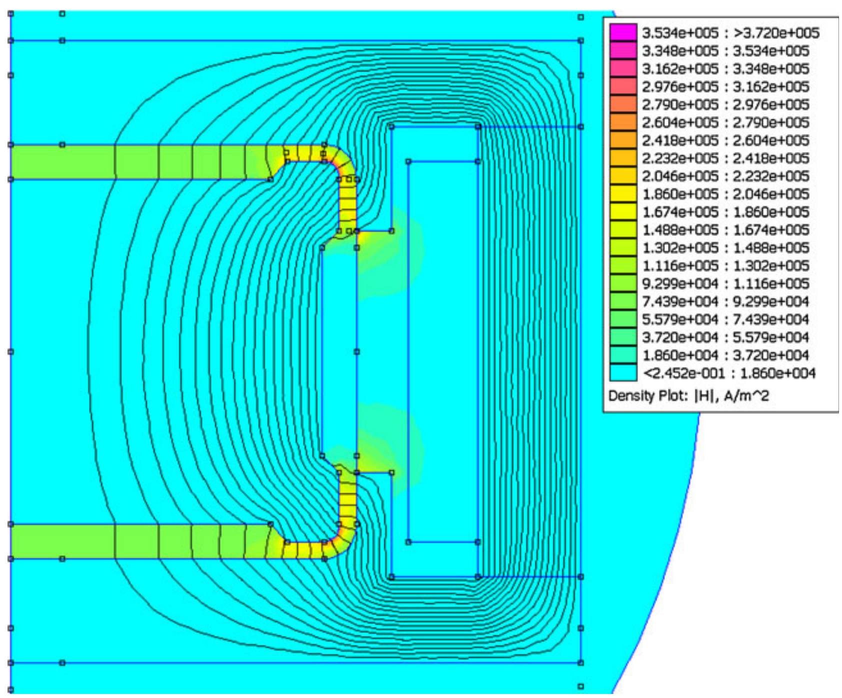
4 Simulation results and analysis

The valve dimensions are given in Figs. 4, 6, and 7. In this simulation, Eq. 2-3 was used for one coil annular flow

Fig. 10 Finite elements analysis for new proposed MR valve **a** magnetic flux density, **b** magnetic strength intensity



a) Magnetic flux density



b) Magnetic strength intensity

resistance gaps, Eq. 2-4 was used for two coils annular flow resistance gaps, and Eq. 2-5 was used for hollow disk and annular flow resistance gaps(new proposed MR valve). The properties of MR fluid 132LD by Lord Corporation is used, whose dynamic yield stress is approximated by Eq. 2-7. The nominal plastic viscosity is assumed to be 0.25 Pa s. The simulation results for the MR valves are shown in Figs. 11, 12, and 13. In Fig. 11, the pressure drops induced by different MR valves as a function of the magnetic flux density are shown when g=0.5 mm and Q=15 cc/s. Observing Fig. 11, all pressure drops through different MR valves increase with the increase of the magnetic flux

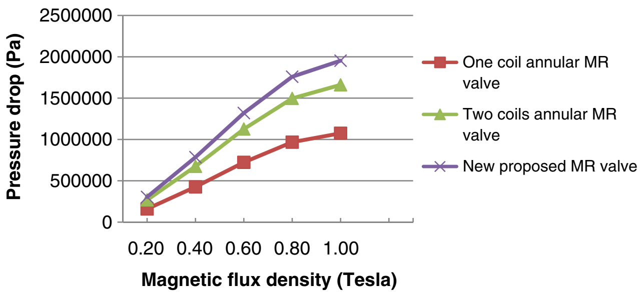


Fig. 11 The relation between pressure drop of MR Valve and magnetic flux density

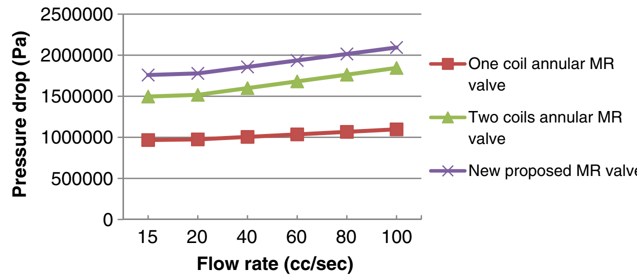


Fig. 13 The relation between pressure drop of MR Valve and flow rate

density. However, the pressure drops for all the MR valves increase slowly when $B \geq 0.8$ 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 two coils type annular flow resistance gaps is much larger than that through the MR valve with one coil annular flow resistance gaps with magnetic flux density. In this case, using the MR valve with the two coils, annular flow resistance gaps can get larger controllable range for the MR fluid than that with one coil annular flow resistance gaps. Furthermore, from Fig. 11, the new proposed MR valve with two of fluid flow resistance channels (hollow disk and annular) 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 Fig. 12, when magnetic flux density $B=0.8$ T and fluid flow rate $Q=15$ 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 g ranges from 0.5 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 Fig. 12, the feasible gap thickness ranges between 0.5 and 1.0 mm. In addition, it can also be seen that the pressure drop induced by the new proposed MR valve will be larger than that induced by two coils annular flow resistance gaps MR valve and one coil annular flow resistance gaps when the gap thickness changes. Figure 13 shows the variation of the pressure drops induced by the MR valves with the flow rate when $g=0.5$ mm and $B=0.8$ T. The pressure drops by the new proposed MR valve is significantly larger than that two coils annular flow resistance gaps MR valve and one annular flow resistance gaps when the flow rate of the MR fluids ranges between 15 and 100 cc/s. Observing Fig. 13, 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 magneto-rheological effect in the magnetic field.

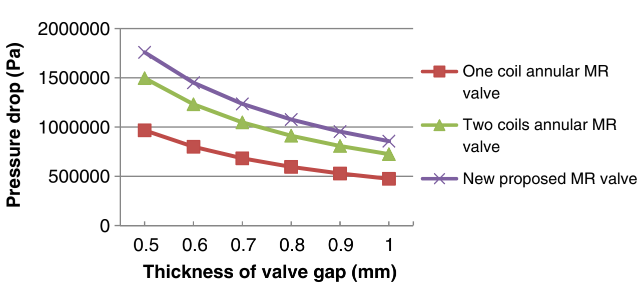


Fig. 12 The relation between pressure drop of MR valve and thickness of valve gap

5 Conclusions

In this work, the new proposed MR valve provides the best design, because the valve achieves best magnetic field strength in valve gap. The valve coil is outside of the effective area of the MR fluid. The overall length of valve is small. The simulation results based on the proposed models show that the efficiency of the MR valve is superior to that with two coils annular fluid resistance gaps and with one coil annular fluid resistance gaps. The results also show that the efficiency of the new proposed MR valve can surpass those with one coil annular fluid flow resistance channels and two coils annular fluid resistance channels simultaneously, 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 newly developed MR valve than those with the MR valves with one coil annular fluid flow resistance channels and two coils annular fluid resistance channels simultaneously.

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