SIMULATION AND DESIGN OPTIMIZATION OF MAGNETO RHEOLOGICAL CONTROL VALVE

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ABSTRACT
Magneto-rheological (MR) Valve is one of the devices generally used to control the speed of Hydraulic actuator using MR fluid. The performance of valve depends on the magnetic circuit design. Present study deals with a new design of MR valve. The finite element analysis is carried out on this valve to optimize its design. The design of the magnetic circuit is accomplished by magnetic finite element software such as Finite Element Method Magnetic (FEMM). The Model dimensions of MR valve, material properties and the circuit properties of valve coil are taken into account. The results of analysis are presented in terms of magnetic strength and magnetic flux density. The valve can be operated with variable flow rate by varying the current. It is found that the current is inversely proportional to the flow rate. High current low flow rate and vice versa.

Keywords: Magneto-rheological (MR) Valve, MR fluid, 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 and silicon oil. The rheological properties of MR fluid can be 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 (Jolly et al., 1998). MR fluid is a controllable fluid. Good amount of research has been carried out in recent years by many researches to determine the properties of MR fluids and their possible usage. Zipser et al. (2001) have described the flow behavior of MR fluids in narrow channels, influenced by variable magnetic fields and temperature. The yield shear stress increases with the increase of magnetic field and decreases proportionally to the temperature. Olabi and Grundwald (2007) have showed the excellent features of the art of an actuator with control of MR technology, like fast response, simple interface between electric power input and mechanical power output. 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 valve can be designed with the absence of moving parts. MR valve has been studied by researcher like, Yokota et al. (1999). They have proposed and fabricated a pressure control valve using MR fluid. The differential pressure and output power change of 0.68MPa and 20W were obtained with the input current and power change 710A.turns and 1.9W at the flow rate of $30cm^3/s$ (1.8L/min). Li et al. (2002) have developed a new type MR fluid relief valve. The construction and working principal of new type valve were introduced, and demonstrated that when input voltage is set to 24 volts and the flow rate is 10 l/min, the regulated pressure is 1Mpa. The regulated pressure can be adjusted by the variation of input voltage. Yoo and Wereley (2002) have designed the miniature MR valve with the maximum performance of MR fluid. They used low permeability premalloy steel material with their MR valve design with a 25.4 mm outer diameter. As a result the valve can achieved 1479.7kpa block pressure. However high permeability material, the size of the valve can be reduced and the active core length can be increased for higher blocking pressure. Li et al. (2003) have optimized the design of a high-efficient MR valve using finite element analysis. They investigated the effects of bobbin shaft, active core length and the thickness of the flux return on the magnetic flux density in the fluid gap. Ai et al. (2006) have come out a new concept of MR valve possessing simultaneously with annular fluid resistance channels and radial flow resistance channels. They observed that the efficiency of the MR valve with circular disk type gap is superior to that with annular gap with the same magnetic flux and the outer radius of the valve, but for MR valve possessing annular with disk type gaps simultaneously can surpass them. Nguyen et al. (2007; 2008) have presented the optimal geometric design of MR valves in order to improve valve performance, such as pressure drop. They showed that the wire diameter does not significantly affect the optimization solution and the limit to the achievable pressure drop of one particular valve type can be smaller or larger than that of valve type. The MR valve geometry has a significant effect on the valve performance such as pressure drop.

In this research, the new design of MR flow control valve is proposed. The main objective of this paper is to present the modeling, the finite element analysis using FEMM[R] software and the simulation of the MR valve design proposal.

2. MR VALVE DESIGN

In general devices that use MR fluids can be classified as pressure driven flow mode and direct shear mode. Valves, dampers and shock absorbers are categorized under pressure driven flow mode. Others are classified as direct-shear mode. Examples of direct-shear mode devices include clutches and brakes. Figure 1 shows these two classifications. The design consideration of the MR valve is carried out as follows. The mechanical energy required yielding the microstructure of MR fluid increases with the increases in magnetic field resulting the yield shear stress to increase as well. It is observed that MR fluid behaves like Newtonian fluids when there is no magnetic field applied. Hence in the presence of magnetic field, the MR fluid follows Bingham's plastic of flow, and the Bingham's equation :-

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

where τ is shear stress, τ_y is field dependent yield shear 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 preliminary equation is used to design the device with MR fluid based.

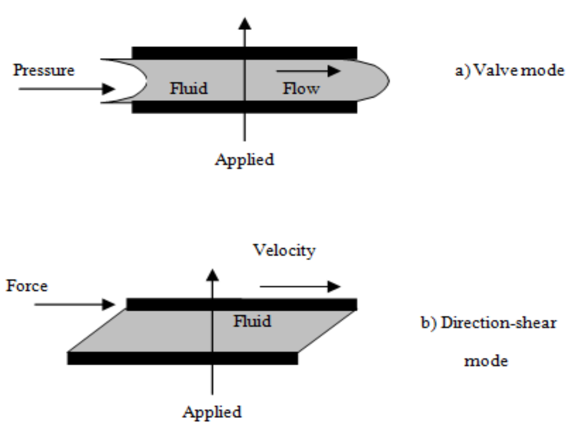


Figure 1 Basic operational mode for controllable fluid devices: (a) valve mode (pressure driven) and (b) direct shear mode.

At the design stage, many parameters including fluid gap g, bobbin diameter and flux return path length L_{steel}, the thickness of core and flux returns as well as the number of wire turns are considered. For better efficiency, the flux density B in the fluid gap should be maintained constant (Edward et al., 2008). The relative permeability of the MR fluid is much smaller than the permeability of bobbin, two cores and flux return, which are made up of low-carbon-steel. Consequently, a smaller fluid gap will be better. Practical gaps typically range from 0.25 to 2 mm for ease of manufacture and assembly (Yoo and Wereley, 2002; Li et al., 2003). In the present study, the gap is set to 0.5 mm. The new design of MR valve proposed in this work consisting of a steel path and a disc gap (hollow disc) with annular gap as shown in Figure 2. Basically the steel path consists of a bobbin, two cores and flux return. Mild steel 1006 are used suitable for steel path which has a high relative permeability of over 1000. In the present study the MR fluid property is considered according to the standard MRF-132DG (Lord Corporation 2005). The current applied is 1.6 Amp. The MR valve has been designed in this research with the coil is outside of the effective area so that it will be easier to replace the coil. The terminals of coil are easy to feed through. The overall body of valve length is short. Thus, it can be used in the future research work. The valve dimensions are given in Figure 2. The strength of the magnetic field will be determined by using finite elements method such as FEMM software.

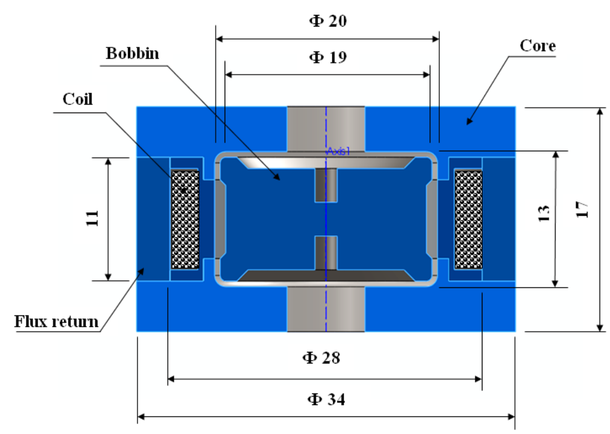


Figure 2 Schematic showing the Design and Dimensions of new MR valve

3. MR VALVE MODELING

The aim in modeling stage is to observed the pressure drop in the MR valve and one way to evaluate it is by summing the viscous component ΔP_η and yield stress component ΔP_τ. Manipulating Equation (1) gives pressure drop:-

$$\Delta P = \Delta P_\eta + \Delta P_\tau = \frac{12\,\eta\,QL}{wg^3} + \frac{c\,\tau_o\,L}{g} \qquad (2)$$

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). Equation (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 valve Equation (2) becomes:-

$$\Delta P = \Delta P_\eta + \Delta P_\tau = \frac{12\,\eta\,QL_g}{\pi g^3 r} + \frac{2c\,\tau_o\,L_g}{g} \qquad (3)$$

where L_g is annular gap length.
If it is applied to hollow disc gap, it becomes:-

$$\Delta P_c = \Delta P_\eta + \Delta P_\tau = \frac{6\,\eta\,Q}{\pi g^3} ln\frac{R}{r} + \frac{c\,\tau_y}{g}(R-r) \quad (4)$$

where R and r is the outer radius and the inner radius of the hollow disc gap respectively. When it is used to apply for annular and hollow disc gaps together, it becomes: -

$$\Delta P = 2\left[\frac{6\,\eta\,QL_g}{\pi R g^3} + \frac{c\,\tau_y\,L_g}{g}\right] + 2\left[\frac{6\,\eta\,Q}{\pi g^3} ln\frac{R}{r} + \frac{c\,\tau_y}{g}(R-r)\right] \qquad (5)$$

From Equation (5), there are three factors directly affecting a pressure drop. The first is the valve geometry which determines the geometric proportions of the model. The second factor is the flow rate Q and the third is the value of yield shear stress τ_y. The yield shear stress τ_y depends on the magnetic field (magnetic strength H) generated in the gap that contains the MR fluid, but it may be pointed out that the valve geometry is the major factor in determining the magnetic field. The necessary amp-turns (*NI*) can be determined using Kirchhoff's Law for the magnetic circuits as shown in equation below.

$$NI = \oint H.dl \qquad (6)$$

$$NI = \sum H_i * L_i \qquad (7)$$

$$NI = H_{fluid} * g + H_{steel} * L_{steel} \qquad (8)$$

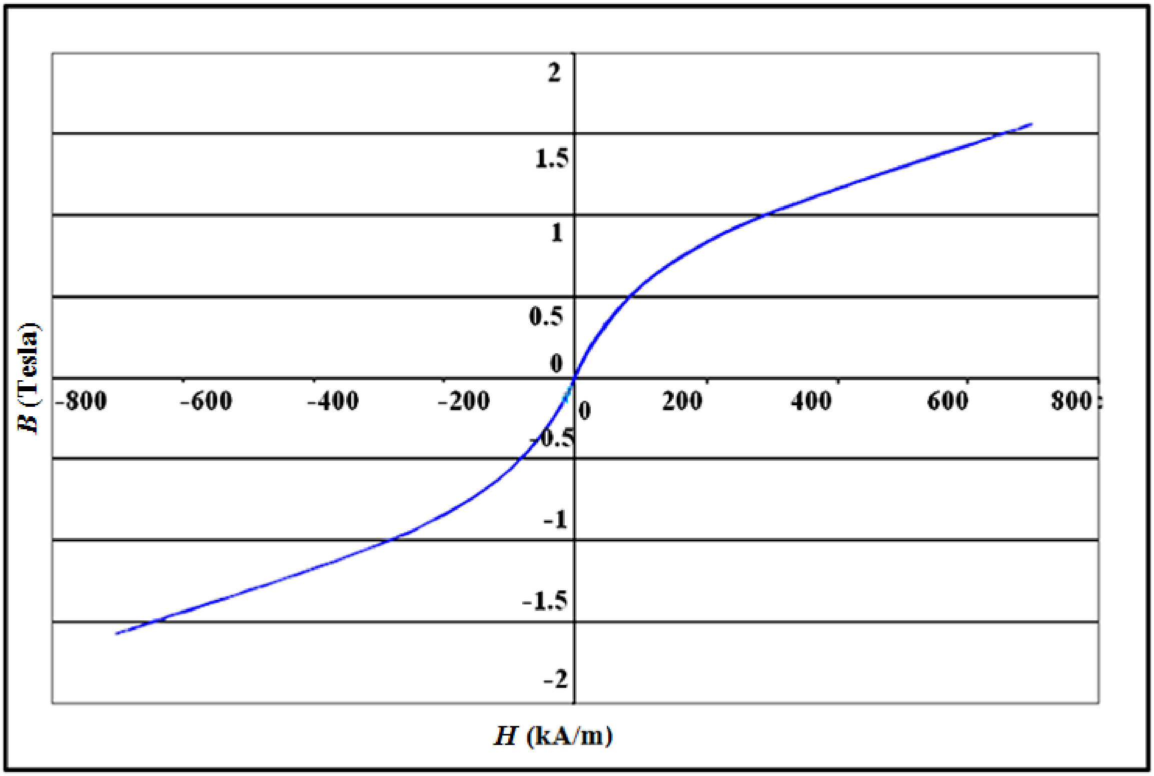
L_{steel} is the total length of steel path through which Magnetic Flux density B goes through. Cylindrical shape of MR valve has complex structure in magnetic analysis. Full optimization of the magnetic design is carried out by using magnetic finite element software (FEMM) capable of treating nonlinear materials.Due to symmetrical shape, the MR valve has been analyzed as a 2-D ax-symmetric model which is sufficient for dimensional analysis of the valve as depicted in Figure 2. From *BH* curve of MR fluid shown in Figure 3a, points (H, B) correspond to the MR fluid, as data for new nonlinear material. A finite element model of the magnetic circuit is developed. This is done using FEMM^R and the corresponding model is shown in Figure 4a. The magnetic strength H and flux density B are determined using FEMM^R shown in Figure 4b. The yield shear stress τ_y can be obtained from τ_y vs. H curve of MR fluid MRF-132DG (Lord Corporation 2005), as shown in Figure 3b. It can also be determined by using polynomial equation.

$$\tau_y = a_3\,B^3 + a_2 B^2 + a_1\,B + a_0 \qquad (9)$$

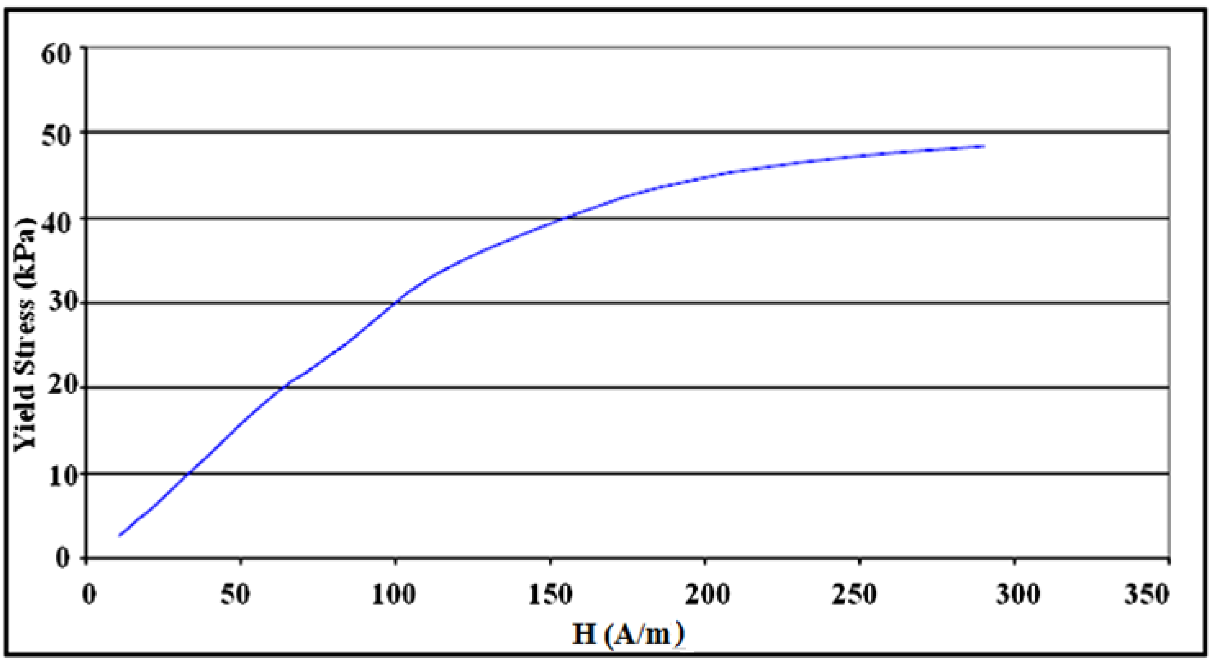
where a_0 = 0.877 kPa, a_1 = 17.42 kPa/T, a_2 = 122.56 kPa/T^2, a_3 = -86.51/ T^3 kPa

4. RESULTS AND DISCUSSION

The results of MR valve design analysis using FEMM software are shown in Figures 5a for magnetic flux density and Figure 5b for magnetic strength. The results are presented in terms of magnetic strength in the effective gap of the valve. The performance of the MR valve is limited by the finite yield stress of MR fluid (Yoo and Wereley 2002). From Figure 3b, the magnetic strength should be in the range of 200-230 kAmp/m where the yield shear stress is about 45kPa. In the present simulation the MR fluid 132LD by Lord Corporation was used, whose dynamic yield stress is approximated by equation (9). Figure 6 shows the relation between the current and magnetic flux density. The nominal plastic viscosity is assumed to be 0.25Pa.s. The simulation results are shown in Figures 7 and 8. In Figure 7, the magnetic flux density induced by different current of MR valve coil as a function of distance of valve gap are shown when g = 0.5mm (see the curve inside the crop area of Figure 7). Figure 7 shows that, all magnetic flux density is almost fixed along distance of valve gap and increases with the increase of current of valve coil. To maximize the controllability of the magnetic field, the design of valves has to be taken into account that the maximum magnetic field does not exceed the saturation magnetic field strength of the MR fluids. Figure 8a, shows the variation of the pressure drops induced by the MR valve with the flow rate at different current values. The pressure drop and flow rate is measure in Pascal and cm^3/sec respectively. It is observed that the pressure drops by the MR valve increases with the increase of the current when the flow rate of the MR fluids ranges between 2 and 100 cm^3/s. Figure 8a demonstrates that the pressure drop induced by the MR valve increases slightly and gradually with the increase in the flow rate, which indicates that the pressure drop of the MR valves are induced mainly by magneto-rheological effect in the magnetic field.

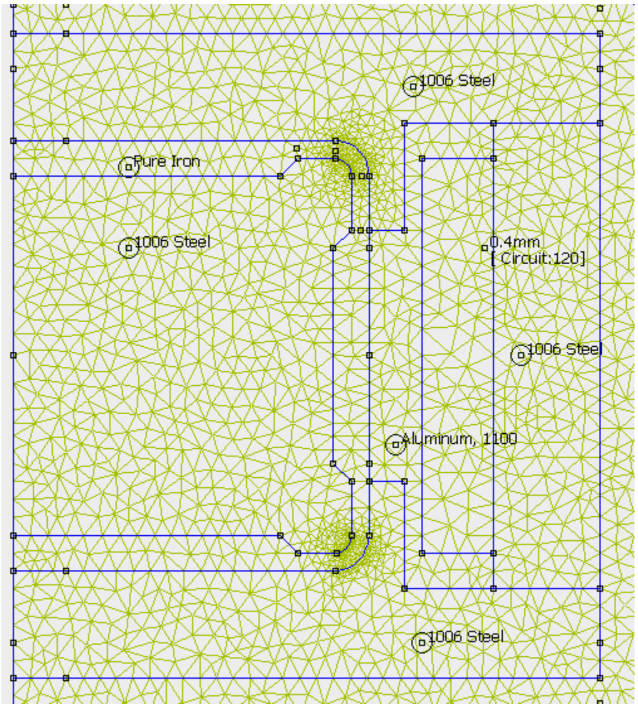


a) Magnetic field B vs. Magnetic field strength H

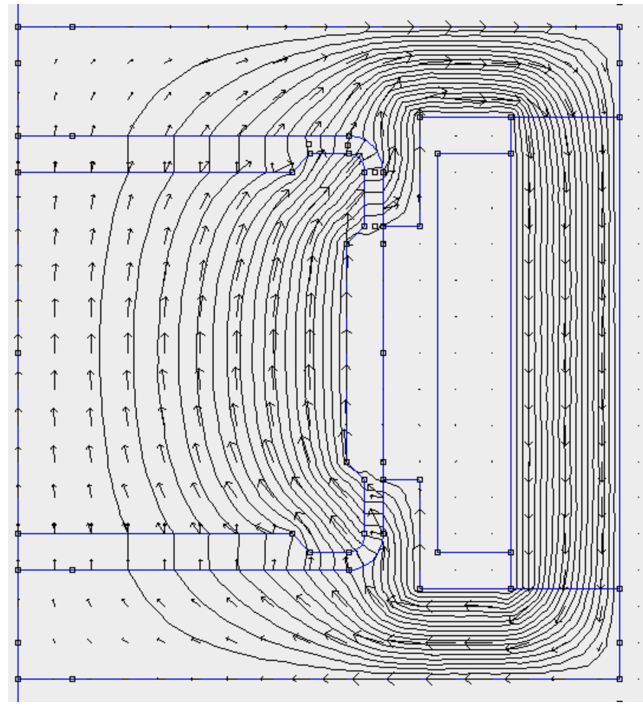


b) Yield stress vs. Magnetic field strength

Figure 3 Specification of MR fluid type MRF-132DG (Lord Copr.2005)

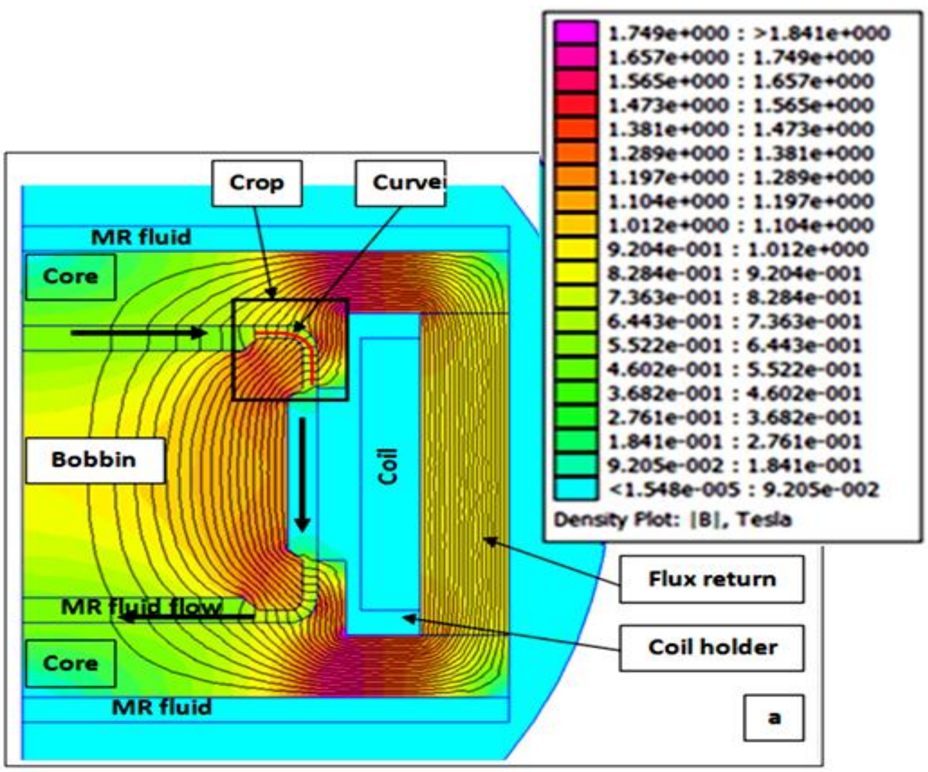


a) Element model and mish for new MR valve

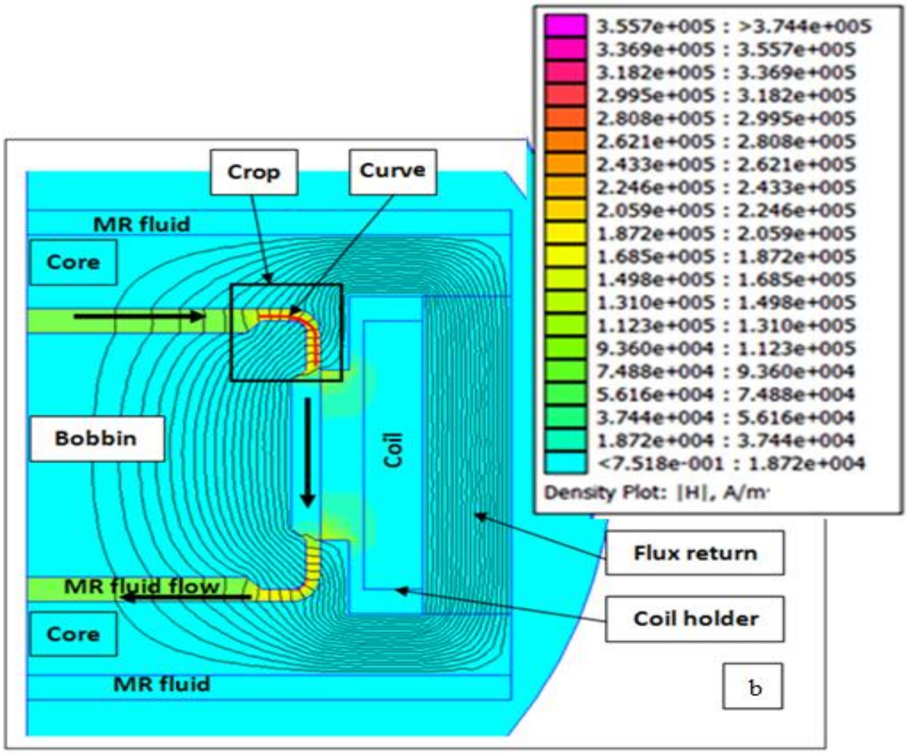


b) Direction of magnetic field of new MR valve

Figure 4 Finite element model of the magnetic circuit for a new MR valve



a) Magnetic flux density



b) Magnetic strength

Figure 5 Results data of FEMM for new MR valve

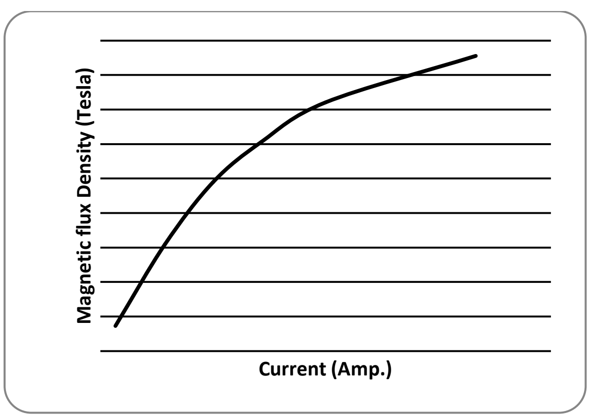


Figure 6 Relation between magnetic flux density and current for new MR valve

The variation of the flow rate of MR valve with the variation of the current under different pressure drop as shown in Figure 8(b). The current is measure in Ampere. From the graph, it is clear that the flow rate of MR valve experienced sharp decreases of flow rate for current ranging from 0A to 1A and shows a slight drop in flow rate from 1.5A to 2.5A for all value of pressure drop. This pattern indicates that the flow rate of the MR valves are affected mainly by magnetic field caused by the current applied to the coil. It may be observed from the graph that the effective region at which the valve is completely closed is at 1.5A and the pressure is 1500kpa. Beyond 1.5A the pressure drop is not significant. Hence, it maybe suggested that the maximum operating current is set to 1.5A. It may be pointed out that the way the valve is operated by changing the current to the coil and the value of flow rate will change accordingly. To justify the simulation work, the experimental test was done. Figure 9 shows the comparison between the simulation and experimental data. The Figure shows the relations for different pressure drops 3, 7, 11, 13.5 bar. In the graph the data for each pressure were allocated. Practically, it is clear that the flow rate of MR valve decreases with the increase in the current, which indicates that the flow rate of the MR valves are effected mainly by magnetic field which is affected by the current of the coil. It is noted that the decreasing of flow rate is almost linear for all level of current. It is same for all pressure drop curves. It can be seen that there are little bit difference in value for each pressure drop and fluctuation in value but reasonable. The maximum error percentage between experimental and simulation is about 11.7% among all curves. The aim for the proposed MR valve in this study has been proven to achieve a best performance.

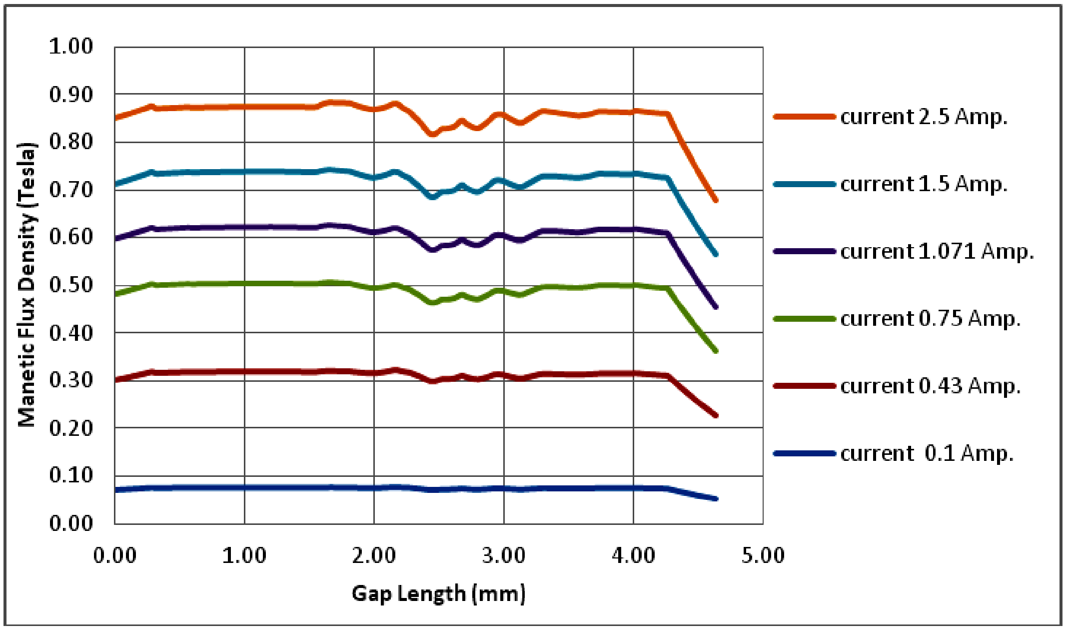
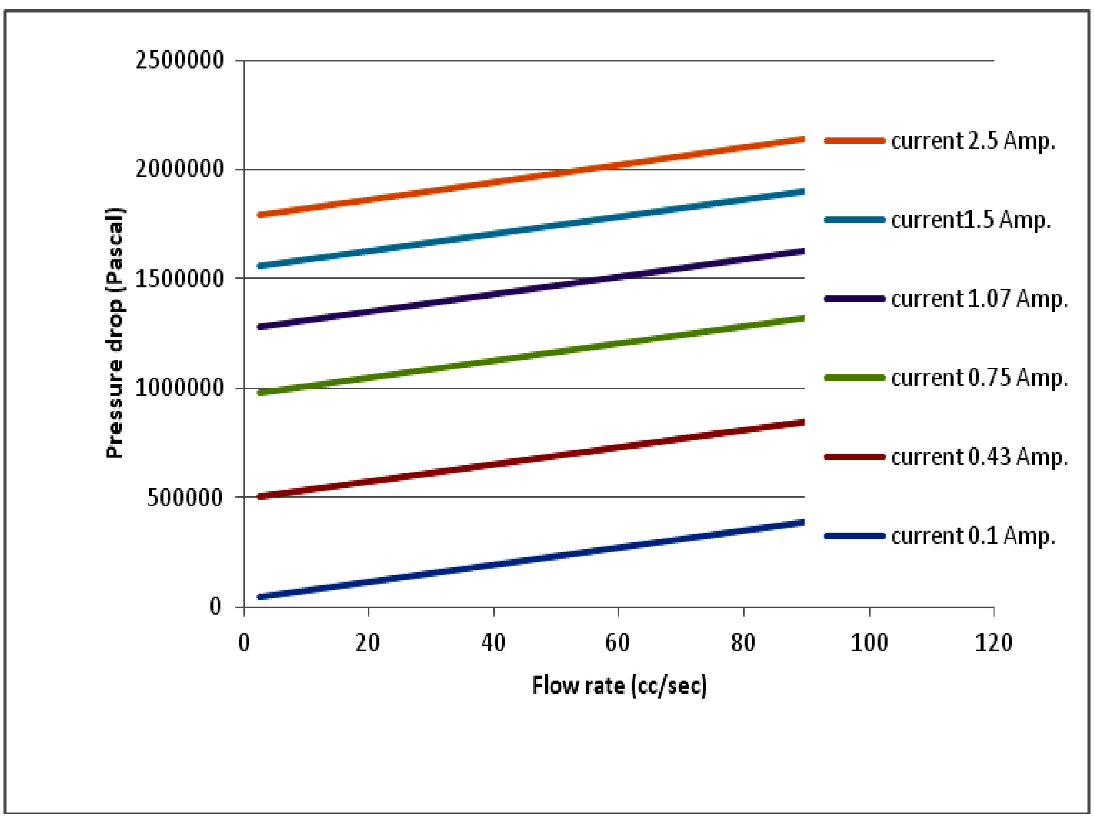
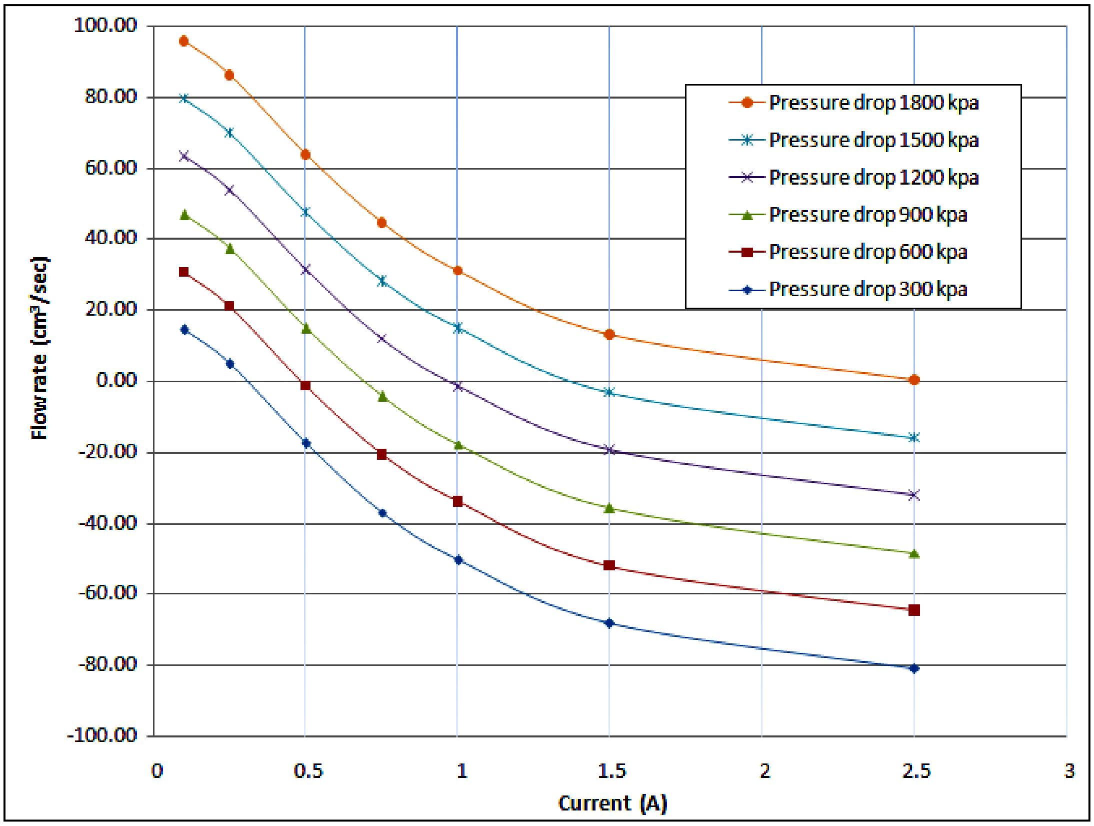


Figure 7 Magnetic flux density along the curve in the gap of MR valve for different current



a) Relation between flow rate and pressure drop for different current



b) Relation between current and flow rate for different pressure drop

Figure 8 Simulation results of new MR valve

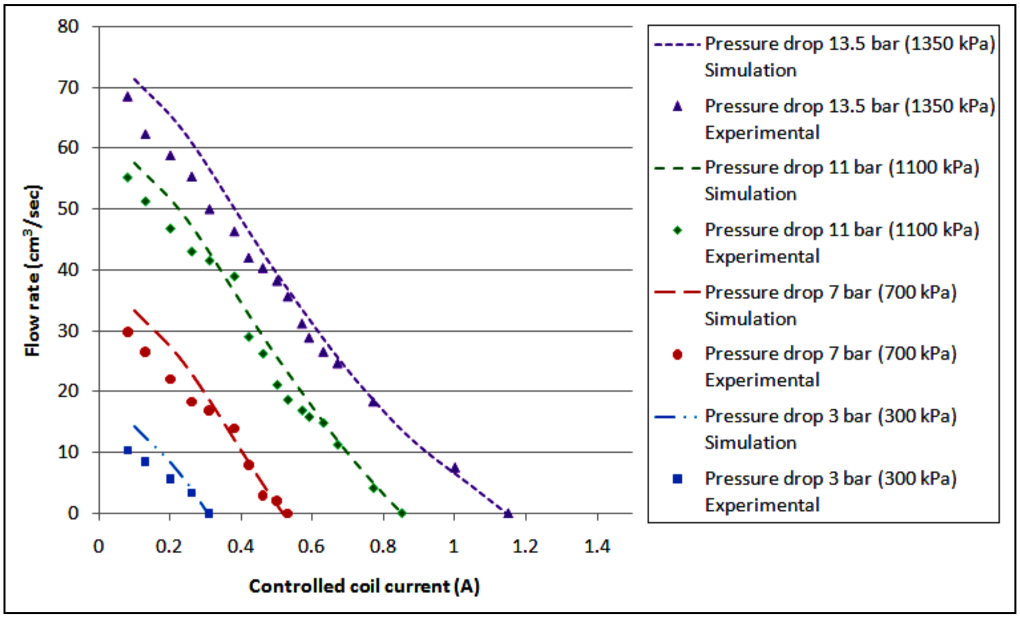


Figure 9 Comparison between experimental data and the simulation

5. CONCLUSION

In the present work, the MR valve performance has been optimized. It is proven that the design has achieved exceptional magnetic field strength in the valve gap and a constant value of magnetic flux density along the valve gap. Although the MR valve is smaller and shorter in profile, it deliver exceptional magnetic field, i.e. the optimum possible value for yield shear stress. Having the smaller valve module means the space can be optimized and the coil's position located at outside the working area for easy access and maintenance. The simulation results based on the proposed models has proven that the flow rate show a significant drop with the increase of current, on the other hand and the pressure drop shows a significant increase upon the increase of current. Note that, the flow rate that is induced by the MR valve decreases with the increase in the current. So, it is observed that the current is inversely proportional to the flow rate. Hence, MR valve can be operated with variable flow rate Q by changing the value of the current.

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REFERENCES

Ai, H.X., Wang, D.H. and Liao, W.H. 2006. Design and Modeling of a Magnetorheological Valve with Both Annular and Radial Flow Paths, Journal of Intelligent Material Systems and Structures 17: 327

Edward, J. Park, Falca˜o da Luz, Luis and Suleman, Afzal. 2008. Multidisciplinary design optimization of an automotive magnetorheological brake design, Computers and Structures, 86 207–216

Jolly, M.R., Bender, J.W. and Carlson, J.D. 1998. Properties and Applications of Commercial Magnetorhological Fluids 5th Annual Int. symposium on Smart Structures and Materials, San Diego, A.

Li, S., Wang, G., Chen, D. and Li, S. 2002. New type relief valve using Mgneto-Rheological fluid, Report of Harbin Institute of Technology Harbin, China

Li, W.H., Du, H. and Guo, N.Q. 2003. Finite Element Analysis and Simulation Evaluation of a Magnetorheological Valve, The International Journal of Advanced Manufacturing Technology 21: 438–445.

LORD Corporation. 2005. Hydrocarbon-Base MR fluidMRF-132DG Product Bulletin.USA

Nguyen, Q.H., Choi, S.B. and Wereley, N.M. 2008. Optimal design of magnetorheological valves via a finite element method considering control energy and a time constant, Smart Materials and Structures 17:12.

Nguyen, Q.H., Han, Y.M., Choi, S.B. and Wereley, N.M. 2007. Geometry optimization of MR valves constrained in a specific volume using the finite element method, Smart Materials and Structures 16: 2242–2252

Olabi, A.G. and Grunwald, A. 2007. Design and application of magneto-rheological fluid, Materials and Design 28: 2658–2664.

Yokota, S., Kazuhiro, Y. and Yutaka, K. 1999. A pressure Control Valve Using MR Fluid, Proc. Forth JHPS-ISFP Tokyo 99:377-380.

Yoo, J.H. and Wereley, N.M. 2002. Design of a High-Efficiency Magnetorheological Valve, Journal of Intelligent Material Systems and Structures 13: 679.

Zipser, L., Richter, L. and Lange, U. 2001. Magnetorhologic fluids for actuators, sensors and Actuators A 92: 318-325.