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Performance Simulation Analysis for Magnetorheological Damper with Internal Meandering Flow Valve

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ABSTRACT

Magnetorheological (MR) damper as a semi-active system for a vehicle suspension is simulated in this study. The proposed design of Magnetorheological (MR) valve consists of meandering flow channel or gaps that fixed in the piston of the damper. The focus of this study is to estimate the performance of proposed MR valve based on actual front suspension parameter of a vehicle. Annular and radial gaps are combined to produce an MR valve with meandering fluid flow path. Furthermore, the damper is filled with Magnetorheological (MR) fluid to energize the damper under the presence of magnetic fields. The magnetic flux density within each gap is obtained via the Finite Element Method Magnetics (FEMM) software. Therefore, the yield stress of MR fluid and magnetic flux relationships both can be predicted. The present paper shows a reduction in pressure drop when the thickness of each gap is increased. Pressure drop is closely affected by the fluid flow rate that enters each gap. This means that the lower flow rate increases the pressure drop of MR valve at various current.

Keywords: MR damper; MR valve; MR fluid; suspension system; displacement.

INTRODUCTION

Magnetorheological (MR) fluid can be classified as one of ‘smart material’ where the rheological of fluid behavior changes under an appearance of the magnetic field. The MR fluid can be made by mixing the carbonyl oil with micron-sized iron particles. The iron particles that immersed in MR fluid can be measured between 1 µm and 10 µm [1]. The rheological fluid properties are very sensitive to the magnetic field [2–6]. This fluid was introduced by Rainbow’s in 1948 for magnetic clutch [7] and started its growth widely in automotive industry in the past decade [8]. When a magnetic field is given, the fluid response time can be estimated within ten milliseconds due to its abilities to provide a simple, fast and robust interface between mechanical components with electronics controls [9]. When exposed to a magnetic field, the iron particles align like a chain structure within milliseconds thus increasing the yield strength of the fluid [10]. Furthermore, the stiffness of MR fluid can be varied by controlling the magnetic field strength. MR fluid has been applied in numerous automotive components such as vehicle clutch, braking, steering, suspension, clutch, and engine mounting system [11–15]. One of the well-known devices that employ MR fluid is Magnetorheological (MR) damper [16–18]. MR damper has since existed as a semi-active and active suspension for high-end passenger vehicles [19].

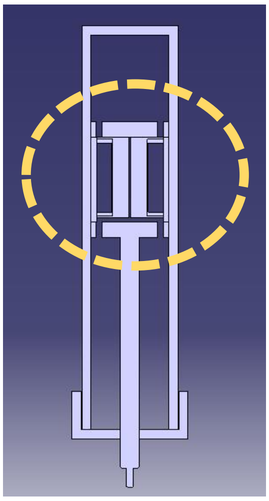
The concept of MR damper working principle is like a viscous MR damper (passive damper) which uses flow restrictions to generate damping force. The conventional viscous damper uses an orifice channel which acts as a valve for flow limiter. The flow restrictions of conventional passive damper are fixed since the orifice channel of the valve is fixed. In the MR damper, MR valve gap size of each channel can be fixed, and only the magnetic field strength in the flow channel can be regulated [20]. Total performance of MR damper hinges on the performance of MR valve to generate higher flow restriction.

Many designs of MR valve for the MR damper was proposed before. Previously, stand-alone MR valve was proposed by Kordonski [21] and expanded by Gorodkin [22] as passive damping systems for MR throttle valve. A control valve using MR fluid for fluid control systems was proposed by Yokota [23] which contains an electromagnetic coil fitted next to the flow channel. Next, a three-port small-sized MR valve using a permanent magnet to minimize the valve size was enhanced by Yoshida [24] for a bellows-driven motion control system. Furthermore, the performance assessments of MR valve annular and orifice type were achieved by Grunwald and Olabi [1] through the performance analysis of the of MR valve. Then, the MR valve type was researched by Ai [25] and Wang [26] through MR valve design with both annular and radial flow path. Imaduddin [27] proposed using the multiple annular and radial gaps of a compact external MR valve which gave higher achievable pressure drop by keeping the outer valve diameter. In 2016, the meandering flow path of a modular MR valve was proposed by Ichwan [28] to evaluate the pressure drop rating of modular structure in three different modular stages.

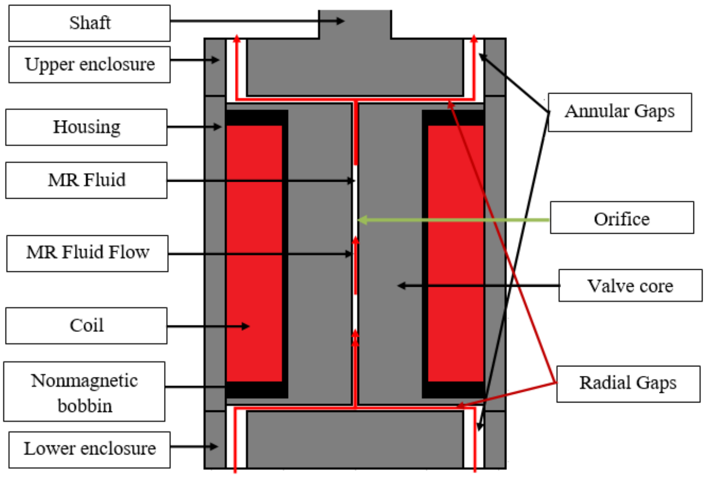
The purpose of this paper is to design and develop meandering flow path of internal MR valve by combining annular and radial gaps for the MR damper as vehicle suspension. The design of MR valve for the magnetic damper simulation of MR valve was simulated using Finite Element Methods Magnetic software to obtain the magnetic flux densities within MR valve gaps. The simulation result from FEMM is used to predict the yield stress of MR fluid in the simulation of MR damper. Finally, the performance of MR valve is discussed towards the end.

MR VALVE STRUCTURE

The preliminary design of the MR valve of the damper is shown in Figure 1(a). MR valve contains several components such as a damper shaft, upper and lower enclosure, valve core, non-magnetic bobbin, cylinder and upper cap. CAD software, CATIA V5, is used to design the overall components of the MR damper and detail design is given in Figure 1(b). The dimension of MR valve is based on the front suspension of Proton Waja. The mild steel American Iron and Steel Institute (AISI 1010) is used to fabricate MR valve components due to its better magnetic properties. Moreover, this mild steel is selected because of good magnetic properties which contain 8 – 13 % of carbon and also considering its cost, permeability, and availability [29].



(a)



(b)

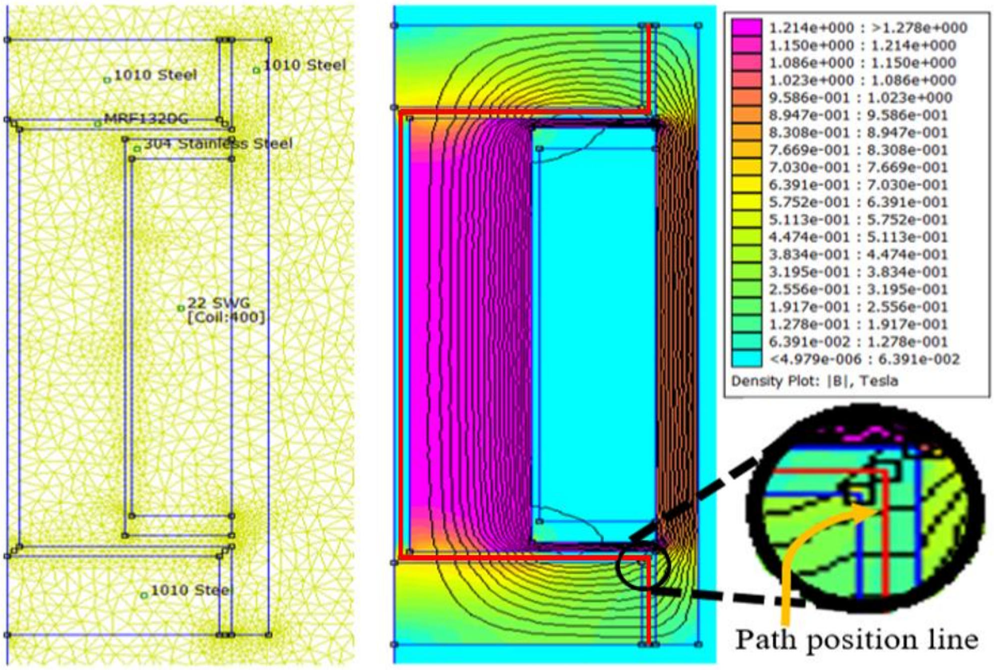
Figure 1. MR valve (meandering flow path); (a) design and; (b) components.

Figure 1(b) shows the annular and radial flow of MR fluid, which flow from lower to the upper gap channel or commonly known as compression stroke. The white area (effective area) represents the flow gap of MR fluid. The thickening of MR fluid depends on the presence of magnetic field. To avoid fluid leakage from entering the coil bobbin, the valve core that embedded with coil bobbin is sealed to the inner housing wall. Moreover, the thickness of the radial gap can be adjusted by using a circular plate with a thickness of 0.5 mm concerning the available radial gap size. However, the annular gap is fixed because the damper shaft is attached to the upper enclosure.

MAGNETIC ANALYSIS

The simulation of magnetic flux densities using FEMM is done to estimate the presence of the magnetic field in the active area of the proposed valve. Generally, this technique is commonly used initial design process of MR devices [18, 27]. Furthermore, the apparent of the magnetic field is hard to measure experimentally and needs to be simulated used FEMM to predict the magnetic flux distribution [28]. In this model, structural and thermal responses are neglected. The magnetic circuit analysis is the easiest method to estimate the MR effect that can be provided by the fluid. The material for valve core, upper enclosure, lower enclosure and valve housing are assigned using low carbon steel (ANSI 1010) because of its better magnetic penetration. In order to prevent the magnetic copper wire from contacting the steel, non-magnetic material stainless steel type 314 is used for the coil bobbin.

In this study, there are several variables that need to be assigned to conduct the simulation. The coil is made using copper wire (type 22 SWG) with the diameter of the coil is 0.71 mm with 400 turns which results to 1.53 Ohm coil resistance from the magnetic analysis. In this analysis, the current is limited to 1 A and 1.53 watts of MR valve power consumptions. Next, the MR valve is modeled in FEMM using two-dimensional axis-symmetry by selecting triangular elements. Based on the simulation, total element number is 10818, and total node number is 5578 are obtained and shown in Figure 2(a). The contour of magnetic flux density is shown in Figure 2(b) where the flux lines covered the active area of the valve. As such, the yield stress of MR fluid for each gap can be influenced when magnetic flux passes through the gaps. The flux across each gap is known as the active area where the flux lines cross the annular and radial gaps without losses. The rheological behavior of fluid can be changed by altering the current input. However, there are no magnetic flux densities passed in the orifice gap. In addition, the meandering of the MR valve means that MR fluid has to pass a 90° junction to cross from annular channel to radial channel. The combination of annular and radial valve mode is identified as, one of the potential methods to increase the pressure drop for the internal MR damper thus improving the damping force [27].



(a) (b)

Figure 2. The predicted magnetic flux density of MR valve; (a) axis-symmetry model, and (b) 2D flux lines.

The results of magnetic simulation as shown in Figure 3 is focusing on the fluid flow path. The magnetic flux density values consistency increases with respect to the increase of the current input from 0.2 to 1.0 A with an increment of 0.2 A. The value variation of magnetic flux density can be defined as the variance magnetic flux density for the outer annular upper and lower gap, inner radial for upper and lower gap and orifice gap. The higher magnetic flux density can be seen in radial gap compared to the annular gap and orifice gap obtained from FEMM. The magnetic flux density occurred at the annular gap is 0.187 T, and the radial gap is 0.718 T when 1 A current is given. Based on proposed design, the radial gap provides more magnetic flux density by 79 % compared to the annular gap at 1 A current input.

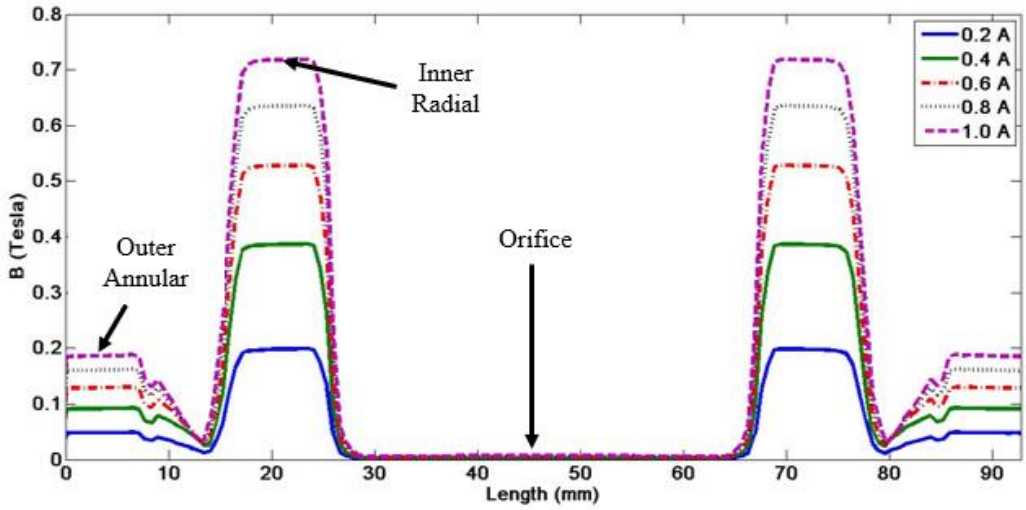


Figure 3. Predicted magnetic flux density within an active area from FEMM.

Next, the yield stress of MR fluid gathered from the simulation is used to estimate the magnetic flux density in the active area. The value of the yield stress for the MR fluid is depending on the magnetic field that is given to the MR valve. Meanwhile, the yield stress characteristic of MR fluid can be varied by adjusting the apparent magnetic field to the valve. The data from the commercial type of MRF-132DG was used in this study [30]. The magnetic flux density and the yield stress relationship of MR fluid type (MRF-132DG) can be approached via third-order polynomial equation in Eq. (1)[28]:

$$\tau_y(B)=\begin{cases}-58.92B^3+74.66B^2+58.92B-3.387, & \text{for } (B)>0\\ 0 & \text{, for } (B)\leq 0\end{cases} \quad (1)$$

where τ_y (B) is the yield stress of MR fluid depending on the magnetic flux density (B) that can be varied. Subsequently, the magnetic flux density within each area of annular, radial and orifice gap is different. Thus the estimated yield stress of fluid should be different. Besides, the pressure drop calculation of each gap can be directly calculated by using a different governing equation. The governing equation of MR valve for the damper can be separated into three different categories which are annular, radial and orifice. The yield stress can be estimated as exposed in Figure 4 based on the fluid flow route of magnetic flux density shown in Figure 3. The pattern variation of yield stress is shown in Figure 4 to be similar to the magnetic flux density obtained in Figure 3. The mean value of the yield stress of the outer annular upper and lower, and inner radial upper and lower is about 8.8 kPa and 42 kPa respectively. However, the yield stress occurred at orifice gap can be neglected due to zero magnetic flux passed through the orifice gaps [31].

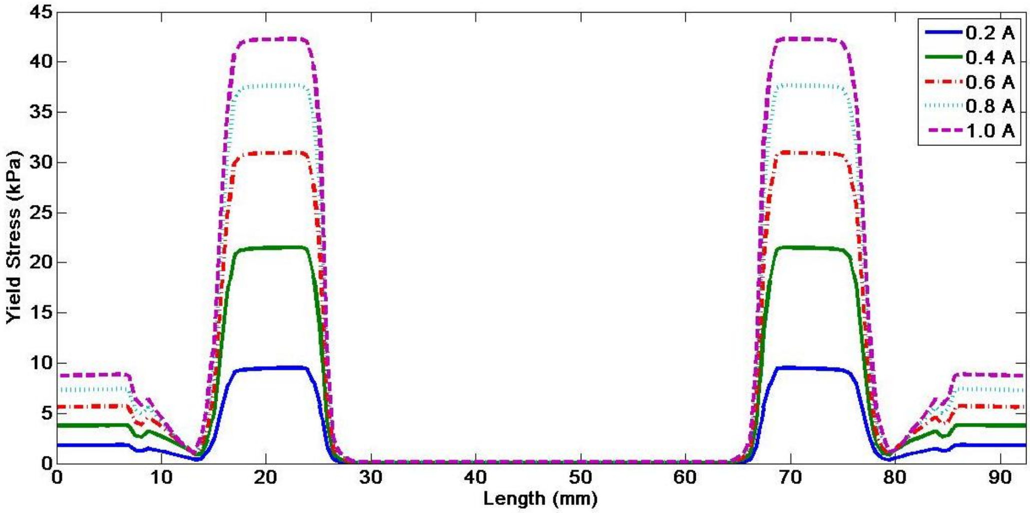


Figure 4. Predicted yield stress within an active area of MR valve.

PREDICTED PERFORMANCE MR VALVE

The MR valve performance is determined by two factors which is the pressure drop due to fluid viscosity and pressure drop due to the apparent magnetic field. The pressure drop is due to fluid viscosity depending fluid viscous and flow rate that enters MR valve. Second, the pressure drop due to the applied magnetic field where the yield stress of fluid can be altered by adjusting the magnetic field. The pressure drop of proposed MR valve for the damper is described by Eq. (2) to (6) [27].

$$\Delta P_{valve}=\Delta P_{annular_{upper}}+\Delta P_{radial_{upper}}+\Delta P_{orifice}+\Delta P_{radial\_lower}+\Delta P_{annular\_lower} \tag{2}$$

$$\Delta P_{valve}=2\Delta P_{annular}+2\Delta P_{radial}+\Delta P_{orifice} \tag{3}$$

$$\Delta P_{annular}=2\left[\frac{6\eta Q L_a}{\pi {d_a}^3 R_a}+\frac{c\tau(B)L_a}{d_a}\right] \tag{4}$$

$$2\Delta P_{radial}=2\left[\frac{6\eta Q}{\pi {d_r}^3}\ln\left(\frac{R_0}{R_i}\right)+\frac{c\tau(B)}{d_r}\left(\frac{R_0}{R_i}\right)\right] \tag{5}$$

$$\Delta P_{orifice}=\frac{8\eta Q L_o}{\pi {d_o}^4} \tag{6}$$

The factor that highly influences the achievable pressure drop is the magnetic field strength and the thickness of gap size for annular and radial. The MR valve model has been estimated by using FEMM analysis by various magnetic field strength where the yield stress of fluid can be predicted by the results of the simulation. The specification data of MR fluid type 132DG shows that the magnetic field strength and yield stress of the fluid have a non-linear relationship between of them. The MR valve parameter is listed in Table 1 where this parameter will be assigned as an actual parameter in the simulation model.

Table 1. MR valve parameters.

Parameter	Description	Units	Value
η (MRF-132DG)	Fluid viscosity	Pa.s	0.112
Q	Flow rate	mL/s	15-30
L_o	Orifice channel length	mm	40
L_a	Annular channel length	mm	8
$d_{a=}d_r$	Annular and radial gap size	mm	0.5-2.5
d_o	Orifice gap size	mm	4
R_1	Outer radius radial	mm	16
R_i=R_o	Inner/orifice radius radial	mm	2

Since each gap has different yield stress value, so the pressure drop that is produced for each area will be different. The equation derived in the mathematical model previously is used to estimate the MR valve performances for the damper as shown in Figure 5 and Figure 6. Based on performance observation, the outer annular gap has the lowest pressure drop compared to the inner radial at 1.0 A current as shown in Figure 5. The outer annular has the lowest pressure drop due to the small magnetic flux passing through the gap but still contributed to providing pressure drop. When zero current is given to the coil, the only pressure drop is coming from the fluid viscosity resistance in the valve. However, as mention before, the pressure drop of orifice gap can be neglected due to zero magnetic flux is passed through the orifice gaps [1, 31, 28]. Moreover, the pressure drops produced by MR valve is decreasing when the gap size increased as shown in Figure 6 at a constant value of flow rate (Q = 15 mL/s). The decrease of the resistance gap will slow down the fluid that passed through each gap [25].

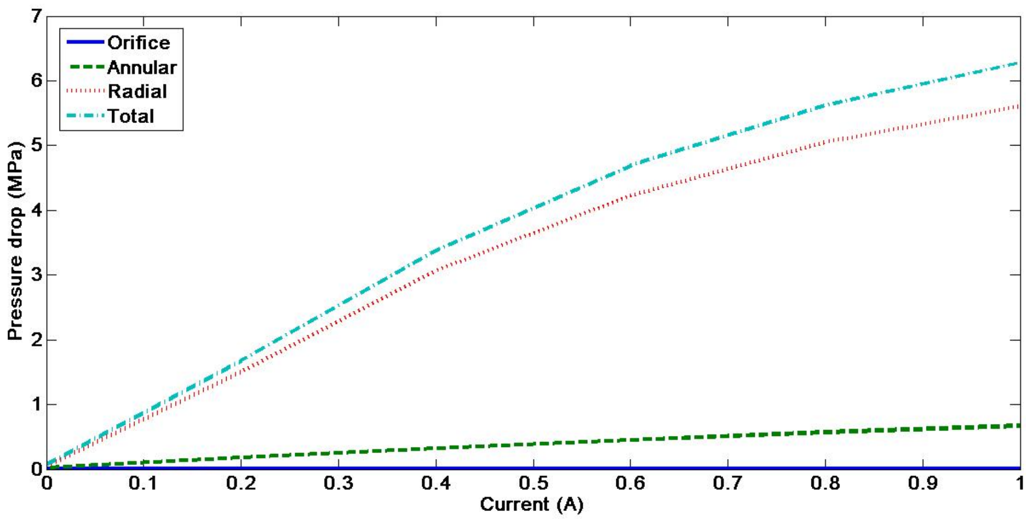


Figure 5. Pressure drop prediction in each gap

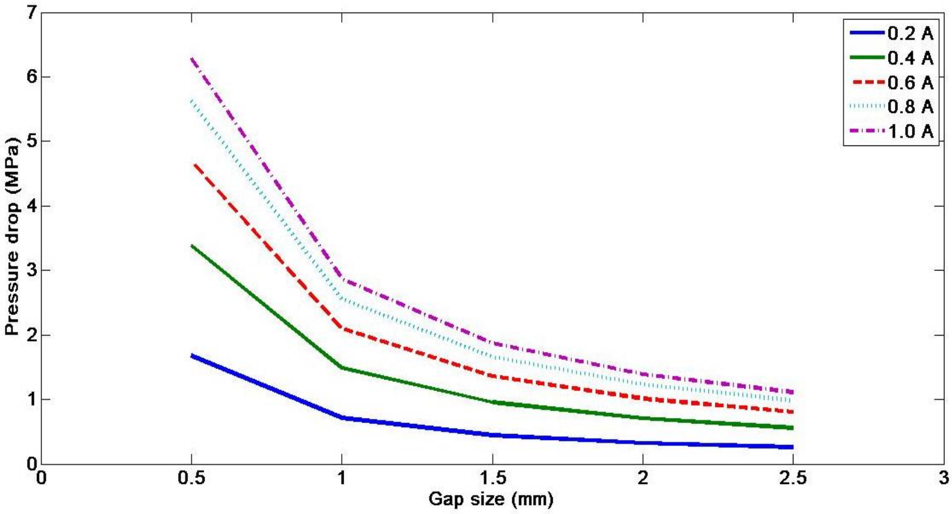


Figure 6. Prediction of pressure drop by varying gap and current input

The relationship between the pressure drop and flow rate in the MR valve by changing the flow rate from 5 mL/s to 30 mL/s is shown in Figure 7. The gap size for both annular and radial is 0.5 mm, while the orifice gap remains constant. The minimal thickness is chosen based on the parameter that has been studied by another researcher which shows the higher achievable pressure drop by the proposed MR valve [28, 31, 32]. Moreover, by changing the flow rate that enters the MR valve gaps, the higher value of achievable pressure drop can be obtained. As seen in Figure 7, the viscous pressure drop is proportionally increased when increasing the flow rate that enters MR valve. At the current input of 1A, the predicted pressure drop for 30 mL/s of flow rate is 6.7 MPa compared to the lower pressure drop for the lower current input which is about 1.86 MPa.

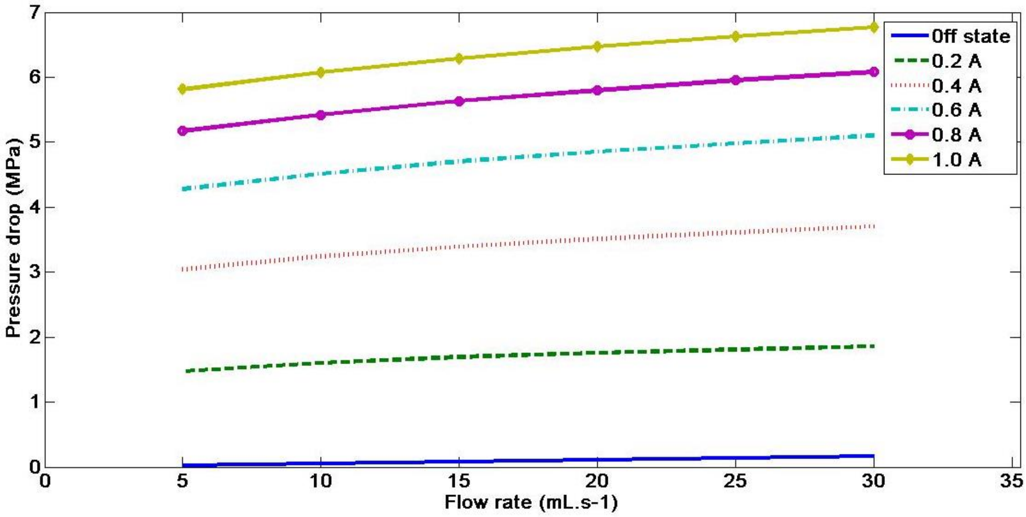


Figure 7. Prediction of pressure drop by changing flow rate and current input.

CONCLUSION

The meandering flow path of MR valve for internal MR damper is successfully presented. The proposed modeled of MR valve was model by FEMM software to study the field response of MR fluid in the active area. Based on the simulation result, it can be concluded that the radial gap provides more magnetic flux density compared to the annular gap at 1.0 A current input. Moreover, the pressure drop is increased due to the slower fluid flow that passed through each gap when the gap is reduced due to the various current inputs.

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