Performance prediction of serpentine magnetorheological valves under various gap size

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Abstract. Magnetorheological (MR) valve is one of the key components in regulating the magnetorheological (MR) fluid flow in MR devices. Due to MR properties enabling magnetic modifications, many MR valve designs have been introduced and are widely utilized in MR devices. Serpentine MR valve has a potential in improving the MR devices performance, whereby using this method it can help to increase the effective region of the valve. Thus, this article is comparing the pressure drops generated under various gap sizes in the effective regions of MR valve. Three different gap sizes are considered for this study. To provide a fair comparison, several parameters are fixed; the size of the MR valves, the number of coil turns and the power consumption. In order to demonstrate the MR valve performance, the pressure drops are calculated based on the mathematical equations derived from MR valve models and the magnetic fields derived from Finite Element Method Magnetics (FEMM) software. The results of the simulations are compared to various gap sizes and, discussed.

1 Introduction

Recently, applications and devices utilizing magnetorheological (MR) fluids are experiencing a rise due to its property uniqueness of magnetic controllable and fast-response rheological change with the magnetic field. MR fluid is a type of smart material where the viscosity of the fluid increases when the magnetic field increases [1]. Currently, MR fluid devices use several modes of operations, and the most commonly used is the valve mode, which is also known as MR valve [2–7]. A conventional MR valve usually includes an electromagnetic coil to generate the magnetic field intensity. With the use of electromagnetic circuit, the
pressure drop of the MR valve can be increased by raising the current in the electromagnetic circuit, which in turn increases the magnetic field strength.

The valve dimensions and configurations had been observed to affect the performances of the MR valve [3]. Researchers have developed several studies on the geometrical arrangements, which utilizes the gaps for the fluid flow path known as annular and radial gaps [8]. An annular gap is a flow channel that allows the MRF to flow axially in the MR valve and the placement of it is parallel to the inlet and outlet of the valve. Meanwhile, for the radial gaps, the fluid flows transversely in a radial manner, forcing the fluid to flow perpendicular to the inlet and outlet of the valve. The applications of these two gaps have been established in the MR devices [9–11]. The progress of the MR valve studies also continues with a new type of configuration which is the serpentine configuration [5,12]. The magnetic flux in the design of serpentine MR valve is weaved into the annular gap by alternating the non-magnetic and magnetic materials. Previous study only investigate two gap sizes for the serpentine configuration therefore to widen the variations of the gap size, three gap sizes are considered [5].

One study reported a methodology in configuring and comparing different MR valve configurations using analytical models and Finite Element Analysis [FEA] [13]. This type of analysis is remarkably time consuming with various processes involved in the evaluation to determine the most suitable design for a particular application. In order to shorten the process, this study aims to compare the pressure drop generated by each types of MR valves involved (no previous mention on how many valves are involved). The operating range (of what?) and the pressure magnitude (pressure drop?) are also discussed. Thus, the analysis serves as a basis in selecting or designing tools for MR valves.

2 MR valve modelling

The performance of an MR valve is analyzed based on its capability and flexibility in producing the pressure drop between upstream and downstream sides. Valve ratings are mainly determined by the pressure drop hence the mathematical modelling of pressure drop is used for each configuration in each section. The basic expression of the pressure drop in the MR valve is observed as [14]:

\[ \Delta P = \Delta P_{\text{Viscous}} + \Delta P_{\text{Yield}} \]  

where, \( \Delta P_{\text{Viscous}} \) and \( \Delta P_{\text{Yield}} \) are the viscous and field-dependent yield stress of pressure drop. The mathematical expressions of viscous and field dependent pressure drop for annular and radial flow path are observed as [3,15]:

| Gaps     | Viscous                  | Yield                      |
|----------|--------------------------|----------------------------|
| Annular  | \( \Delta P_{\text{Viscous}} = \frac{6}{\pi d^3} \frac{Q L}{R} \) | \( \Delta P_{\text{Yield}} = \frac{c \tau (B) L}{d} \) |
| Radial   | \( \Delta P_{\text{Viscous}} = \frac{6}{\pi d^3} \ln \left( \frac{R_0}{R_i} \right) \) | \( \Delta P_{\text{Yield}} = \frac{c \tau (B)}{d} \left( R_0 - R_i \right) \) |

where \( d \) is the valve gaps for both annular and radial gaps, \( \nu \) is the fluid base viscosity, \( Q \) is the flow rate, \( L \) is the annular channel length of the valve, \( R \) is the channel radius, \( \tau (B) \) is the field dependent yield stress value and \( c \) is the flow velocity profile coefficient. Also the \( R_0 \) and \( R_i \) referring to the inner and outer radius of radial gaps respectively.
The coefficient of $c$ can be obtained through the calculation of ratio between viscous pressure drop and the total pressure drop as seen following[3]:

$$c = 2.07 + \frac{12Q}{12Q + 0.8\pi R d^2 \tau (B)}.$$  \hspace{1cm} (2)

Meanwhile, for the equation on the orifice gaps, the expression is slightly different since there is no field dependent yield stress on the MR fluid. The pressure drop equation of orifice gaps solely expressed in viscous resistance as shown [2]:

$$\Delta P = 2 \frac{8 Q L}{\pi R^4}.$$  \hspace{1cm} (3)

3 MR valve configuration
In this research paper, the strength of magnetic flux densities was evaluated to predict the performance of MR valve. The magnetic field strength of MR valves are difficult to measure through experimental method thus the numerical approach was chosen to aid the prediction of MR effect. FEMM (Finite Element Method Magnetics) software was chosen to analyze magnetic simulations in this study.

Parameters are required when conducting the simulation to obtain the magnetic flux distributions. The coils of each MR valve were designed and fixed with 450 turns of 24 AWG copper wires and a total resistance of 5.5 $\Omega$. Due to the maximum current applied to the coil being 1 A, the power consumption is only 5.5 watt. The simulation was conducted in 2D axis-symmetric with different total elements and node according to the type of MR valves. The permeability of MR fluid was obtained from the manufacturer. Meanwhile, the permeability of magnetic materials of MR valve is assumed to be similar to the B-H curve of AISI 1020 while the permeability of non-magnetic materials are following the B-H curve of AISI 6061-T6. The results are discussed in each section for each type of MR valve.

![Figure 1 Configuration of Serpentine type MR valve](image-url)
4 Pressure drop generated by serpentine MR valve

Figure 2 depicts the pressure drop versus current for the serpentine MR valve that was proposed in this study with three gap sizes and flow rate of 10 ml/s. The figure shows the MR valve could experience various pressure drop under various gap sizes due to the MR effect was generated by the coils and also the fluid path. During the off-state, the MR valve would work based on the viscosity of the MR fluid. It was identified that the serpentine MR valve with a 0.5 mm gap size can produce a pressure drop of 0.13 MPa in the absence of the input current and could be increased up to 7.3 MPa by applying the input current of 1.0 A with flowrate of 10 ml/s. Meanwhile serpentine MR valve with a 0.75 mm gap size can produce a pressure drop of 0.06 MPa in the absence of the input current and could be increased up to 3.9 MPa by applying the input current of 1.0 A with flowrate of 10 ml/s. The lowest pressure drop generated is from 1.0 mm gap size, with a pressure drop of 0.03MPa in the absence of the input current and could increase up to 2.9 MPa by applying the input current of 1.0 A in the flowrate of 10 ml/s. Specifically, the smallest gap size generates the highest pressure drop.

Figure 3 depicts the off-state pressure drop generated by each gap size for various flowrate. The figure shows 0.5mm gap size having the highest force and 1.0mm gap size is the lowest. Meanwhile, Figure 4 shows the on-state pressure drop generated for each gap size with various flow rate. Results shows that smallest gap size is the highest pressure drop generated follows by the 0.75 mm and the 1.0 mm gap size.

Figure 5 illustrates the dynamic range of the pressure drop generated from each gap size of serpentine MR valves. Valve with 0.50mm gap size produced the biggest value compared to the other gap size. Meanwhile, valve with 0.75 mm is ranked the second highest in pressure drop generated the lowest falls to 1.0 mm gap size.
Figure 3 Off-state pressure drop of serpentine MR valve

Figure 4 On-state pressure drop of MR valve

Figure 5 Dynamic range of each gap size of serpentine MR valve
5 Conclusion

The presented study has discussed the comparison of three gap sizes of serpentine MR valve: 0.50, 0.75, and 1.0 mm. For each type of gap size, the same mathematical modelling of pressure drop for serpentine MR valves were developed and the results were compared. The proposed approach aims to study the performance of serpentine MR valve based on different gap sizes. The analysis also considers constant size of MR valves, number of turns and power consumption. The simulation results have shown that the smaller gap size, which is gap 0.50 mm can generate a higher pressure drop and higher dynamic range. Finally, the proposed studies have reported useful insight of MR valve types and new information for the selection of gap size of serpentine MR valves with different application requirement and valves performances.

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