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DESIGN AND PERFORMANCE ANALYSIS OF MAGNETORHEOLOGICAL VALVE MODULE WITH ANNULAR-RADIAL CONCEPT

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ABSTRACT

In this study, a new design of magnetorheological (MR) valve module using annular-radial gaps concept are developed to improve the design flexibility and manufacturability towards commercialization process. In commercial perspective, a product with flexible performance capacity is sometimes more preferable than a high performance product but with fixed specifications since frequent design resizing can be inefficient in terms of manufacturing process. This paper proposes a new design of a compact MR valve using annular-radial concept as an effort to enhance the performance of an MR valve while at the same time improving the easiness of performance range and the simplicity of manufacturing process using a fully modular valve structure. In order to evaluate the valve performance, the conceptual design module MR valve, the proposed design is evaluated in terms of pressure drop characteristics with respect to the magnetic field strength and current input in the perspective of module performance. The simulation results have shown that the proposed design has successfully improved the achievable pressure drop with additional advantage in performance flexibility through modular valve concept.

Keywords: magnetorheological valve, annular-radial concept, modular MR valve.

INTRODUCTION

Magnetorheological (MR) fluid is a fluid suspension made from a mixture between base liquid, micron-size ferrous particle and some additives in such a way so that it has very sensitive rheological properties to magnetic field [1]. When the fluid is triggered with magnetic field (on-state condition), the rheological behavior is changing due to inter-particle interaction, which increase the shear stress of the fluid [2]. Where there is no magnetic field induced (off-state condition) the rheological behavior are highly determined by the fluid viscosity [3]. As an exceptional benefit, in most cases of MR fluid based devices, no moving parts are required in the operation and therefore the vulnerability of the devices to wear and tear are significantly lower. One of the early concept of a stand-alone annular MR valve was proposed by [4], which consisted of an annular flow channel and electromagnetic coil fitted in adjacent to the flow channel. A different approach of MR valve using radial type concept was proposed by [5] to be applied in a large-scale seismic damper in a bypass configuration. The advantage of radial over annular MR valve particularly lies in the pressure drop rating superiority as well as the capability to be arranged in a multi-stage arrangement. [6] proposed the combination approach to improve the performance of MR valve through an MR valve design with both annular and radial flow paths. The involvement of both types of resistance channels were successfully increased the on-state resistance force while maintaining valve size and magnetic flux density. In order to expand the total effective area, the latest advancement of MR valve was proposed by [7] and [8] through the development of an MR valve with multiplication of annular and radial flow path. In their design, multiple combination of annular and radial flow path channel was intentionally made to extend the length of effective area without increasing its valve geometrical size and power consumption.

In spite of the extensive advancement of MR valve, most designs of MR valve are currently made for a particular device and therefore will not suitable for other purpose unless having major resizing process to suit the new requirements. For that reason, the development and manufacturing cost of an MR fluid based device is normally quite expensive since every specific device requires a specific design and manufacturing plan. The development and manufacturing cost can be reduced if one of the major components, such as the valve, can be mass-manufactured but still able to meet to various device and application requirements due to the flexible performance capability. In order to achieve performance flexibility, this study proposes a modular type MR valve, which can be assembled, dismantled and reassembled again in different stack configurations, so that the performance range of the MR valve is wider. In particular, since the performance of the valve module is very important and highly determined the performance of the overall MR valve, the main objective of this study is to demonstrate the performance of the MR valve module, as the key component in a modular type MR valve.

MR VALVE STRUCTURAL DESIGN

Basically, the common way to improve the performance of MR valve in terms of pressure drop is by augmenting the yield stress of MR fluid along the fluid resistance gap area, which known as effective area [7]. Effective area is an area where the fluid viscosity of MR fluid can be continuously regulated by controlling of strength of magnetic field. Increasing the magnetic flux density will enhance the yield stress of MR fluid, but, at the same time will excess in larger dimension of coil which increase the size of MR valve. Recently, an approach to enhance the performance of MR valve without having to enlarge the coil size was proposed by [7] and [8]. Their approach mainly powered by the effective utilization of flow path inside the valve which is able to increase the effective area in a limited space. The valve structural design in this study employs the same principle, which utilizes the serpentine flow path which is able to increase the effective area by extending the fluid flow path inside the valve. However, due to the intention of making the valve performance flexible, the serpentine flow path along with the electromagnetic coil are designed in several sections of module package.

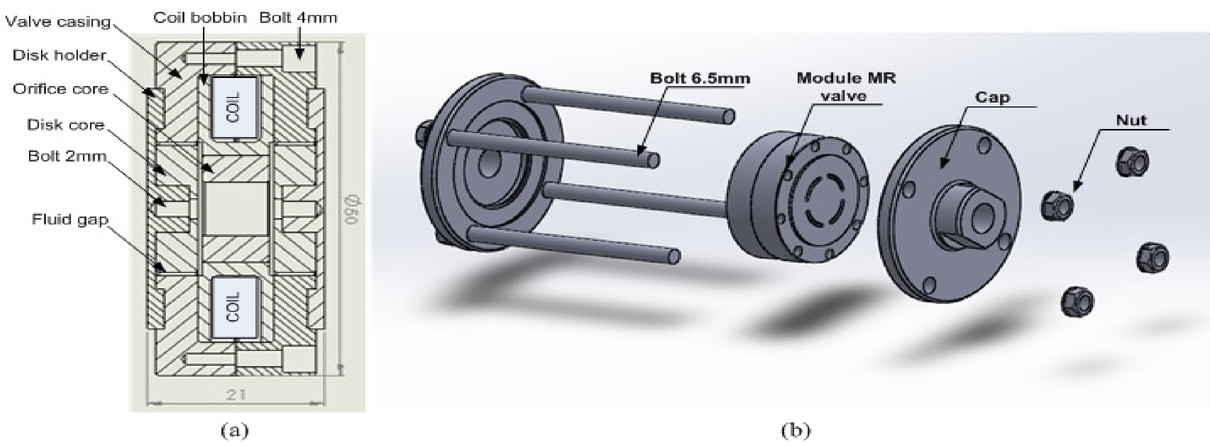

Figure-1. (a) Module MR valve and (b) Exploded view of the module valve.

The main structure of the proposed MR valve is located at the module component as shown in Figure-1. The module can be divided into four different components, namely the caps, the module casing, the coil, and the module core. The caps are made from aluminum 1100 material and consist of two identical parts. Each cap has four holes with diameter of 6.5 mm, which are used as a part of locking mechanism using bolts and nuts. The module casing consists of several parts, namely male casing, female casing and disc core holder. Both male and female casing are made from American Iron and Steel Institute (AISI) 1010 material while the disc core holder is made from aluminum 1100 material. As a locking mechanism for the casing, eight threaded holes with diameter 4 mm are used to tighten the male and female casing together by bolts. Meanwhile, the disc holders are used to hold the disc cores of the module core, which are made from AISI 1010 material, with the help of 2 mm bolt from the inner side of the disc cores. Lastly, the coil consists of an aluminum coil bobbin and copper wire windings, which is tightly connected with the steel-made orifice core of the module core component. Since the valve concept is modular, the structural design of the valve should ensure that component of the valve can be installed interchangeably, so that less part should be customized for different module arrangements. The structural design is also required to be robust, in the meaning that the any configurations of valve module would not deteriorate the mechanical strength of the valve as well as capable to prevent leakages.

MR VALVE MODELLING AND SIMULATION

The derivation of quasi-steady phenomenological model of MR valve design is important at the first stage of simulation process to predict the performance of the MR valve. Typically, the quasi-steady model of the valve will be expressed in terms of the achievable pressure drop, which is consist of two parts, pressure drop from viscous properties of the fluid and pressure drop from the field dependent yield stress of the fluid. The basic expression of pressure drop in an MR valve can be declared by following quasi-steady equations in Equation (1) [9]:

$$\Delta P = \Delta P_{viscous} + \Delta P_{yield} \quad (1)$$

$$\Delta P_{viscous} = \frac{6\eta QL}{\pi d^3 R} \quad (2)$$

$$\Delta P_{yield} = \frac{c\tau(B)L}{d} \quad (3)$$

where the pressure drop of an MR valve is expressed from two parts, the viscous part and the field dependent part. The viscous part in Equation (2) is proportionally related to the fluid base viscosity (η), flow rate (Q), and annular channel length of the valve (L), but inverse-cubical to the valve gaps (d) and inverse proportional to the channel radius (R). Meanwhile, the field dependent part in Equation (3) is proportionally associated with the field dependent yield stress value $\tau(B)$ of MR fluid, annular channel length (L), and flow-velocity profile coefficient

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(c) but inverse-proportionally related to the gap size (d). The coefficient c is obtained by calculating the ratio between field dependent pressure drop and viscous pressure drop using the approximation function as defined by [10] in the following equation:

$$c = 2.07 + \frac{12Q\eta}{12Q\eta + 0.8\pi R d^2 \tau(B)} \tag{4}$$

However, the expressions in Equation (2) and Equation (3) are only valid for MR valve with annular gaps. For radial gaps, the viscous pressure drop and the yield pressure drop can be expressed as [6]:

$$\Delta P_{viscous} = \frac{6\eta Q}{\pi d^3} \ln\left(\frac{R_o}{R_i}\right) \tag{5}$$

$$\Delta P_{yield} = \frac{c\,\tau(B)}{d}\left(R_o - R_i\right) \tag{6}$$

where the valve gap size (d) in Equation (5) and Equation (6) refers to radial gaps while the R_0 and R_i refer to the outer radius of the radial gaps and the inner radius of the radial gaps, respectively.

Since the proposed design of the MR valve module utilized both annular and radial gaps, the mathematical expressions of pressure drop should include all the expressions in Equations (2) to (6). However, to simplify the derivation, the valve gaps are separated into three different zones, the annular gaps zone, the radial gaps zone, and the orifice gaps zone as shown in Figure-2. The valve needs to be clustered into three zones because each zone was presumed to have different magnetic flux density.

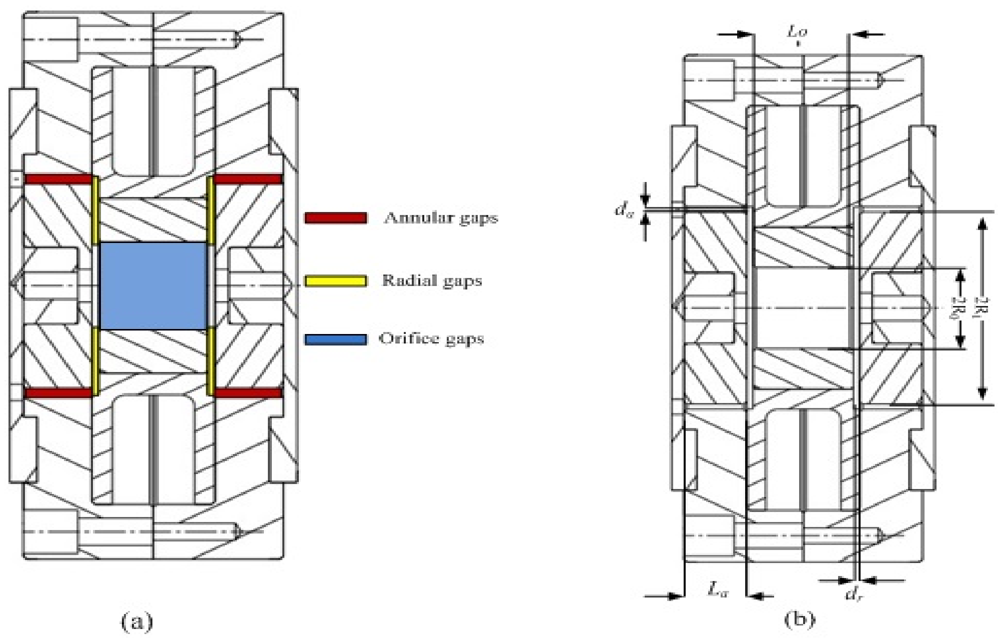

Figure-2. (a) Gaps zone in module MR valve and (b) Dimension variables of module.

From Figure-2 it can be seen that in module MR valve there are two annular gaps, two radial gaps, and one orifice gaps. Using the expressions of annular and radial pressure drop in Equation (2) to Equation (6) with additional expression of orifice gaps pressure drop from [12], the quasi-steady pressure drop of the MR valve module can be described in the following equations:

$$\Delta P_{valve} = \Delta P_{annular} + \Delta P_{radial} + \Delta P_{orifice} \tag{7}$$

$$\Delta P_{annular} = 2\left[\frac{6\eta Q L_a}{\pi d_a^3 R_a} + \frac{c_a \tau_a(B) L_a}{d_a}\right] \tag{8}$$

$$\Delta P_{radial} = 2\left[\frac{6\eta Q}{\pi d_a^3}\ln\left(\frac{R_1}{R_0}\right) + \frac{c_r \tau_r(B)}{d_r}\left(R_1 - R_0\right)\right] \tag{9}$$

$$\Delta P_{orifice} = \frac{8\eta Q L_0}{\pi R_0^4} \tag{10}$$

The MR fluid used in this study is MRF132DG from Lord Corp, which is commercially available. The complete parameters of the modular MR valve are shown in Table-1, while the dimension for each corresponding variables

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are shown in Figure-3. In order to predict the valve performance, the magnetorheological effect of the MR fluid should be determined. The magnetorheological effect normally expressed in the magnitude of yield stress of MR fluid which is specific for each type of MR fluid. For the MRF-132DG, which is one of the commercial type MR fluid, the yield stress can be expressed in the following form [8]:

$$\tau_y(B) = \begin{cases} -58.92B^3 + 74.66B^2 & \tau_y(B) > 0 \\ +35.74B - 3.387B, & \\ 0, & \tau_y(B) \le 0 \end{cases} \tag{11}$$

Table-1. Parameter of single-stage modular MR valve.

Parameters	Descriptions	Units	Value
η	Fluid viscosity	Pa-s	0.112
Q	Flow rate	ml/s	40
d_a	Annular gap size	mm	0.5
d_r	Radial gap size	mm	0.5
L_a	Annular gap length	mm	5
L_0	Orifice gap length	mm	7.5
R_1	Outer radius radial	mm	9.5
R_0	Inner radius radial	mm	2.5

The yield stress $\tau_r(B)$ is expressed as a function of B, which is the magnetic field strength in the form of flux density in Tesla. Therefore, the determination of magnetic flux density is needed to determine the magnetorheological effect which is a prerequisite in the valve performance prediction process.

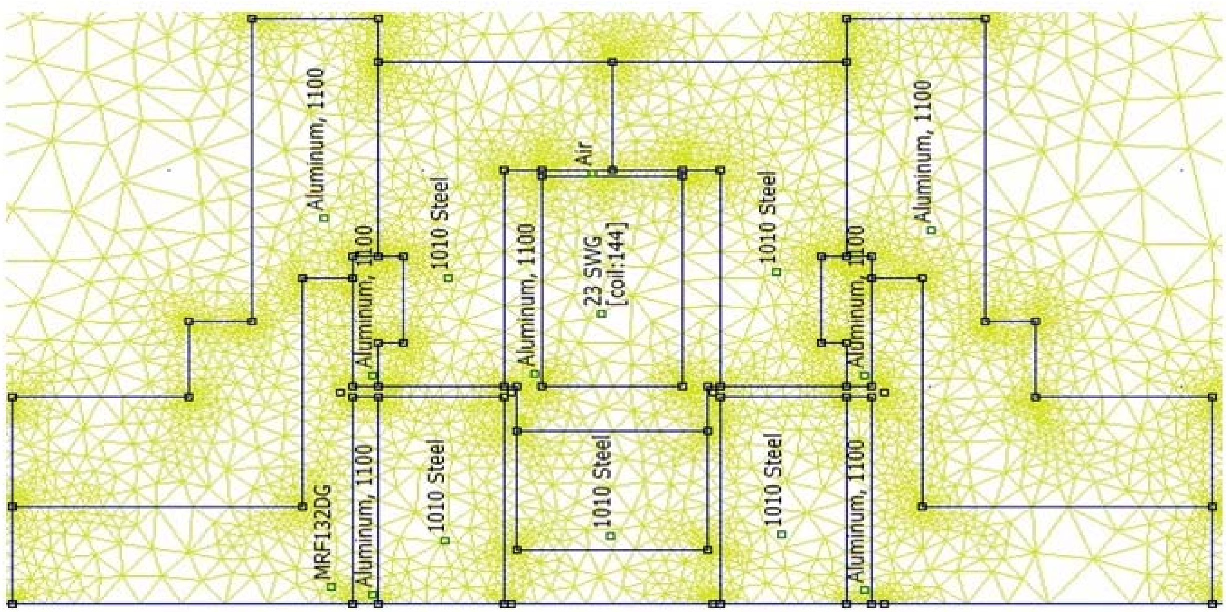

Figure-3. Axisymmetric meshed model of the single-stage modular MR valve.

Several parameters need to be initially determined to conduct the simulation. The coil of each valve module is determined to be made of 144 turns of 23 SWG copper wires with total resistance of 1.6 Ω. Given that the current input was limited to 1 A, the maximum power consumption of the valve is only 1.6 W. Figure-4 shows the two dimensional axisymmetric meshed models in the FEMM using triangular elements with total element number of 12662 and total node number of 24747. Since the coil number of turns was already determined and the permeability of magnetic material was assumed to follow the B-H curves of AISI 1010, the magnitude of magnetic flux density can be simulated for each corresponding current input.

RESULTS AND DISCUSSIONS

The results from FEMM are shown in Figure-4. The distribution of magnetic flux density value along with the flow path channel for 0.5 mm gap size inside the module MR valve. From Figure-4, the magnetic flux density are consistently increased with the increase of current input to the electromagnetic coil, the applied current input in this study is limited to maximum 1 A.

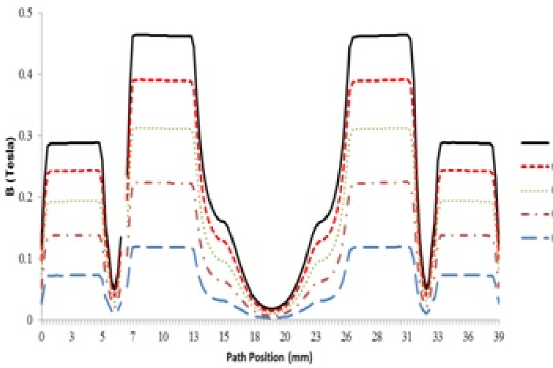

Figure-4. Magnetic flux density along flow path in modular MR valve.

From the simulation results in Figure-4, the highest flux density that can be reached at current input of 1 A is around 0.47 T, which occurs at the radial flow gaps. The second highest flux density is shown at the annular flow gaps with the flux density around 0.28 T. Meanwhile, the orifice gap is shown to be the gap with the lowest flux density. Since the strength of magnetic field relates with pressure drop almost in linear correlation, the magnetic simulation results can be interpreted as the major contribution of radial gaps to the pressure drop performance followed with the annular gaps. Meanwhile, the field strength at the orifice gap is so low it can be neglected so that it has only viscous fluid resistance without any magnetorheological effect. The magnetic flux density values for each corresponding current input are used to predict the yield stress of MR fluid using Eqn. (3). The value of yield stress at each valve module for every corresponding current input are needed to do the estimation of pressure drop using Eqn. (7). The Eqn. (2) are used to calculate the pressure drop rating of the valve at each zone for every corresponding current input. The calculation results of pressure drop estimation for single-stage module valve are shown in Figure-5. From Figure-5, the pressure drop prediction results are in accordance with the results of magnetic flux density simulation, which showed that the pressure drop from the radial gaps is the highest contributor to the total achievable pressure drop of the MR valve. The pressure drop contribution of orifice gaps is also significantly small in comparison to the annular and radial gaps, since the slope line of orifice gap is barely appeared. The results also show that the maximum achievable pressure drop of a module at 40 ml.s^{-1} flow rate with current input of 1 A is around 2.1 MPa. As a comparison, the achievable pressure drop of the previous design of compact MR valve at 40 ml.s^{-1} flow rate is less than 2 MPa [15]. In other words, the proposed MR valve design has shown the ability to improve the achievable pressure drop of a compact MR valve with additional advantage in design flexibility through simple modular concept while maintaining the size dimension.

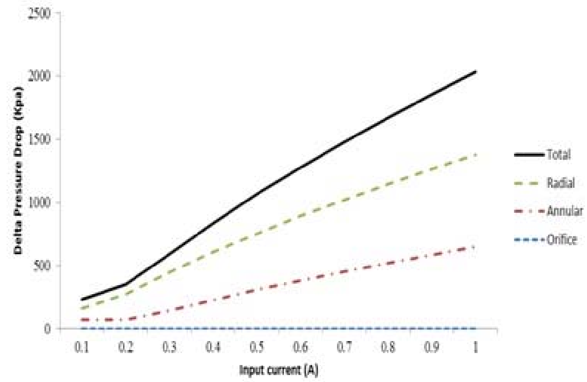

Figure-5. Estimation of achievable pressure drop in each zone of modular MR valve.

CONCLUSIONS

A new design of modular MR valve with annular-radial gap concept has been described in this study. The design is proposed as an effort to enhance the achievable pressure drop of an MR valve while at the same time improving the design flexibility, manufacturability without enlarging the valve diameter size. The performance estimation of the proposed valve is conducted by clustering the valve module into three zones, namely the annular gaps, the radial gaps, and the orifice gaps to simplify the derivation of mathematical model. The performance of the proposed design is evaluated based on the effect of the applied current input in terms of MR valve performance rating. According to the simulation results, the module design is able to achieve pressure drop in term of MR valve performance is around 2.1 MPa. In addition, the radial gaps have shown as the most significant contributor to the overall pressure drop, while annular gaps are followed as the second contributor. The orifice gap is, unfortunately, appeared to be the lowest contributor of pressure drop, because of the magnetic field strength in the orifice gap is too low, the magnetorheological effect can be neglected so that it has only viscous fluid resistance.

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