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An Innovative Design of Magnetorheological Lateral Damper for Secondary Suspension of a Train

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Abstract

This article delivered an innovative idea of a magnetorheological (MR) damper for secondary suspension of train bogie. The valve inside MR damper adopted meandering of both fluid flow and magnetic flux for improving magnetization area. In this work, the design and working principle of the MR valve were presented including a mathematical model to predict the pressure drop. In the early stage, the finite element method magnetics software (FEMM) simulation could predict the magnetic flux density across the passages. Based on the amount of magnetic flux, the corresponding shear yield stress could be determined from its basic physical properties. The mathematical model covered pressure drop prediction for both off-state and on-state. The FEMM simulation results showed that the meandering flow and serpentine flux design could improve the effective area of magnetization. Consequently, the pressure drop of the valve could have wider ranges and achieve a high value of pressure differences. This result could be potentially improving the performance of the damping forces of the lateral damper in a bogie train.

Keywords

Lateral damper; Magnetorheological damper; Secondary suspension; Magnetorheological valve

1 Introduction

The valve is a vital part of many flow control mechanisms. To control the fluid flow, a hydraulic system is usually associated with solenoid valve and electronic devices. The conventional valve system is made by several parts that are moving inside the valve, which makes it more vulnerable to wear and tear while at the same time less responsive. To overcome this drawback, a magnetorheological (MR) valve was recommended to replace the conventional valve system and increase the performance of the valve without any moving part compared. MR valve is equipped with MR fluid which can be adjusted its viscosity using magnetic flux. This smart fluid consists of several materials such as liquid carrier, micron-size soft magnetic particles, and some surfactant. It is; therefore, the fluid is sensitive to magnetic field resulting in interchangeable intrinsic properties [1].

Since the 1940s, the discovery of MR fluid has a massive impact on the engineering world because it has various new applications. The MR fluid has been massively implemented in MR damper where the MR valve is its main component. This product has been penetrating high-end cars to be functioned as semi-active suspension [2] and an adjustable damper [3]. The semi-active suspensions are gained popularity because of its characteristic that stands between the conventional suspension and active suspension [4]. Furthermore, there are many new applications of MR dampers such as prosthetic devices [5] and seismic damper [6].

Researchers have been investigating MR fluid for a long time ago because of its reversible properties upon applied magnetic fields. The MR fluid has an extraordinary ability. It is capable of reversal from a Newtonian fluid class to non-Newtonian fluid within less than ten milliseconds due to exposure in magnetic fields. Therefore, its yield strength is controllable from the maximum shear yield stress of 50 kPa to 100 kPa [7]. The change of shear yield stress leans on several factors such as particle size, composition, volume fraction as well as the magnetic field strength. A system utilizing MR fluid-based actuators have more trustworthy than existing devices [7].

MR-based device involves non-moving components. For that reason, it is less susceptible to wear issue. The circumstance of MR materials has made the MR-based devices have faster response, more simple design with lower power demand compared to the conventional semi-active actuator [8]. Moreover, it has made a massive advancement in a wide range application such as automotive components [9], medical devices [10], and civil or construction [11]. In MR damper, the main

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aspect that affects its performance is determined by the achievement of the MR valve. Therefore, to significantly increase the performance of MR damper, a substantial enhancement of the MR valve must be accomplished [8].

A magnetorheological valve consists of an electromagnetic coil, valve core, valve body, and a fluid channel. Each MR valve has various configuration, contingent upon its particular design purpose. However, its fundamental function is usually similar. The damping property is a special characteristic that influences the vibratory of dynamic systems in which vibration control or suppression needs to be done by dissipating the energy in heat form [12]. For a brief explanation, when a certain electric current induces the electromagnetic coil, magnetic flux is generated. Thus, the magnetic flux alters the flow resistance. Consequently, the pressure drops changes proportional to the amount of magnetic field strength. Due to this flow restriction changing, the fluid flows slower or even stopped [13].

The MR valve is usually placed inside the piston. Many MR valve models have been introduced, due to the importance of MR valve [14]. The annular type MR valve can be designed into various MR valves such as the inner coil design [15], the outer coil design [16] and the multiple-coil design [17]. Researchers have paid attention to the annular type of valve in an MR damper due to its simple design compared to other models. Despite annular type, Radial-type have also been introduced as an alternative design with the capability of increasing the pressure drop capacity by providing modular stages [18]. Compare to annular type, radial type provides a higher on-state effect but intricate design. Lately, the annular and radial types are combined to achieve the advantages of each type [13]. This combination has revealed promising achievement. It has already been implemented in the engine mount design [19].

Although it has been studied a lot, the focus on developing the valve on the MR damper for lateral dampers is rarely found. The lateral damper, so far, still adopts conventional shock absorber. Consequently, it only covers a narrow frequency of vibration. It is because the damping capacity is not as wide as MR damper. The main purpose of this work is to improve the performance of the MR valve for lateral damper which can achieve a higher pressure drop than the existing counterparts. This article delivers an original concept of an MR valve combining meandering flow channels to achieve a higher pressure drop as well as serpentine magnetic flux.

2 Valve Design

MR valve performance can be justified by its ability to produce and adjust the pressure drop between its compression and extension period. The degree of achieved pressure drop mainly determines the MR valve rating. The other abilities such as linearity, hysteresis and time constant are also potential to be investigated. However, to limit this work, the evaluation of MR valve performance in this article only covers the achievable pressure drop.

In general, increasing the shear yield stress along the fluid passage (effective area) would be improving the pressure drop [20]. Here, an effective area is defined as an area where the strength of the magnetic field can continuously control the MR fluid viscosity. The effective area of an MR valve must be in the MR fluid passage. The shear yield stress of the smart fluid increases along with the rise of magnetic flux until it reaches the saturation value. However, the tradeoff is to achieve the higher magnetic flux; it needs higher space of coil to accommodate several turns. Consequently, the size of the MR valve will be expanded. The recent approach to augment the MR valve performance without expanding the electromagnetic coil space was performed by Imaduddin et al. [21]. However, the design is still limited to resizing the main parts. Consequently, each specific necessity must be built in a tailored achievement rating.

The MR valve design process consists of two stages. namely structural design and valve design. The structural design comprises of a FEMM simulation where it ensures the magnetic fluxes passing through the designated passages. Moreover, it confirms the location of excessive magnetic flux losses. The FEMM simulation process can also be used to determine the appropriate MR valve materials. By choosing suitable material, manipulation of the magnetic flux forming the serpentine flux flow can be realized. Once the magnetic circuit was decided, it is further used as a basis for the valve design. The valve design focuses on the calculating appropriate valve parameters such as flow rate, pressure drop and so on.

2.1 Equation

The basic equation to determine the pressure drop can be divided into two equations, those are pressure drop implied by the viscosity of MR fluid in the absence of magnetic field called off-state, and pressure drop produced as the presence of magnetic field namely on-state condition. The off-state pressure drop is mainly caused by head loss in the fluid passages. Meanwhile, the on-state pressure drop is generated from the change of fluid viscosity caused by magnetic flux across the fluid passages.

The following equation provides a calculation of total pressure drop (ΔP) in both off and on states condition [22],

$$\Delta P = \Delta P_{viscous} + \Delta P_{yield} \tag{1}$$

Although the valve design features both meandering fluid flow and serpentine magnetic flux flow, the passage in the MR valve comprises of several annular and radial types. The expression of equation (1) has to be divided into the annular and radial mathematical equations. Equation (2) and (3) express the governing equation for annular pressure drop in off-state and on-state condition, respectively:

$$\Delta P_{annular,viscous} = \frac{6\eta QL}{\pi d^3 R} \tag{2}$$

$$\Delta P_{annular,yield} = \frac{c\tau_y(B)L}{d} \tag{3}$$

where η is the fluid base viscosity, Q is the fluid flow rate, L is the annular channel length, d is the valve gaps, and R is channel radius. It can be seen that the magnetic induced pressure drops in equation (3) is proportional to the magneto-induced shear yield stress $\tau_y(B)$ of the MR fluid, the annular channel length L, and coefficient of velocity profile, c. Nevertheless, it is inversely proportional to the gap size, d. The coefficient c can be attained by calculating the ratio between on-state pressure drop and off-state pressure drop as introduced by Nguyen et al. [23] as stated in equation (4),

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

Equations (2) and (3), work only for an annular type MR valve. Meanwhile, for the radial type, both off-state pressure drop and on-state pressure drop are governed in equation (5) and (6) as follows [13],

$$\Delta P_{radial,viscous} = \frac{6\eta Q}{\pi d^3} \ln\left(\frac{R_0}{R_i}\right) \tag{5}$$

$$\Delta P_{radial,yield} = \frac{c\tau_y(B)}{d}(R_0 - R_i) \tag{6}$$

where d is the radial valve gap size in Equations (5) and (6), while R_0 and R_i are the outer and inner radius of the radial gaps, respectively. The flow rate of the MR fluid is required to be determined firstly by using equation (7) in which the flow rate depends on the piston area $\frac{\pi d^2}{4}$ and speed v.

$$Q = \frac{\pi d^2 v}{4} \tag{7}$$

The calculation for the magnetic field effect on MR fluid consists of some steps. The first step was to decide the corresponding shear yield stress of the MR fluid refers to the quantity of magnetic flux in the effective area. The MRF-132DG from Lord Corp. is utilized in this lateral MR damper development. The consideration of choosing this MR fluid was its resistance to heat degradation. The relation between the shear yield stress of the fluid and magnetic flux is expressed by the polynomial equation as previously proposed in [24] (see equation (8))

$$\tau_y(B) = -58.92B^3 + 74.66B^2 + 35.74B - 3.387, \tag{8}$$

for $\tau_y(B) > 0$

$\tau_y(B) = 0$, for $\tau_y(B) \le 0$

where $\tau_y(B)$ is the shear yield stress as a function of flux density, and B is the flux density in Tesla. After the simulations being conducted, the average flux density on each zone was determined to be the function of this equation on each zone, respectively.

The final step was calculating the total pressure drop by adding the off-state condition with the on-state condition as the function of shear yield stress. For the whole assessment, these equations were calculated for each zone and to be summed up for the final pressure drop. The parameters used in those equations are detailed in Table 1. Moreover, Figure 1 illustrates the cross-sectional area of the proposed design.

Table 1 Parameter of the MR valve

Parameters	Description	Value
η (*MRF-132DG*)	Fluid Viscosity	0.112 Pa-s
d	Gap size	1 mm
L_{a1}	Annular channel length 1	7.91 mm
L_{a2}	Annular channel length 2	7.95 mm
R_1	Outer radius (radial)	14.5 mm
R_2	Inner radius (radial)	17.5 mm
D	Piston diameter	50 mm

As shown in Figure 1, the new design proposed in this article using a meandering flow MR fluid. The flow goes through six annular gaps and five radial gaps. The exploded view of each part in the MR valve is shown in Figure 2. The MR valve is constructed of six components. Those are the lower casing, piston rod, inner valve, bobbin, coil, outer valve, and the upper casing. The base material of MR valve components must be magnetic or non-magnetic types. The selection of material strongly affects the flux flow. MR valve casing is made of American Iron and Steel Institute (AISI) 1020 steel which has a low remnant. The electromagnetic coil was copper wire windings type 26 AWG, and an aluminum alloy was selected as coil bobbin. The spacer must be made of a nonmagnetic material. In this case, aluminum was taken. Considering the types of materials, hopefully, the magnetic flux could form the serpentine flux flow.

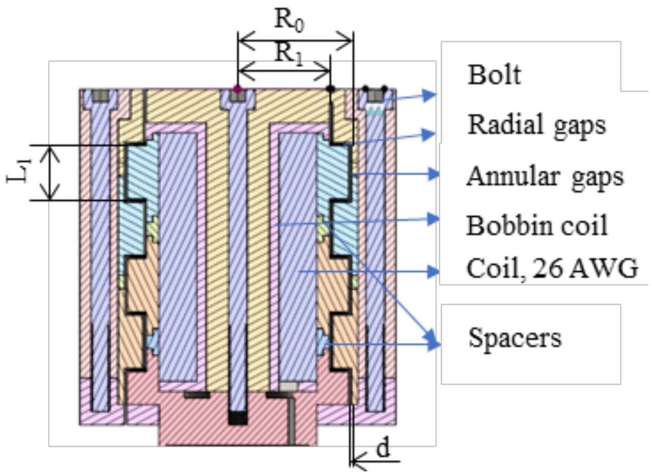

Figure 1 A cross-sectional view of the proposed MR valve

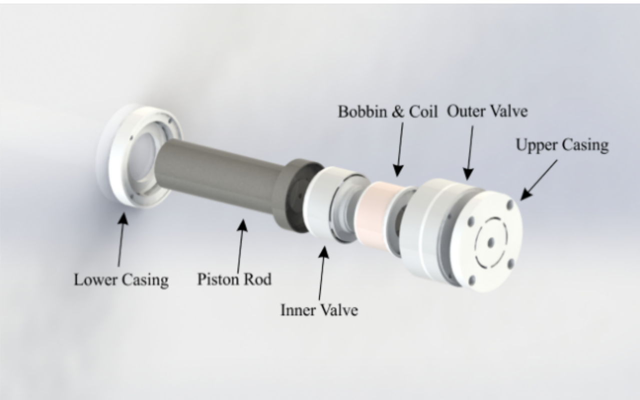

Figure 2 Exploded view of the MR damper valve

2.2 Simulation

The prediction of the MR valve performance strongly depends upon the magnetic flux that goes across the fluid passages. FEMM simulation was employed to determine the magnetic field strength in the effective area. In case, the value of the flux magnetics determines the MR fluid viscosity that affecting the peak pressure drop. So far, the use of finite element method magnetics has been becoming standard procedure at the preliminary design of many MR-based devices [24]. This is because the real measurement of magnetic flux within the fluid passage cannot be carried out experimentally. The magnetic circuit simulation would help us predict the MR effect of the MR fluid. Materials used in the simulation were AISI 1020, aluminum alloy 1100, MR fluid, SWG 26 coil, and air. Upon selection, aluminum alloy 1100 was used because of its non-magnetic properties that could turn the direction of the magnetic flux.

3 Results and Analysis

The parameters of the proposed MR valve are given in Table 1. These parameters are used for further calculation, which will be provided in two subsections. The first section explained the magnetic flux simulation, while the second section explained the pressure drop prediction of the design.

3.1 Magnetic flux simulation

This subsection discusses the magnetic simulation of the proposed MR valve using FEMM. The simulation was arranged in two-dimensional and axis-symmetric condition since the valve shape is cylindrical. Figure 3 portrays the meshing results of half cross-sectioned.

The constant current input will vary between 0.5 A, 1A, 1.5 A, and 2 A. These variations are selected to observe the controllability of the damper itself. However, the magnetic simulation results were not all provided in this article. To briefly figure out the flux flow, this article only provides magnetic simulation result for only 1 A electric current. The flux density profile of the proposed MR valve is captured in Figure 4. It can be observed that the inner of the valve has a dense flux magnetic while the outer of the valve has a sparse flux magnetic. This is caused by the inner side of the valve has a smaller space than the outer side.

Several parameters were determined during the simulation. The total of 900 coil winding of 26 AWG copper wire and the maximum current applied to the coil is limited to 2 A. The permeability of magnetic material follows the B-H curves of AISI 1010 stainless steel. Aluminum 1100 is used in the simulation for the un-magnetized material parameter. The boundary condition of FEMM simulation is stated as follows: (i) simulation is conducted in two-dimensional axis-symmetric; (ii) triangular elements is chosen as the mesh model with a total node number of 16579 as given in Figure 3.

Figure 5 depicts the results of the magnetic flux trend along the fluid flow passage for various electric current. It can be seen that the magnetic flux density values show a consistent increment with the increase of electric current supplied to the electromagnetic coil. The trend of magnetic flux density follows the region of both annular and radial zones. The annular region has the highest flux density which is around 0.43 T at 2 A electric current. While the flux density in radial gaps achieves the second highest flux density occurred about 0.34 T at 2 A electric current.

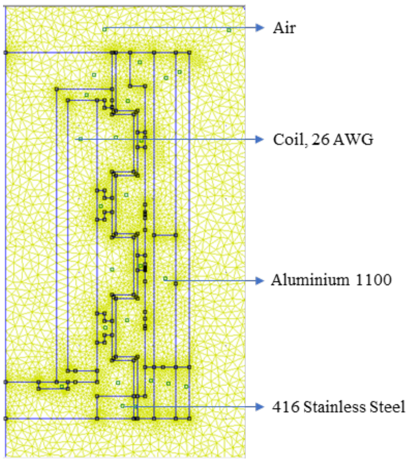

Figure 3 Meshed model

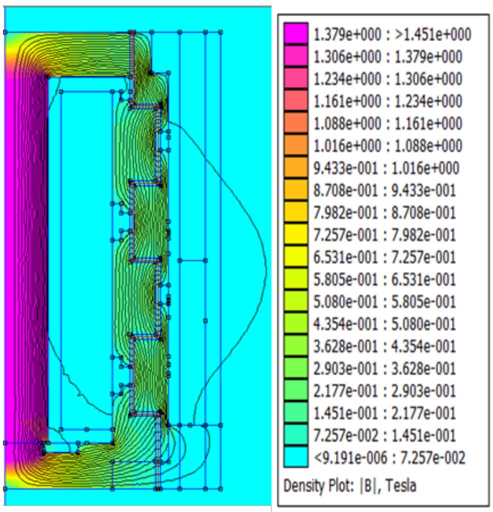

Figure 4 The magnetic flux density of the MR valve on 1A electric current induced using FEMM

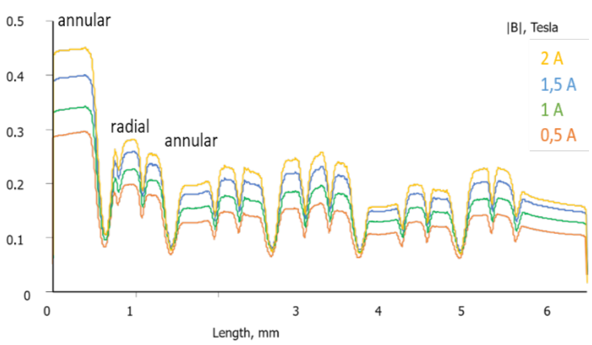

Figure 5 Trends of the magnetic flux density at 0.5A, 1A, 1.5A and 2A electric current

3.2 Pressure drop prediction

The calculation of the pressure drop uses equation (2) for the annular gap and equation (5) for the radial gap. To assess the trends of pressure drop, piston velocity was varied instead of applied current. The variation of piston velocity implies the flow rate of the MR fluid. Figure 6 portrays the trends of pressure drop at different piston velocity at the off-state condition. The chart shows that the pressure drop increases proportionally to the piston velocity. As seen in the figure, the pressure drop for the off-state condition of MR damper at 50 mm/s piston velocity is 0.62 MPa, at 100 mm/s piston velocity is 1.24 MPa and for the 150 mm/s piston velocity the pressure drop is 1.86 MPa. From the graphics show a significant increase from 0.62 MPa to 1.86 MPa. The proportional increment agrees with the summation of equations (2) and (5). The trend of pressure drop in this figure is not linear because of the degree of variable diameter is not equal to one.

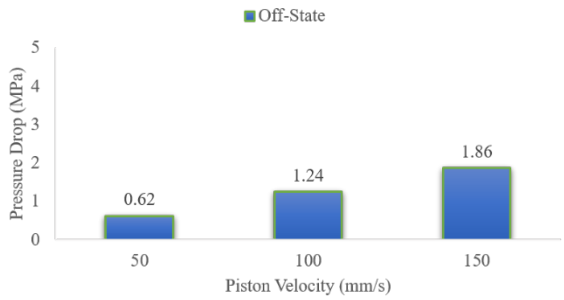

Figure 6 Off-state pressure drop vs. piston velocity of the MR valve

For the on-state condition, the formulas used are equations (3), (6), and (8). The results of the calculation are shown in Figure 7 in the form of pressure drop vs. piston velocity for each electric current induced. From the figure, it can be concluded that the pressure drops of the on-state condition which has been calculated are much higher than the off-state condition. It can also be concluded that the pressure drop is proportional to the electric current induced, respectively.

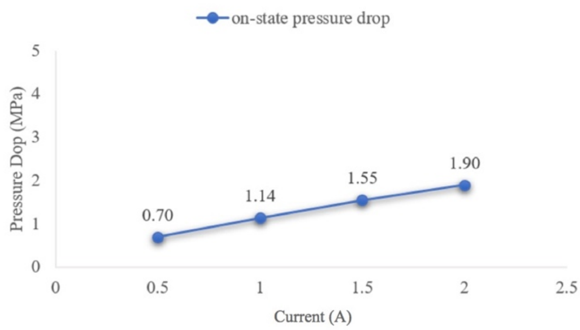

Figure 7 On-state pressure drop vs. electric current of the MR valve

From the figures above, the pressure drop increase along with the increasing value of electric current induced into the coil inside the valve. The value of the pressure drop is 0.7 MPa for 0.5A electric current induced. For 1 A electric current induced, the pressure drop is 1.14 MPa. For 1.5 A electric current induced, the pressure drop is 1.55 MPa. For 2 A electric current induced, the pressure drop is 1.90 MPa.

Based on Figure 8, the total pressure drop increase along with the increasing value of electric current induced into the coil inside the valve. For the 50 mm/s piston velocity, when 0.5 A of electric current induced, the value of the pressure drop is 1.32 MPa, for 1 A electric current induced the pressure drop is 1.76 MPa, for 1.5 A electric current induced the pressure drop is 2.17 MPa, for 2 A electric current induced the pressure drop is 2.52 MPa. For the 100 mm/s piston velocity, when 0.5 A of electric current induced, the value of the pressure drop is 1.95 MPa, for 1 A electric current induced the pressure drop is 2.38 MPa, for 1.5 A electric current induced the pressure drop is 2.79 MPa, for 2 A electric current induced the pressure drop is 3.14 MPa. While for 150 mm/s piston velocity, when 0.5 A electric current induced the value of the pressure drop is 2.57 MPa, for 1 A electric current induced the pressure drop is 3.00 MPa, for 1.5 A electric current induced the pressure drop is 3.41 MPa and for 2A electric current induced the pressure drop is 3.77 MPa.

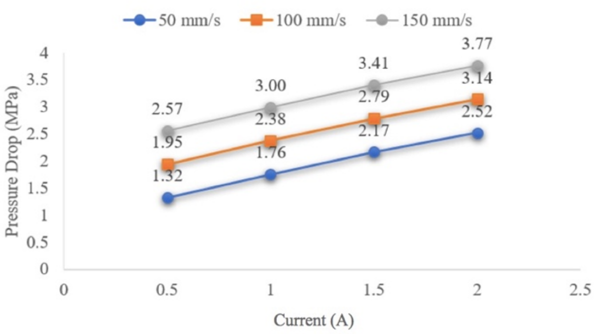

Figure 8 Total pressure drop vs. Electric Current of the MR valve at 50mm/s, 100mm//s and 150mm/s piston velocity

From Figure 9, the proposed MR damper design can surpass the requirement damping force both on jounce (positive X axis) and rebound (negative X axis) condision based on reference (base). The reference is get from the technical data of PT Kayaba Indonesia specificly lateral damper on train.

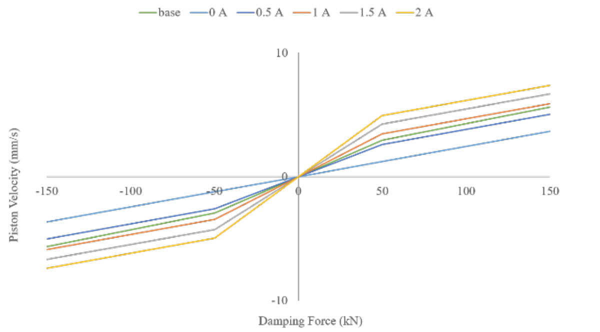

Figure 9 Damping force vs piston velocity from base, 0A, 0.5A, 1A, 1.5A and 2A

4 Conclusion

An original design and performance evaluation of an MR valve for lateral MR damper featuring meandering fluid flow path and serpentine magnetic flux have been delivered. Analytical work to predict the performance of the proposed concept has been undertaken. The analytical work was conducted by simulating the magnetic flux density of the proposed concept and being calculated by analytical assessment. The meandering flow path structure that constructed of the annular and radial channels hybrid with serpentine magnetic flux has proven to improve the performance of the MR valve. According to the simulation results, the serpentine magnetic flux has been successfully designed based on the proposed structure. The FEMM simulation results showed that the meandering flow and serpentine flux design could improve the effective area of magnetization. From the analytical work, it can be concluded that the proposed design can effectively increase the achievable damping force. Consequently, the pressure drop of the valve could have wider ranges and achieve a high value of pressure differences. This result could be potentially improving the performance of the damping forces of the lateral damper in a bogie train.

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