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The Design of an Innovative Multi-Winding Magnetorheology Damper Featuring Embedded Flow Passage

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Abstract. Multi-winding structure is a valid method to improve the damping force in the design of magnetorheology devices. Because of the arrangements of several windings in cylinder, it can greatly improve the effective area of magnetorheology(MR) fluid to achieve much larger damping force in limited space compared to conventional MR damper. In order to further promote the dynamic range and electromagnetic efficiency of MR damper, this paper shows the design of an innovative multi-winding MR damper, which has flow passage embedded in each magnetic core. Based on this special design, the effective length of the flow passage can be dramatically increased, so as the electromagnetic efficiency of the damper. It means that the damper can produce the same damping force with less power consumption. The feasibility of the design philosophy for multi-winding MR damper with embedded flow passage was verified by the simulation results of electromagnetic field and damping force. The research results show that the proposed multi-winding MR damper has much higher dynamic range and efficiency than a conventional one.

1. Introduction

Magnetorheological fluid is an intelligent material and its mechanical properties are controlled by electromagnetic field[1]. MR fluid behaves like a low viscosity fluid without electromagnetic field, as it's composed of micronsized ferromagnetic particles and carrier oil. The ferromagnetic particles in MR fluid will form chain structures in a short time when an external magnetic field is applied. Then the MR fluid becomes quasi-solid and produce a high shear stress to resist flow. This reversible mechanical properties of MR fluid is the so called MR effect, and many MR devices are fabricated based on it , such as dampers, suspension, brakes and clutches[2-4]. MR fluid and devices are widely used in automotive industry, civil engineering, aerospace and bioengineering[5-7] .

As the MR damper has an excellent comprehensive performance in semi-active vibration control, it has been extensively researched to promote its performance[8, 9]. Conventional MR dampers usually feature a single-winding structure, which is assembly on the piston, and the direction of the magnetic pole is parallel to the axis of piston rod. Thus, a very small area of MR fluid is employed to create viscous resistance and the controllable damping force is relatively small. For a conventional MR damper, it always needs much larger size of device to achieve a larger adjustable range of damping force. It is a viable method to enhance the damping capacity of the MR damper under the premise of limited space by increasing the efficiency of magnetic field.

In the design of MR dampers, the multi-winding structure can enlarge the effective area of MR fluid, and a more regularly distributed and mighty magnetic field could be provided in this way. Shiao first applied the multi-winding structure to the design of magneto-rheological brake to gain much higher braking torque[10] . Sassi first proposed an inner multi-winding structure MR damper to

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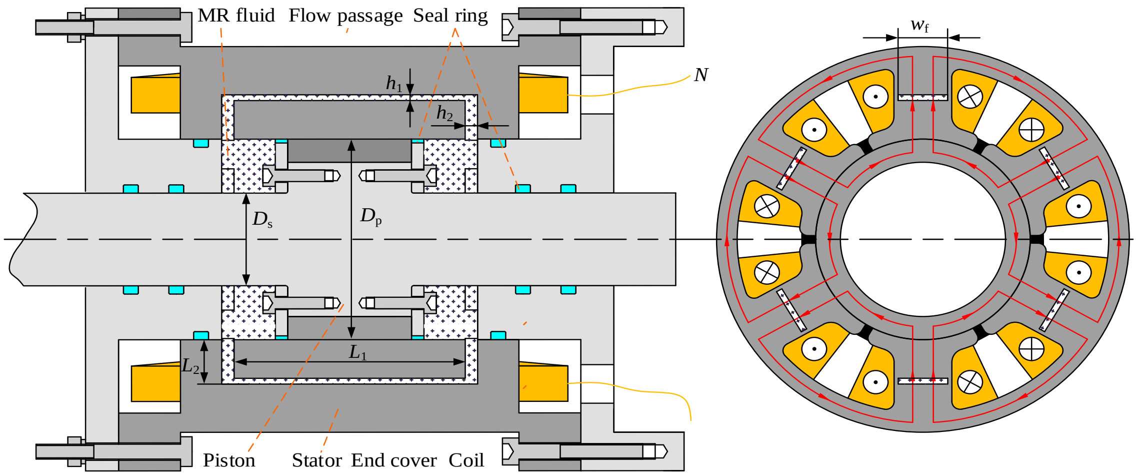
achieve large controllable damping force[11]. Liu et al designed an outer multi-winding MR damper, which has a relatively higher dynamic range compared to traditional MR damper[12]. However, multi-winding structure means more power consumption. To further improve the electromagnetic efficiency of MR damper, an innovative multi-winding MR damper with embedded flow passage is proposed in this research. In this paper, the design principle of the proposed MR damper and the mathematical model of damping force is reported, and the damping force performance is investigated by simulation.

2. Structural Design

In this study, a novel multi-winding MR damper with embedded flow passage is presented and its structure is shown in figure 1. This novel MR damper aims to further improve the electromagnetic efficiency of multi-winding MR dampers. The annular flow passage configuration in conventional MR dampers is changed into multiple embedded flow passages in the novel MR damper. As shown in figure 1(b), the novel MR damper has six magnetic cores, and the magnetic field produced by the two adjacent coils is strengthened for their reversed winding direction. Because the flow passage is embedded in cylinder, the effective length of the flow passage is larger than the length of piston(i.e. the length of annular flow passage in conventional MR damper). By such a novel and unique design, the effective area of the MR damper is extremely maximized, and the utilization of electromagnetic field is also increased significantly.



(a) Axial section view (b) Radial section view

Figure 1. Schematic diagram of the novel multi-winding MR damper

As shown in figure 1, the novel designed MR damper consists of stator, two end covers, six coils mounted in stator, six flow passages, eight sealing rings, six sealing strips, piston and piston shaft. The flow domain of MR fluid is limited in the enclosed space formed by end covers, stator and piston, and the sealing between these components is ensured by using several O-type FKM seals. When the piston moves along the axis relatively to the stator, a higher-pressure region is formed by the MR fluid that is compressed by the piston, and a low-pressure region is formed on another side of the piston. The MR fluid flow from the higher-pressure region to the low-pressure region through six flow passages embedded in stator. To keep the volume balance of the two regions, a double-ended piston shaft is chosen.

In this study, the 50H470 silicon steel with high magnetic permeability is selected as the soft magnetic material to manufacture stator and piston. The layered stacking process of silicon steel sheets is suitable for the processing of stator with embedded flow passages. The MRF-132DG from Lord Company is selected as the MR fluid for its low sedimentation ratio, high stability and appropriate yield stress. Aluminum was used as the structural material to make end covers and piston shaft. Some structural parameters of the novel multi-winding MR damper are presented in table 1, and the selection

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of these dimensions follows the principle of optimal design. The following magnetic simulation and performance evaluation are based on these specifications.

Table 1. Specifications of the novel multi-winding MR damper

Parameter	Value	Parameter	Value
Length of effective flow passage L_1	56mm	Diameter of piston D_p	52mm
Length of ineffective flow passage L_2	10mm	Diameter of piston shaft D_s	24mm
Thickness of effective flow passage h_1	1.5mm	Width of flow passage w_f	12mm
Thickness of ineffective flow passage h_2	3mm	Turns of coil N	220

3. Models of Damping Force

The damping force F_d of the novel multi-winding MR damper can be resolved into a dynamic viscous force F_μ caused by the kinetic viscosity of MR fluid, a Coulomb damping F_ε caused by the shear yield stress of MR fluid and a friction force F_f . The damping force F_d can be written as follows:

$$F_d = F_\mu + F_\varepsilon + F_f \tag{1}$$

and the expressions of F_μ and F_ε are as follows:

$$F_\mu = \frac{2\mu(L_1 + 2L_2 h_1/h_2)Q}{w_f h_1^3} \times S_p \tag{2}$$

$$F_\varepsilon = \frac{cL_1\varepsilon_y}{h_1} \times S_p \tag{3}$$

where Q is the flow rate of MR fluid through six flow passages and $Q = S_p V$ (V is the movement velocity of piston); μ is the viscosity of MR fluid under laminar flow; S_p is the area of the piston squeezing the MR fluid, and it can be expressed as follows:

$$S_p = \pi \times (D_p^2 - D_s^2)/4\,; \tag{4}$$

c is a coefficient that depends on the shear yield stress and flow rate of the MR fluid through the flow passage, and it can be expressed as:

$$c = 2.07 + \frac{12Q\mu}{12Q\mu + 2.4 w_f h_1^2 \varepsilon_y}\,; \tag{5}$$

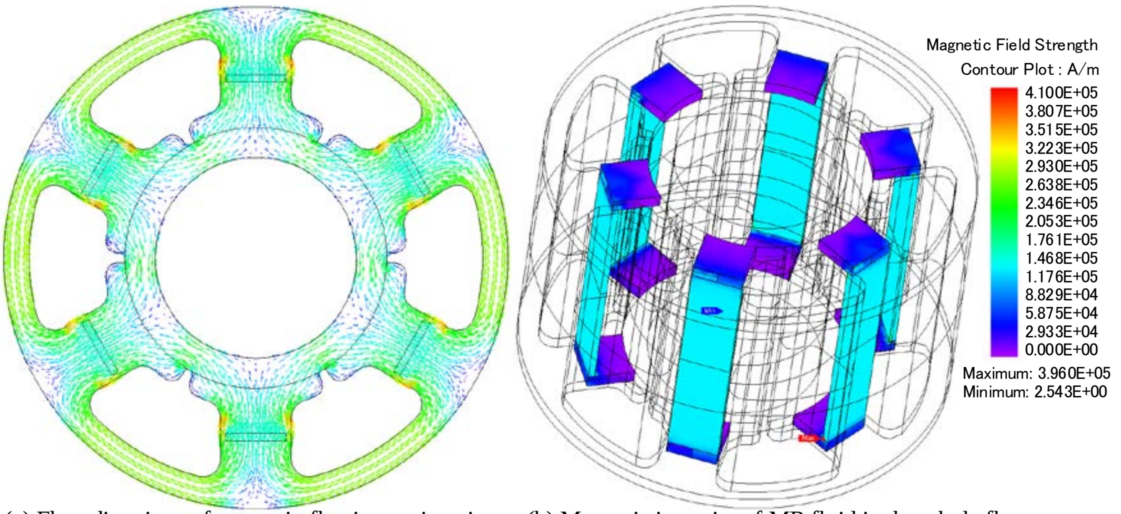
and the definitions & values of structural parameters in equation(2)-(4) are stated in table 1.

The damping force F_d can be resolved into a controllable part (i.e. F_ε) and an uncontrollable part, which includes a viscous damping F_μ and a friction force F_f .The dynamic range of damping force is the ratio between the total damping force F_d and the uncontrollable part, and it can be expressed as:

$$D = 1 + \frac{F_\varepsilon}{F_\mu + F_f} \tag{6}$$

4. Magnetic Simulation and Performance Evaluation

The 3D magnetic finite-element simulation for the novel multi-winding MR damper is conducted using JMAG-Designer software. Figure 2(a) shows the distribution of magnetic flux lines, which start from one pole, pass through the MR fluid in embedded flow passage and piston, then enter the adjacent core, penetrate the MR fluid in adjacent flow passage, along the outer ring of stator, go back to the starting core to constitute a closed magnetic circuit. Two adjacent magnetic cores have opposite direction of magnetic field, and the total magnetic flux density is enlarged. Figure 2 (b) shows the magnetic field intensity of MR fluid in the all six flow passages under a driving current of 1A. It can be seen that the distribution of magnetic field is uniform in the whole effective length of flow passage, and the magnetic field strength in effective area is much larger than that in ineffective area. Although the permeability of piston is much higher than that of MR fluid, it doesn't affect the effective length of flow passage by the special embedded design. The magnetic simulation result in figure 2 (b) confirm the validity of the design philosophy, and the utilization of electromagnetic field is further improved by embedding flow passages in the stator of a novel multi-winding MR damper.



(a) Flow directions of magnetic flux in section view (b) Magnetic intensity of MR fluid in the whole flow passage

Figure 2. Magnetic field distribution of the novel multi-winding MR damper

Figure 3 shows the magnetic flux density of MR fluid in effective length of embedded flow passage when the driving current varies from 0-1.5A, and the growth rate of magnetic flux density reduces with the increase of driving current. When a driving current of 1.5A is applied, the magnetic flux density is around 0.85T, which approximates to the saturation flux density of MRF-132DG. The yield stress of MR fluid under different driving current can be acquired by referring to the material properties of MRF-132DG in [13] and the B-Current characteristic in figure 3. The damping force of the novel multi-winding MR damper can be obtained under different movement velocity and driving current by substituting the yield stress of MR fluid into equations (1)–(5). The friction force F_f is supposed to be 100N in the numerical simulation of damping force. Figure 4 shows the simulated damping force characteristics of the designed MR damper under different velocity excitation. When the driving current reaches the maximum value of 1.5A, the maximum damping force is about 6.4kN. As shown in figure 4, the influence of driving current on damping force is much higher than that of the excitation velocity, while the latter mainly affects the viscous damping force.

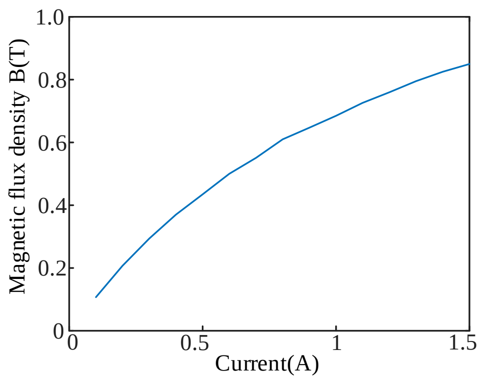


Figure 3. The B-Current characteristic of MR fluid in embedded flow passage

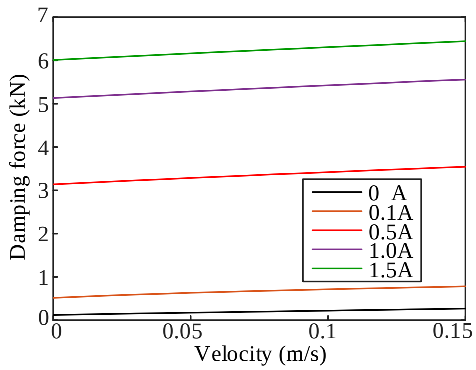
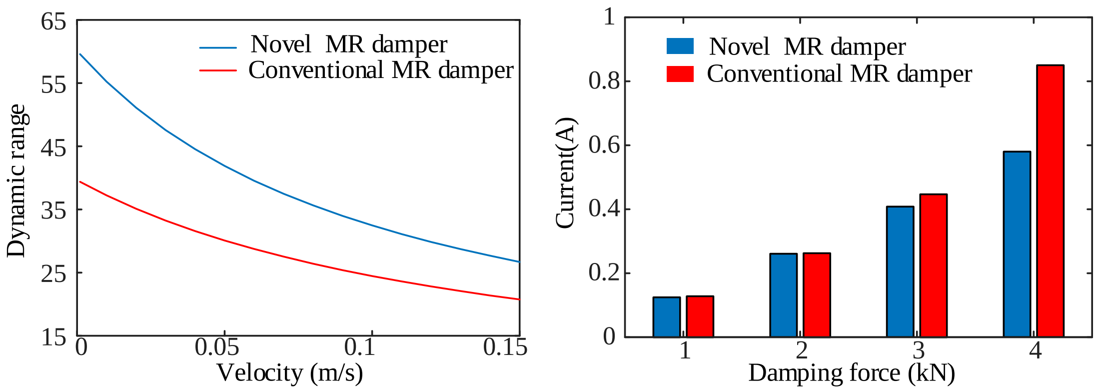


Figure 4. The damping force characteristic of the novel multi-winding MR damper

In order to further objectively evaluate the performance of the novel designed MR damper, an outer multi-winding MR damper[12] with the same dimensions is selected for comparison. The result of performance comparison between the novel and conventional multi-winding MR damper is shown in figure 5, and all the data is obtained by simulation. Figure 5(a) shows the comparison of simulated dynamic range of the two MR dampers under a driving current of 1.5A with the raising of movement velocity. The novel designed MR damper has a dynamic range of 26.7 when the movement velocity is 0.15m/s, which is 29% larger than that of a conventional multi-winding MR damper. Figure 5(b) shows the comparison of power consumption of both MR dampers when they produce the same damping force. It can be seen from Figure 5(b) that both MR dampers has similar power consumption when the damping force below 2kN, and the novel designed MR damper has higher electromagnetic efficiency when damping force exceeds 3kN. The power consumption of the novel MR damper is about 53.4% less than that of a conventional MR damper when a damping force of 4kN is produced.



(a) Dynamic range under 1.5A (b) Force–current relation

Figure 5. Performance comparison between the novel and conventional multi-winding MR damper

5. Conclusion

In this research, a novel multi-winding MR damper with embedded flow passage is designed. The structural design principle of the novel MR damper is to enlarge the effective area of MR fluid by the special arrangement of flow passage embedded in magnetic core. The mathematical model of the damping force is established to evaluate the damping performance of the novel MR damper. An electromagnetic FEA of the designed MR damper is performed, and the damping force characteristics are numerically investigated. Simulation results show that the novel designed MR damper can afford a high dynamic range of 26.7, which is 29% larger than a conventional one, and a relatively large damping force of 6.4kN under a movement velocity of 0.15 m/s. Compared to a same-size multi-winding MR damper, this novel MR damper can save 53.4% electrical energy when produce 4 kN damping force. It confirms that the novel MR damper can increase the effective length of flow passage in limited space and enhance the electromagnetic efficiency further more.

6. Acknowledgments

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