Design of multi-magnetic couple MR damper with full channel effective damping

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Abstract. A multi-magnetic couple magnetorheological damper with full channel effective damping is designed. By designing the magnetic outer ring of the magnetic couple into a structure with gradual cross-sectional area, the purpose of effective damping of the full channel can be achieved, so that the entire damping channel is affected by the magnetic field. Through the magnetic circuit simulation analysis, the rationality of the design is verified, and the magnetic induction intensity on the damping channel can reach the theoretical design value, which reflects the efficient magnetic field utilization rate of the damper.

1. Introduction
Magnetorheological (MR) damper is a semi-active actuator with excellent electromagnetic controllability, which uses MR fluid as working medium[1]. MR damper is characterized by its fast response speed, low energy consumption and easy control[2], and has broad application prospects in vehicles, buildings, bridges, human prosthesis and other fields [3-5].

At present, in the structural design of MR damper, the magnetic circuit structure of radial winding is mainly adopted, that is, a piston with I-shaped structure is designed, and the excitation coil is wound on the winding frame in the middle of the piston radially. This structure is simple and effective, but the magnetic circuit can only make the damping channels on both sides of the piston receive the magnetic field effectively, the middle part of the damping channel is not used, so the overall effective damping channel is relatively low [6-7], which makes the working performance of MR damper limited.

In view of the above problems, this paper designs a MR damper with multi-magnetic couple piston structure by winding the excitation coil axially, and optimizes the magnetic circuit structure through the gradual change of the cross-sectional area of the magnetic outer ring, so as to achieve the full channel effective damping.

2. Structural characteristics analysis

2.1. Structure composition
The axial structure of multi-magnetic couple MR damper with full channel effective damping are shown in Figure 1.
Figure 1. Structural of multi-magnetic couple MR damper with full channel effective damping

1: cylinder; 2: MR fluid; 3: excitation coil; 4: magnetic outer ring; 5: winding frame; 6: magnetic inner ring; 7: gap; 8: piston rod; 9: magnetic lines of force; 4-1: outer arc; 4-2: inner arc; 4-3: chamfer.

The main body of the damper is composed of a cylinder, a piston and a piston rod. The piston of the MR damper is composed of four symmetrical magnetic couples. Each magnetic couple consists of a magnetic inner ring, a winding frame and a magnetic outer ring, one end (inner end) of the winding frame is connected with magnetic inner ring, and extends outward along the radial direction, and is connected with the magnetic outer ring to form a T-shaped magnetic couple structure. The magnetic outer ring is composed of an inner arc and an outer arc, in which the outer arc is a uniform arc, the inner arc is a progressive curve, and the inner arc starts from the outer end port of the winding frame and passes through the chamfer smoothly, and connects with the outer arc at the end to form an extension structure with a gradually changing cross-sectional area, and the cross-sectional area of the extension structure at the end tends to zero. The adjacent magnetic couples are connected at the end of the magnetic outer ring to form a smooth curved surface. A damping channel is formed between the curved surface and the cylinder and filled with MR fluid. The excitation coil is wound on the winding frame, and the magnetic gap is formed to provide enough winding space. The piston rod vertically passes through the middle hole of the magnetic inner ring, cooperates with the magnetic inner ring.
2.2. Working principle

The working principle of the damper is: for a single magnetic couple, the magnetic lines of force are emitted from the winding frame, and shunt at the magnetic outer ring. As the magnetic lines of force continue to deepen into the extension of the magnetic outer ring, the cross-sectional area that passes through is continuously reduced. Based on the conservation of magnetic flux, the magnetic lines will shunt to the magnetorheological fluid passing by, and all of them will flow out when they reach the end, so that all the damping channels of a single magnetic couple can be used, and the magnetic field lines are evenly distributed. For the whole multiple magnetic couples, the adjacent magnetic couples are connected at the end of the outer magnetic ring to form a complete damping channel. Because the cross-sectional area at the end of the magnetic outer ring tends to 0, the magnetic resistance at this position tends to infinity, so the magnetic lines of force can not be directly connected from one magnetic couple to the adjacent one. Based on the structure itself, the magnetic resistance effect between the magnetic couple is achieved, the magnetic lines of force need to pass through the MR fluid and cylinder to reach the adjacent magnetic couple from one magnetic couple, so as to achieve the effect of effective damping of the whole channel.

3. Size design of MR damper

3.1. Magnetic circuit size design based on flux conservation

The structure size design of MR damper is mainly the size of magnetic part, which can be designed according to the method of flux conservation[8]. According to the analysis in Section 2, the length of the damping channel of each magnetic couple is equal, and the adjacent magnetic couples are connected in the magnetic outer ring to form an effective damping of the whole channel. The length of the damping channel of each magnetic couple can be expressed as follows:

$$L = \frac{2\pi R_0}{4}$$

In equation (1), $L$: The length of the damping channel of each magnetic couple.

The saturation flux of MR fluid on the damping channel of each magnetic couple can be determined:

$$\phi_{MRF} = \frac{2\pi R_0 B_{MRF}}{4}$$

In equation (2), $\phi_{MRF}$: the saturated magnetic flux of MR fluid on the damping channel of each magnetic couple, $B_{MRF}$: the saturated magnetic induction of MR fluid.

Based on the conservation of magnetic flux, the following relation is satisfied:

$$\phi_{MRF} = \phi_w = \phi_{h_i} = \phi_{h_k}$$

In equation (3), $\phi_w$: the magnetic flux of the winding frame, $\phi_{h_i}$: the magnetic flux of the magnetic conducting inner ring, $\phi_{h_k}$: the magnetic flux of the cylinder.

Based on equation (2) and equation (3), some magnetic circuit size parameters can be determined:

$$w = \frac{2\pi R_0 B_{MRF}}{4B_p}$$

$$h_3 = \frac{\pi R_0 B_{MRF}}{4B_p}$$

In equation (4) and equation (5), $B_p$: The saturation magnetic induction of piston.
In equation (6), $B_c$: Saturation magnetic induction of cylinder.

3.2. Dimension design of magnetic outer ring

The inner arc of the outer magnetic ring of the multi couple piston is a gradual curve, and its size cannot be determined directly, but it can be optimized through three points of the arc. According to the analysis in Figure 1, there will be a large magnetic flux at the junction of the winding frame and the inner arc. The thickness $h_1$ of the extension section at the beginning should satisfy the magnetic flux and no local magnetic saturation will occur. The thickness $h_1$ is proportional to the width $w$ of the winding frame:

$$h_1 = k_1 w$$  \hspace{1cm} (7)

In equation (7), $k_1$: scale coefficient.

When the magnetic characteristics of magnetic materials are determined, the width $w$ of winding frame directly reflects the magnitude of magnetic flux. Therefore, with the increase of the $w$, the $h_1$ should also increase proportionally. The ratio coefficient $k_1$ can be taken from 1/2 to 1/3.

On this basis, the length $h_2$ of the winding frame is adjusted and designed according to the $h_1$.

The two ends of the inner arc of the magnetic outer ring are respectively connected with the winding frame and the outer arc. Based on equation (1), the contact point of the outer arc and the inner arc can be determined. Based on equation (7), the contact point of the winding frame and the inner arc can be determined. After the points of the two ends (beginning and end) are determined, the position of the middle point of the inner arc also needs to be determined. The specific form of arc segment is roughly determined by the position of three points. The position of the middle point of the inner arc can be determined by calculating the thickness of the extension section of the magnetic outer ring at the middle point. The thickness $h_5$ of the extension at the midpoint is proportional to the thickness $h_1$ at the beginning end. Set the thickness $h_5$ at the midpoint to be proportional to the thickness $h_1$:

$$h_5 = k_2 h_1$$  \hspace{1cm} (8)

In equation (8), $k_2$: the proportional coefficient. $k_2$ is determined according to the ratio of the permeability $\mu_p$ of the piston to the permeability $\mu_c$ of the cylinder, and satisfies such a relationship:

$$k_2 = H \\frac{\mu_p}{\mu_c}, \quad H: \text{the engineering coefficient.}$$

The larger the ratio $\frac{\mu_p}{\mu_c}$, the smaller the value $H$ will be. Because with the better magnetic conductivity of the piston, more magnetic lines of force will first converge to the end of the extension section. Therefore, it is necessary to make the curvature of the inner arc larger and the cross-sectional area of the extension section decrease faster, and the convergence of the magnetic lines of force to the end is further restricted. On the contrary, the larger the value $H$.

4. Simulation calculation and analysis of magnetic circuit structure

In the magnetic part, the cylinder is made of 45 steel, and the piston is made of silicon steel with high magnetic conductivity. The size parameters are shown in the Table 1.
Table 1. structural dimension parameters of MR damper

| Parameter | Value (mm) |
|-----------|------------|
| R0        | 3          |
| R1        | 4          |
| h1        | 7          |
| h2        | 1          |
| h3        | 2          |
| h4        | 8          |

The saturation magnetic induction of MR fluid is set to be 0.5T. According to Table 1, the overall magnetomotive force is calculated by using the ohm theorem of magnetic circuit. It can be estimated that the number of turns of each winding coil is 200, and the current is 1A. ANSYS Maxwell is used to analyze the magnetic circuit of MR damper.

Figure 2. distribution of magnetic lines of force

Figure 2 is the distribution of the overall magnetic lines of force. It can be clearly observed that the magnetic lines of the magnetic couple converge in the winding frame area and diverge in the magnetic outer ring area and pass through the damping channel evenly. The magnetic lines between the adjacent magnetic couple are not directly connected, and the magnetic lines are evenly distributed on all damping channels and act on the MR fluid vertically, which achieves the effect of effective damping of the whole channel. Because of the winding direction of coils between adjacent magnetic couples is opposite, the magnetic fields are symmetrically superimposed, forming a symmetrical and uniform closed magnetic circuit.

Figure 3. distribution of magnetic induction intensity
Figure 3 is the distribution cloud diagram of the overall magnetic induction. The distribution of the magnetic induction intensity is uniform, and the magnetic induction intensity in the piston area is basically around 1.5T, and there is no saturation in the magnetic circuit, indicating that the designed size is reasonable. At the end point of the magnetic outer ring, the magnetic induction intensity of the material reaches the saturation value of the set magnetization curve. Based on the structure itself, it avoids the direct connection of the magnetic lines of force at the junction of the adjacent magnetic couple, so there is no need to occupy part of the damping channel to set the resistance magnetism.

Figure 4 is the distribution curve of magnetic induction intensity at damping channel.

Figure 4 is the distribution curve of magnetic induction intensity on the whole circumferential damping channel of MR damper. Each block curve in the figure corresponds to the magnetic induction intensity at the damping channel of a single magnetic couple. It can be seen that the magnetic induction intensity of MR fluid reaches the designed 0.5T, and the distribution is relatively flat. There is only a very narrow interval between the block curves, so the overall utilization rate of the damping channel is very high, which achieves the effect of effective damping of the whole channel.

5. Conclusions
(1) The designed MR damper has compact structure and better magnetic properties. The magnetic outer ring is designed as an extension structure with gradual change of cross-sectional area, which can make the distribution of magnetic lines of force on the damping channel more uniform, and the adjacent magnetic couples are connected at the end of the extension section, and there is no need to set the magnetic separation section, so as to achieve the effect of effective damping of the whole channel.

(2) The rationality of the design is verified by magnetic field simulation. The compactness and symmetry of the whole magnetic circuit of the damper can be seen from the distribution of magnetic lines; through the magnetic induction intensity cloud image, it can be seen that the overall structure of the magnetic circuit has no magnetic saturation, and the magnetic resistance effect is achieved based on the structure itself; through the magnetic induction intensity distribution curve at the damping channel, it can be seen that the MR fluid in the working area has reached the set value, and the curve is straight and full, which reflects the working characteristics of the whole channel damping.

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