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The design and simulation of magneto-rheological damper for automobile suspension

Kang Lulu, Luo Yiping, Ren Hongjuan

(College of Automotive, Shanghai University of Engineering Science, Shanghai, 201620)

Abstract: As the application of magneto-rheological (MR) damper in automobile suspension semi-active control, according to the character of the MR fluid and the relations between the damping force of MR damper and the structure parameters, the new-type automobile suspension MR damper was designed. At present, the design method of MR damper is still depended on the experience of the designer, which can't be calculated accurately. In this paper, after a review of the features and models of MR materials and devices, geometrical design and magnetic circuit design of MR damper were presented and discussed in detail, then the performance of MR damper was analyzed by MATLAB. Simulation results showed that the design method of this automobile suspension MR damper was feasible and the test performance was satisfactory, which could meet the requirements of damping system for automobile suspension and achieve the required adjustable range of anticipative damping force.

The keyword: magneto-rheological damper; automobile suspension; semi-active control

I. Introduction

Magneto-rheological(MR) damper is a semi-active control damper with magneto-rheological fluid(MRF) as the medium, the external magnetic field strength can be changed by the control of the input current, which can change the rheological properties of the MRF in milliseconds, to realize the change of the MRF in the fluid and the semi solid. Furthermore, it can provide controllable damping force, which has the advantages of simple structure, convenient control, fast response, small power consumption, strong anti pollution ability and large output force.

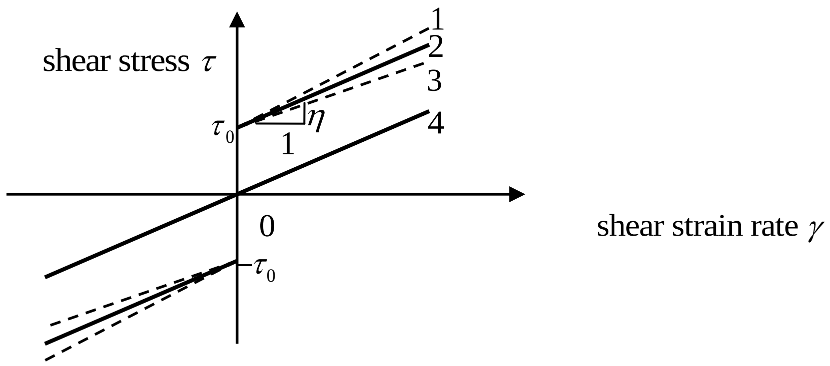
The operating modes of the automobile suspension MR damper are divided into valve type, shear type and extrusion type according to the classification standards of the working modes of the MRF. These operating modes can also be used to design a MR device, which is called a hybrid operating mode.

At present, it is urgent to develop a automobile suspension MR damper with reasonable structure and excellent performance to promote its application in the vehicle engineering field. The key in the design of the MR damper is to make full use of the excellent properties of the MRF. However, the design theories of the MR damper are not perfect. In this paper, in order to further strengthen the research on the precise design method of the MR damper, the design and analysis of the MR damper for automobile suspension had been completed.

II. Damping force calculation model and magnetic circuit design of the automobile suspension MR damper

2.1 Rheological constitutive model of MRF

The behavior of the MRF is a visco-plastic fluid in the external magnetic field. So far, there is no a single or simple constitutive equation can accurately describes the rheological properties of MR fluid, only several empirical equations are in accord with the actual fluid in a certain range. Two kinds of rheological models of the most widely used MRF are shown in Fig.1: Bingham model and Herschel-Bulkley model.



1—shear thickening($m>1$); 2—Bingham($m=1$); 3—shear thinning($m<1$); 4—Newton fluid
Fig.1.Visco plastic model of MRF

Bingham model [1] is a most simple constitutive relation model of MRF. The stress-strain relationship of model is:

$$\tau=\tau_0\,\mathrm{sgn}(\gamma)+\eta\gamma \tag{1}$$

Where τ_0 is the yield strength of MRF, H is the magnitude of the magnetic field, $\mathrm{sgn}(\cdot)$ is the sign function, γ is the shear strain rate and η is the dynamic viscosity coefficient.

Herschel-Bulkley model [2] assumed that the viscosity of the fluid was a power function associated with the shear strain rate γ:

$$\tau=(\tau_0+K|\gamma|^{1/m})\,\mathrm{sgn}(\gamma) \tag{2}$$

where m is the flow characteristic parameter, K is the uniformity coefficient, m 、 K > 0.

According to (2), when $m>1$, the viscosity will be reduced with the increase of γ, which describes the shear thinning phenomenon of MRF. When $m=1$, which is the Bingham model. In the case of high shear rate or high magnetic field strength, Herschel-Bulkley model can consider the shear thinning or shear thickening phenomena occurring in the post yield region.

2.2 The damping force calculation models of MR damper

In flow pattern, the damping force of the MR damper consists of the damping force ΔP_η caused by the viscosity of MRF and the damping force ΔP_τ caused by the magnetic field. In shear pattern, the shear stress consists of the shear stress F_η caused by the viscosity of MRF and the shear stress F_τ caused by the magnetic field.

In this paper, a pair of permanent magnets are installed inside the MR damper, which will produce the corresponding repulsive force F_c. When MR damper working under mixed mode of valve type and shear type, the total damping force is:

$$F=\Delta P_{\eta}+\Delta P_{\tau}+F_{\eta}+F_{\tau}+F_{c}$$

$$=\frac{12\mu_0 QL}{g^3 w}A_p+\frac{c\tau_y L}{g}A_p+\frac{\mu_0 Lw}{g}V_0+\tau_y Lw+\frac{1.5}{1+aL_0}\times\left(\frac{B_g}{4965}\right)^2 A_g \tag{3}$$

Where, $Q=V_0A_p$, $w=2\pi R_1$, $g=R_2-R_1$, $L=2l$, $c=3$, combining those with (3):

$$F=\frac{12\mu_0 l A_p{}^2}{\pi R_1(R_2-R_1)^3}V_0+\frac{3lA_p}{R_2-R_1}\tau_y+\frac{4\pi R_1\mu_0 l}{R_2-R_1}V_0+4\pi R_1/\tau_y+\frac{1.5}{1+aL_0}\times\left(\frac{B_g}{4965}\right)^2 A_g \tag{4}$$

where μ_0 is the zero magnetic field viscosity of MRF, L is the piston's length, Q is flow in the gap, g is the gap's thickness, w is the piston's circumference, τ_y is the yield stress, the value range of the c is 2～3 (when $\Delta P_{\tau}/\Delta P_{\eta}\le 1, c=2$; when $\Delta P_{\tau}/\Delta P_{\eta}\ge 100, c=3$), V is the relative speed of the plate, A_p is the effective working area of the piston, B_g is the magnetization of the permanent magnet, the value range of the correction factor c is 3～5, L_0 is the gap between two permanent magnets.

According to (3), the main factors that affect the damping force of MR damper are: the maximum yield strength τ_y, volume flux Q, piston's length L and gap's thickness g. The size of the damping force is inversely proportional to g, is proportional to piston's length L.In order to increase the maximum damping force, within the allowed range of increasing L and decreasing g. Therefore, this paper mainly focuses on the design of these parameters.

2.3 The design of magnetic circuit system of MR damper

The performance of MR damper mainly depend on its geometrical size, magnetic circuit and the performance of MRF. In the case of the given performance parameters of MRF, the key to design a good damper are the structure design and magnetic circuit design of damper. In addition, it also includes dust, leakage, magnetic separation, sealing, cooling and connection [3-4].

The purpose of magnetic circuit design of MR damper is to determine the number of turns of the coil. In order to make the magnetic field strength reach the maximum, the damper has larger controllable damping force. In addition, the temperature of the coil shall not exceed the allowable value, the size of coil should be matched with the piston dimensions.

According to the characteristics of MRF, the function of dynamic yield stress and magnetic field strength can be determined:

$$\tau_y=\alpha H^{\beta} \tag{5}$$

where α and β are the constants for specific materials.

The magnetic circuit structure of MR damper is shown in Fig.2, in the case of no leakage magnetic field, the magnetic flux and the magnetic field strength of each part of Fig.2 are respectively:

$$\Phi_B = B_i S_i \tag{6}$$

$$H_i = \frac{B_i}{\mu_i} = \frac{\Phi}{\mu_0 \mu_{ri} S_i} \tag{7}$$

where B_i is the magnetic flux density of each segment, μ_i is the permeability of each segment, Φ is the closed magnetic flux, μ_0 is the permeability of vacuum, μ_{ri} is the relative permeability of medium, S_i is the each end surface area of magnetic circuit.

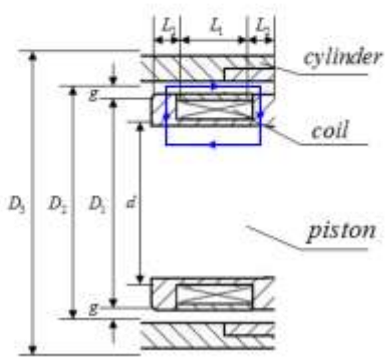


Fig.2. Schematic diagram of magnetic circuit system

Assuming that the number of the field coils is N, the current in the coil is I. According to ampere loop theorem, the magnetomotive force of the whole circuit[5]:

$$\varepsilon_m = NI \tag{8}$$

The calculation of each part of resistance is as follows:

Magnetic core: $$R_1 = \frac{4(L_1 + 2L_2)}{\pi \mu_1 d^2} \tag{9a}$$

Magnetic yoke: $$R_2 = \frac{\ln(D_1/d)}{2\pi \mu_2 L_2} \tag{9b}$$

Cylinder: $$R_3 = \frac{4(L_1 + 2L_2)}{\pi \mu_3 (D_3^2 - D_2^2)} \tag{9c}$$

Working gap: $$R_g = \frac{\ln(D_2/D_1)}{2\pi \mu_{MRF} L_2} \tag{9d}$$

Total reluctance: $$R_m = 2R_1 + 4R_2 + 2R_3 + 4R_g \tag{9e}$$

where $\mu_i = \mu_0 \cdot \mu_{ri}$, μ_{ri} is the relative permeability of each transmission medium, μ_0 is the vacuum permeability, $\mu_0 = 4\pi \times 10^{-7}\ H/m$.

According to ampere theorem, $\Phi_B(2R_1 + 2R_2 + 4R_3 + 4R_g) = \varepsilon_m$, where Φ_B is the magnetic flux. According to (6): in damping passage of the MR damper, the relationship between the magnetic flux and the magnetic induction intensity is $\Phi_B = BS$.

Synthesize above-mentioned formula can be:

$$B = \frac{\varepsilon_m}{S(2R_1 + 4R_2 + 2R_3 + 4R_g)}$$

$$= \frac{4\varepsilon_m}{\pi(D_2^2 - D_1^2)(2R_1 + 4R_2 + 2R_3 + 4R_g)} \quad (10)$$

According to (6), the magnetic field strength in the damping ring can be obtained:

$$H = \frac{4\varepsilon_m}{\pi(D_2^2 - D_1^2)\mu_g(2R_1 + 4R_2 + 2R_3 + 4R_g)} \quad (11)$$

Combining (8) with (11) can be obtained:

$$H = \frac{NI}{S(2R_1 + 4R_2 + 2R_3 + 4R_g)} \quad (12)$$

According to (12), it can be known as long as the structure parameters and the number of field coil turns are confirmed, the magnetic field strength in the damping ring can be completely controlled by the input current.

In this paper, the magnetic field lines of the magnetic circuit are shown in Fig.3, the magnetic field lines are uniformly through the magnetic field, there will be the corresponding damping force.

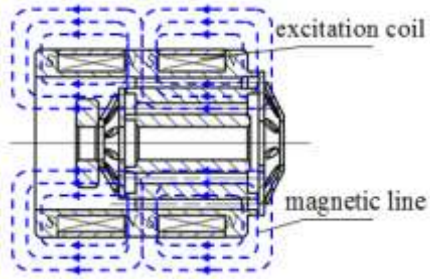


Fig.3. Distribution of magnetic circuit

III. The structure design of MR damper

As a mechanical component, the design of automobile suspension MR damper should consider the strength and rigidity of the components. The main contents of the structural design are the selection of the material of the piston and cylinder, the determination of the section size, the stress analysis of the component.

In the design, the shear yield strength τ_0 , viscosity coefficient η and size parameters of the cylinder of MRF are known, assume gap is g , range of value is 1～2mm. According to (3), the piston length is determined, which needs to be adjusted according to the design of magnetic circuit.

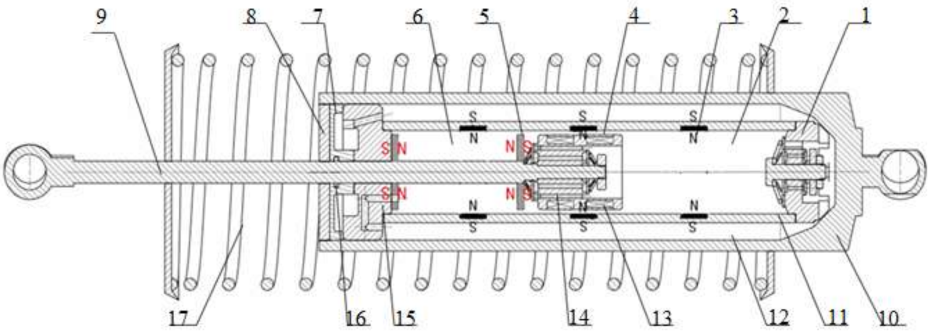
The design should be based on the standard formula of the mechanical design for verifying the cylinder thickness δ and the diameter d of the piston rod, the formula is as follows:

$$\delta \geq \frac{p \times D}{2[\sigma]} \tag{13}$$

$$d \geq \sqrt{\frac{4F}{\pi[\sigma]}} \tag{14}$$

where p is the highest working pressure, the unit is Pa, D is the inner diameter of cylinder, $[\sigma] = \sigma_b / n$ is the allowable stress of cylinder material, σ_b is the material tensile strength, n is the safety factor, F is the axial force of the piston rod.

In this paper, the structure of the MR damper is shown in Fig.4:



where 1 is the valve components, 2 is the working chamber A, 3 is the permanent magnetic ring, 4 is the protection ring of excitation coil, 5 is the tensile permanent disk, 6 is the working chamber B, 7 is the liquid seal, 8 is the cap of damper, 9 is the piston rod, 10 is the storage cylinder of liquid, 11 is the working cylinder, 12 is the storage cavity C of oil, 13 is the excitation coil, 14 is the piston components, 15 is the guide seat components, 16 is the sealing ring, 17 is the spring components.

Fig.4. Schematic diagram of the structure of the MR damper

IV. Simulation analysis of MR damper

In order to test the feasibility of the MR damper, the simulation analysis is carried out by MATLAB. According to the stroke of the damper and the working condition of the recovery valve and the compression valve, the computer simulation of the damper is performed according to fig.5.

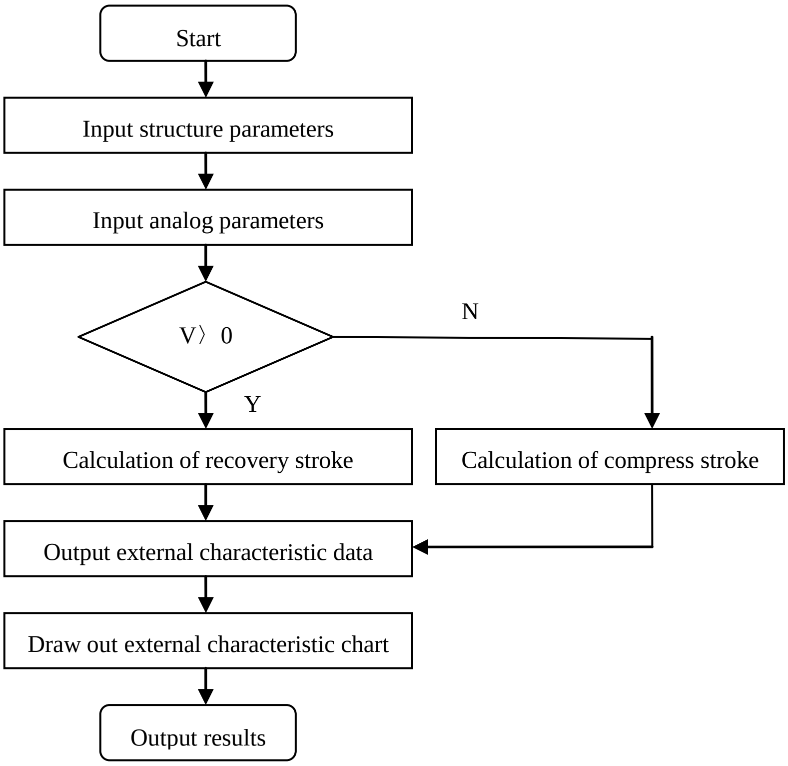
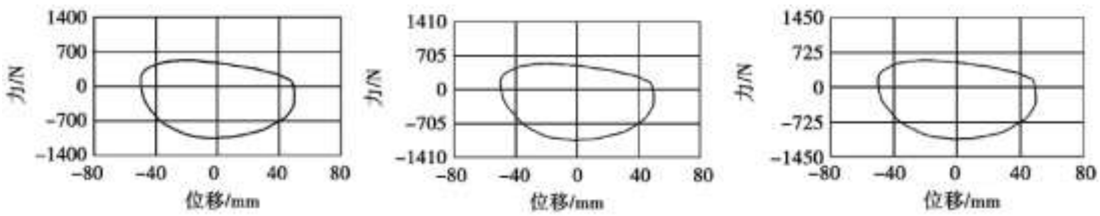
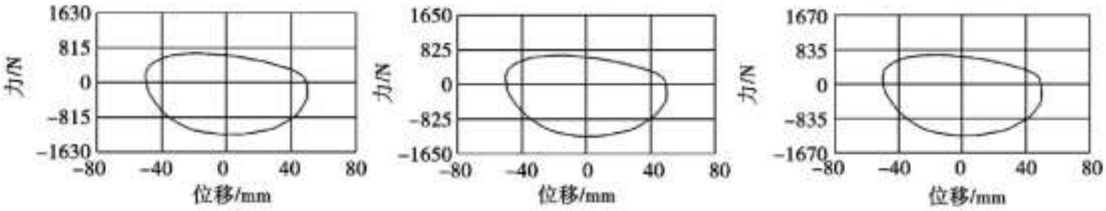


Fig.5. Flow chart of simulation of damping characteristics

Combined with the design parameters of the MR damper, the simulation is based on the sinusoidal excitation. The maximum speed are respectively $0.39\,m/s$, $0.52\,m/s$, the amplitude are $\pm 50.0mm$. Different size of the simulation driven current are applied to the excitation coil, the range of current is $0 \sim 3A$. A record interval is 0.2A, the reactive characteristic curve is shown in Fig.6. The simulation results show that with the increase of the coil current, the area of reactive power will increase, which shows that the damping force of the damper will increase and the power dissipation will increase in the same condition. Under the same input current, the damping force is proportional to the vibration velocity. When velocity is $0.39\,m/s$, the restoring force has increased from $478.1N$ to $560.2N$. When velocity is $0.52\,m/s$, the restoring force has increased from $628N$ to $693N$. Simulation results showed that the MR damper accords with the technical requirements of the automotive suspension, the test performance is desired and the damping force attains the adjustable range.



(a) $v = 0.39\,m/s, I = 0.2A$ (b) $v = 0.39\,m/s, I = 0.4A$ (c) $v = 0.39\,m/s, I = 0.6A$



(d) $v = 0.52\,m/s, I = 0.2A$ （e） $v = 0.52\,m/s, I = 0.4A$ （f） $v = 0.52\,m/s, I = 0.6A$

Fig.6.Simulation curve of damper

V. Conclusion

The design of MR damper refers to many subjects such as materials, electromechanical, mechanical and so on. The key is to establish the relationship between the damping force and the geometrical size of the damper and the magnetic circuit parameters. In this paper, the structure and magnetic circuit of the MR damper are introduced in detail. Finally, the performance of the MR damper is simulated. The results show that the simulation results are consistent with the theoretical data of the MR damper and accord with the technical requirements of the automobile suspension, which means that the design method is feasible.

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