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RESEARCH ARTICLE

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Study on damping properties of magnetorheological damper

Abstract To research the properties of a new kind of smart controllable MR (magnetorheological) fluid, in this paper, the rheological models are discussed. On the basis of analyzing the structural forms of MR dampers, an improved structure of the MR damper is introduced; the properties of the novel MR damper are then tested. The experimental results reveal that the Herschel-Bulkley model predicts the force-velocity well; the damping properties of the ameliorated structure of the MR damper have improved; when the excitation is a trigonal signal, the MR damper reveals a thinning effect at high velocity; and when the excitation is a sinusoidal signal, the MR damper reveals a nonlinear hysteretic property between the damping force and relative velocity. Finally, the main unsolved problems have been put forward.

Keywords MR (magnetorheological) fluid, rheological model, MR damper, damping properties

1 Introduction

The initial discovery and development of the MR (magnetorheological) fluid can be credited to Jacob Rabinow (1948–1951) at the US National Bureau of Standards in the late 1940s. MR fluids are a new kind of smart material that can influence rheology by the application of a magnetic field.Typically, when a magnetic field is applied to MR fluids, MR fluids have the ability to increase the dynamic yield stress considerably. Moreover, this rheologicl property can be implemented within a very short time, typically microseconds. Now, MR fluids have been considerably interesting because this rheological property can provide simple, rapid-response, and strong interface between magnetic field and mechanical systems. Many MR-fluid-based engineering devices, such as servo-valves, clutches, brakes, and suspensions, have been designed and widely researched. Spencer et. al. developed a phenomenological model for an MR damper based on the Bouc-Wen hysteresis model [1, 2]. In China, MR fluids have been studied and developed at Fudan University and Chongqing University. MR dampers are being tested for civil engineering applications and mechanical systems at Shanghai Jiao Tong University [3] and Harbin University of civil engineering and architecture [4]. In this paper, the ameliorated structure of an MR damper based on the Herschel-Bulhley viscoplasticity model has been designed and the damping properties have been tested.

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2 MR fluid models

A simple Bingham viscoplasticity model, as show in Fig. 1, is effective in describing the essential field-dependent fluid characteristics. In this model, the total shear stress τ is given by:

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

where τ_0 is the yield stress caused by the applied field, H is magnitude of the applied magnetic field, $\dot{\gamma}$ is shear strain rate, and η is field-independent plastic viscosity, defined as the slope of the measured postyield shear stress versus shear strain rate.

Note that the postyield viscosity of the fluid is assumed to be a constant in the Bingham model. Because MR fluids exhibit shearing thinning effect, the Herschel-Bulhley viscoplasticity model can be employed to accommodate this effect. In this model, the constant postyield plastic viscosity in the Bingham model is replaced with a power law model dependent on shear strain rate [5]. Therefore,

$$\tau = \left(\tau_0(H) + K|\dot{\gamma}|^{\frac{1}{m}} \right) \mathrm{sgn}(\dot{\gamma}) \quad (2)$$

where m, K are fluid parameters and $m, K > 0$. Comparing Eq. (2) with Eq. (1), the equivalent plastic viscosity of the Herschel–Bulkley model is:

$$\eta_e = K|\dot{\gamma}|^{\frac{1}{m}-1} \quad (3)$$

Equation (3) indicates that the equivalent plastic viscosity η_e decreases as the shear strain rate $\dot{\gamma}$ increases when $m > 1$ (shearing thinning). Furthermore, this model can also be used to describe the fluid shear thickening effect when $m < 1$. The Herschel-Bulhley model reduces to the Bingham model when $m = 1$, therefore $\eta_e = K$.

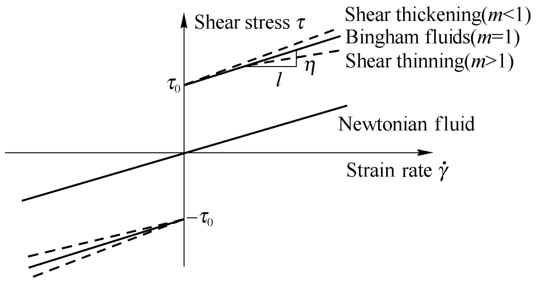

Fig. 1 Viscoplasticity models of MR fluids

3 The ameliorated structure of an MR damper

Previous studies had employed the Bingham plastic model, based on the parallel-plate Bingham model, which was developed and validated in the previous section. The controllable force and the dynamic range are two of most important parameters in evaluating the overall performance of an MR damper. To maximize the effectiveness of the MR damper, the controllable force and dynamic range should be as large as possible. For certain sizes of devices, the gap size has a direct impact on both parameters, therefore a small gap size is required. Thus the choice of an appropriate gap size is pivotal in the MR damper geometry design. The size should be selected so that large values for both controllable force and dynamic range are achieved to meet design requirements. A typical relationship between gap size, dynamic range, and controllable force have been provided by Guangqiang Yang in Fig. 2 [1], where gap ratio (h/R_2) is the ratio between the flow gap (between the piston and the cylinder housing) and the diameter of the damper piston.

Now most available MR dampers have the same structure shown by Fig. 3, which presents the effective magnetic circuit of this structure. Obviously we can find out disadvantages: magnetic lines do not completely go through the effective magnetic circuit because of the conducting effect of the cylinder house, which makes magnetic lines escape outside or sideways along the cylinder house, thus influencing working performance. On this account, this paper puts forward an improved structure of an MR damper, as shown by Fig. 4. It is structured by the respective layers of a magnetic conductor and a magnetic resistor. Layers of the magnetic conductor lead all magnetic lines to go through the effective magnetic circuit while layers of the magnetic resistor prevent magnetic lines from escaping. In addition, the cylinder house uses magnet resistance material, and forms magnetic defence. Experiments followed prove that adopting this kind of structure can significantly enhance the damping property of MR dampers.

4 Experimental test of the MR damper

To investigate the fundamental behavior of the MR damper designed in this paper, the MR damper was used to study the damping property at the Institute of Sound and Vibration Control at Xi'an Jiaotong University. A hypo-frequency oscillational experimental equipment was used to give respective displacement excitation of a triangular wave and a sinusoidal wave to determine relations between damping force and velocity, amplitude, as well as frequency.

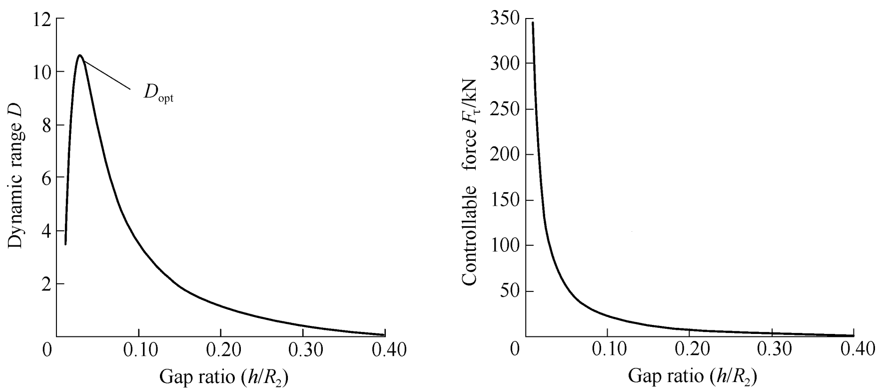

Fig. 2 Relationship between gap size, dynamic and controllable force

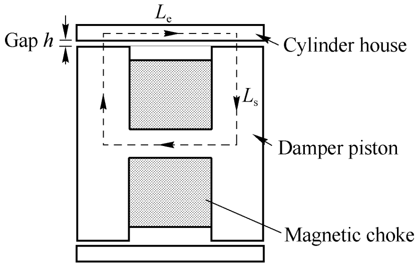

Fig. 3 Simple figure of forthcoming magnetic circuit of MR dampers

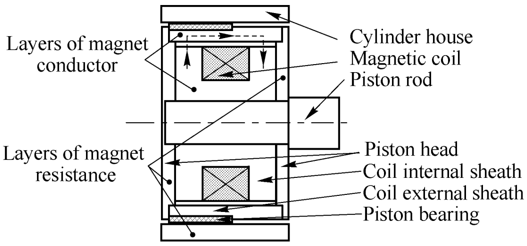

Fig. 4 Simple figure of modified magnetic circuit design of MR dampers

4.1 Damper testing under triangular displacement excitations

Force-displacement and fore-velocity tests under triangular displacement excitation were conducted to investigate the fundamental behavior of the MR damper. In this experiment, 12.5 mm triangular displacement excitations at velocities of 0.25, 0.5, 1, 2, 2.5, and 5 cm/s were employed.The input current to the damper coil was constant at 0.25, 0.5, 0.75, 1, 1.5, and 2 A, respectively. Note that the triangular waveform does not introduce inertial forces into the overall system except when the velocity changes direction. This allows for an accurate measurement of the damping force. The displacement and force signal were measured to get velocity signal after handling data. The result is presented by Fig. 5. Curves of Fig. 6 that correspond to the plot for force-displacement at the velocity of 5 cm/s, from internal to external curves are respectively in accordance with input current at 0.25, 0.5, 0.75, 1, 1.5, and 2 A.

From Figs. 5 and 6 we can find out that while at the velocity of 5 cm/s, damping force without current is about 0.11 kN, whereas when connected to current at 2 A, it becomes 0.52 kN. So the damper's dynamic range of damping force is 0.52/0.11= 4.73. With regard to the system of cars, usually its working frequency is around 1 Hz, corresponding to a velocity of 1.25 cm/s as shown in Fig. 6 . Then the dynamic range becomes more than 5. Compared with Literation [4], our experiment results in higher dynamic range, which means better damping property under the condition of diminishing general structure, so our design is much more reasonable.

Figure 5 shows that damping force increases as velocity increases, however, its extent turns smooth. That is, the phenomenon of shear thinning begins to appear at the velocity of 2.5 cm/s in Fig. 5. The bigger the velocity, the more the thinning quantities become; for example, while current is at 1.5 A and velocity is 5 cm/s, the quantity of thinning is 0.073 kN and the rate of thinning is 17.7 %. It is obvious that adopting the Bingham model will give rise to comparatively larger error while the Herschel–Bukley model fairly accurately presents force-velocity relation of the MR damper. In addition, according to Fig. 5, shear thinning changes as current changes. This phenomenon must be paid great attention to when the MR damper becomes an accurate model.

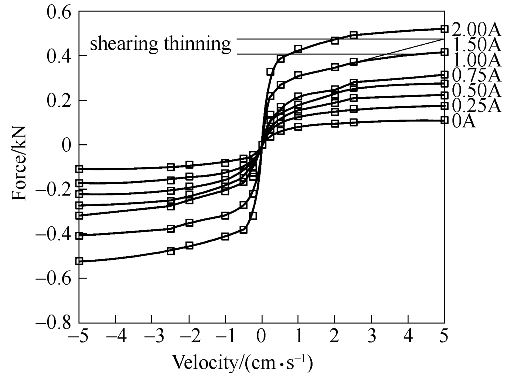

Fig. 5 Force-velocity relationship at trigonal excitation

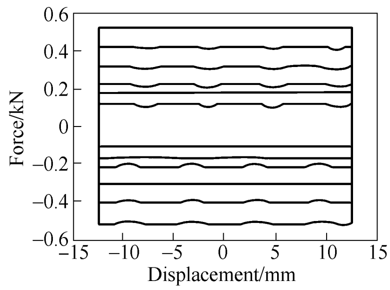

Fig. 6 Plot for force-displacement at velocity is 5 cm/s

4.2 Damper testing under sinusoidal displacement excitations

Input excitation is a sinusoidal signal. With an amplitude of 10 mm and a frequency of 1 Hz, curves of velocity and damping force as shown by Fig. 7 are monlinear retardant curves clearly.

1) Input wave form is a sinusoidal wave signal. When keeping amplitude unchanged, frequency f changes at 2, 1, 0.5, 0.2, 0.1, and 0.05 Hz. Figure 8 shows the plot of the amplitude of 10 mm. From this we can see that the velocity increases as frequency increases and thus makes the viscous resisting force increase. In experiments, this is displayed by the increase in the damping force. Also when the input wave form is a sinusoidal wave signal, if we keep the frequency unchanged, but gradually alter the amplitude at 20, 15, 10, 5,

2, and 1 mm, and provide current at 1 A, Fig. 9 shows the plot of frequency at 1 Hz. From Fig. 9 we can find out: Velocity grows as amplitude increases, thus damping force increases correspondingly.

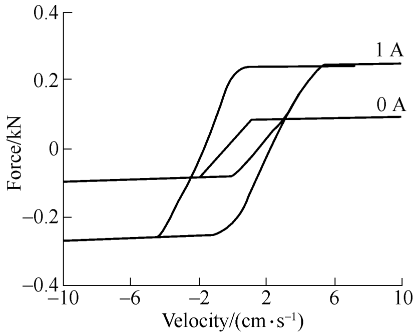

Fig. 7 Force-velocity relationship at sinusoidal excitation

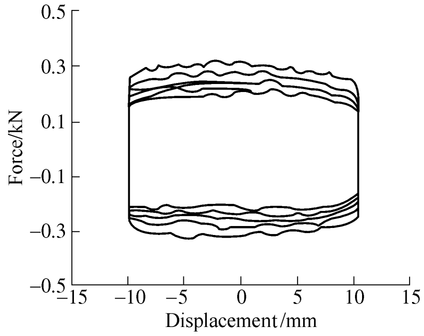

Fig. 8 Plot for force-displacement at stable amplitude with changeable frequency

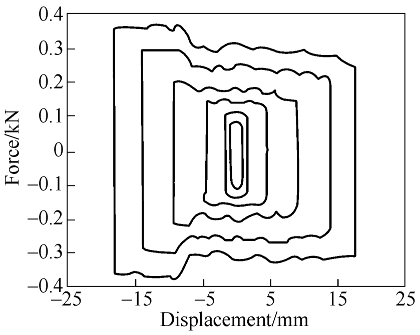

Fig. 9 Plot for force-displacement at stable amplitude with changeable frequency

2) At the displacement of –8.5 mm, damping force has an obvious increase, which still exists after several repeated experiments. It results from the phenomenon of serious layer dividing after MR fluids remain stagnant for a long time; MR fluids under the displacement of –8.5 mm precipitate clearly. The phenomenon of precipitation changes slightly when stirring the fluids with the technique adopted in this paper was researched and produced domestically. It is obvious that although the LORD Corporation has announced detailed data of the six formulas for producing MR fluids, our country still needs to improve on this research.

5 Conclusions

Result of research in this paper indicates:

1) Herschel-Bulkley model can present the force-velocity relationship of MR damper more precisely.

2) Damping property of MR damper improves after adopting the structure of magnetic conductor and magnetic resistor.

3) MR fluids have the phenomenon of shear thinning under triangle wave excitation while the phenomenon of nonlinear retardation appears under sinusoidal wave excitation.

4) Precipitation of ameliorated MR fluids is a problem that needs to be researched at present.

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