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Analysis of magnetorheological fluid damper

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Abstract: Magnetorheological fluids(MRF) are smart materials consisting of silicon oil and very small soft-magnetic particles. In a magnetic field, the viscosity and the flow behaviour of the fluid are considerably changed. MRF damper is a device to give damping by the shear stress of MR fluids. A MRF damper has the property whose damping changes quickly in response to an external magnetic field strength. The design method of a new MR fluid damper is investigated theoretically and the structure is presented. The equation of the damping by MR fluids within damper is derived to provide the theoretical foundations in the design of the damper. Based on this equation, after mathematical manipulation, the calculations of the volume, thickness and width of the annular MR fluids within the MR fluids damper are yielded and discussed.

Key words: magnetorheological(MR) fluid; damper; damping equation

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1 Introduction

Magnetorheological(MR) fluids consist of stable suspensions of micro-sized, magnetizable particles dispersed in a carrier medium such as silicon oil or water. When an external magnetic field is applied, the polarization induced in suspended particles results in the magnetorheological effect of the MR fluids. The magnetorheological effect is direct influences on the mechanical properties of the MR fluids. The suspended particles in the MR fluids become magnetized and align themselves, like chains, with the direction of the magnetic field[1]. The formulation of these particle chains restricts the movement of the MR fluids, thereby increasing the yield stress of the fluids. The change is rapid, reversible and controllable with the magnetic field used in the construction of magnetically controlled devices such as damper, brake, clutch[2−8]. To design the MR fluid damper for a given specification, one must establish the relationship between the shear stress developed by MR fluids and the parameters of the structure and the magnetic field strength.

In this paper, the fundamental design method of the MR damper is investigated theoretically. Bingham model is used to characterize the constitutive behavior of the MR fluids subject to an external magnetic field strength. The theoretical method is developed to analyze the shear stress by the MR fluid within the damper. An engineering expression for the shear stress is derived to provide the theoretical foundations in the design of the damper. Based on this equation, being algebraically manipulated, the volume and thickness of the annular MR fluid within the damper is yielded.

2 Operational principle

MR fluid damper is a device to give damping by the shear stress of MR fluid. A MR damper has the property whose damping changes quickly in response to an external magnetic field strength. The operational principle of the cylindrical MR damper is shown in Fig.1. The MR fluid is filled in the working gap between the fixed outer cylinder and inner cylinder. The inner cylinder moves at a speed v. In the absence of an applied magnetic field, the suspended particles of the MR fluid cannot restrict the relative motion between the fixed outer cylinder and inner cylinder. However, in the course of operation, the magnetic flux path is formed when the electric current puts through the solenoidal coil. As a result, the particles are gathered to form the chain-like structures, with the direction of the magnetic flux path. These chain-like structures restrict the motion of the MR fluid, thereby increasing the shear stress of the fluid. The damper can be achieved by utilizing the shear force of MR fluid. The damping values can be adjusted continuously by changing the external magnetic field strength.

3 Properties of MR fluids

MR fluids are suspensions of micron-sized,

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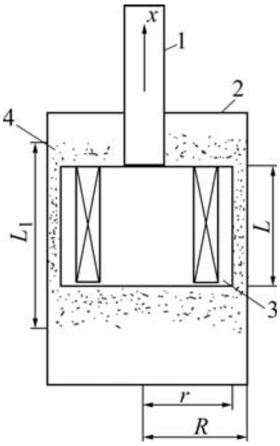

Fig.1 Operational principle of MRF damper

MR fluids are suspensions of micron-sized, magnetizable particles in a carrier fluid. They mainly consist of the following three components: magnetizable particles, a carrier fluid, and some additional additives. The magnetizable particles in MR fluids induce polarization by application of an external magnetic field, which results in the magnetorheological effect of the MR fluids. The carrier fluid serves as a dispersed medium and ensures the particles in the fluid homogeneity. The additional additives include the stabilizers and surfactants. The stabilizers serve to keep the particles suspended in the fluid. The surfactants are adsorbed on the surface of the magnetic particles to enhance the polarization induced in suspended particles by application of a magnetic field.

In the absence of an applied magnetic field, the particles in MR fluid disperse randomly in a carrier fluid. MR fluid flows freely through the working gap between the fixed outer cylinder and rotor. MR fluid exhibits Newtonian-like behavior and the shear stress of MR fluids can be described as

$$\tau = \eta \dot{\gamma} \tag{1}$$

where τ is the shear stress, η is the viscosity of MR fluid with no applied magnetic field and $\dot{\gamma}$ is the shear rate.

When the magnetic field is applied, the behavior of the fluid is often represented as a Bingham fluid having the variable yield strength. In this model, the constitutive equation is derived by the least square method[1].

$$\tau = \tau_B + \eta \dot{\gamma} \tag{2}$$

where τ_B is the yield stress developed in response to an applied magnetic field. Its values are dependent upon the magnetic induction field B.

Fig.2 shows the relation, obtained from the experiment, between shear rate and shear stress depending upon the applied magnetic field strength. As can be seen, the MR fluids have the variable yield strength. The shear stress increases as the applied magnetic field strength. The shear rate has little influence on the shear stress. This result indicates that the MR fluid exhibits Bingham plastic model.

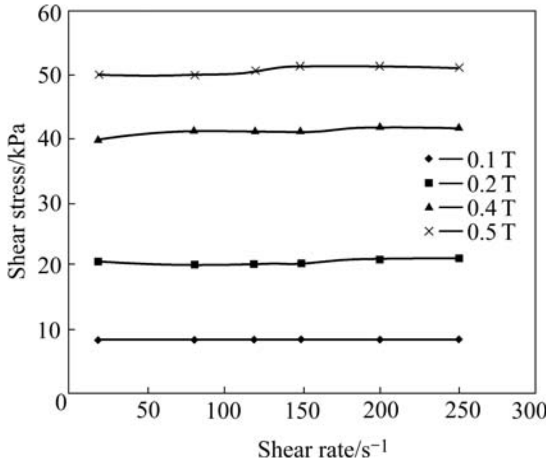

Fig.2 Relationship of shear rate and shear stress

4 Damping of MR damper

The key question in the design of MR fluid damper is to establish the relation between the damper and the parameters of the structure and magnetic field strength. As the magnetic field is applied, the damping F developed by MR fluid can be calculated by[9]

$$F = \frac{12\eta L \pi r^2}{\pi R h^3} v + \left(\frac{K_0 L \tau_B \pi r^2}{h} + f\right) \mathrm{sgn}(v) \tag{3}$$

where v is the speed of piston; f is friction of piston and cylinder; K_0 is a coefficient (0.8−1.0); h is the thickness of the annular MR fluid between the piston and outer cylinder. The value of h can be given by

$$h = R - r \tag{4}$$

If it is assumed that the value of f is much smaller, Eqns.(3) and (4) can be mathematically manipulated to yield

$$F = 2\pi L \tau_B r^2 + \frac{2\pi \eta L r^3 v}{h} \tag{5}$$

Eqn.(5) shows that the damping developed in the cylindrical MR fluid damper can be divided into a magnetic field dependent induced yield stress component F_B and a viscous component F_η[10].

$$F_B = 2\pi L \tau_B r^2 \tag{6}$$

$$F_\eta = \frac{2\pi \eta L r^3 v}{h} \tag{7}$$

The total damping F is the sum of F_B and F_η.

5 Thickness of MR fluid

The active volume of annular MR fluid in the cylindrical MR damper can be obtained through the integration the radius of annular MR fluid as follows:

$$v = 2\pi L \int_{r}^{R} r \mathrm{d}r \tag{8}$$

And then

$$v = 2\pi rLh \tag{9}$$

Eqns.(6)−(9) can be manipulated to yield

$$v = \left(\frac{\eta}{\tau_{\mathrm{B}}^{2}}\right)\left(\frac{F_{\mathrm{B}}}{F_{\eta}}\right)\left(F_{\mathrm{B}}\omega\right)v \tag{10}$$

Eqn.(11) gives the minimum active MR fluid volume that is necessary within the damper in order to achieve the desired control damping ratio (F_{B}/F_{η}) at a given speed v and a specified controllable damping F_{B}.

Eqns.(6) and (7) can be algebraically manipulated to derive the thickness of annular MR fluid as follows:

$$h = \left(\frac{\eta}{\tau_{\mathrm{B}}}\right)\left(\frac{F_{\mathrm{B}}}{F_{\eta}}\right)rv \tag{11}$$

Eqn.(11) provides geometric constraints for MR fluid damper based on MR fluid material properties (η/τ_{B}), the desired control damping ratio(F_{B}/F_{η}) at a given speed v and a radius r of the piston.

The length L of the effective length of the MR fluid can be obtained from Eqns.(9) and (11).

6 Conclusions

The geometric design method of a cylindrical MR fluid damper is investigated theoretically. The damping developed by MR fluid within the damper under different magnetic field strength conditions is analyzed. The engineering design calculations of the volume, thickness and width of the annular MR fluid within the damper are derived. The parameters of the thickness and width of the fluid in the damper can be calculated from the equations obtained, when the required mechanical power level, the speed of the piston, and the desired control damping ratio are specified.

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