Theoretical Studies on Magnetorheological Fluid Brake

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Abstract

A Magneto-Rheological (MR) fluid brake is a device to transmit torque by the shear force of an MR fluid. An MR rotary brake has the property that its braking torque changes quickly in response to an external magnetic field strength. In this paper, the design method of the cylindrical MR fluid brake is investigated theoretically. The mechanical part is modeled using Bingham's equation, an approach to modeling the magnetic circuit is proposed in this work. The equation of the torque transmitted by the MR fluid within the brake is derived to provide the theoretical foundation in the cylindrical design of the brake. Based on this equation, after mathematical manipulation, the calculations of the volume, thickness and width of the annular MR fluid within the cylindrical MR fluids brake are yielded.

Keywords

Magnetorheological Fluid, Brake

I. Introduction

Magneto-Rheological (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 MR effect of the MR fluids. The MR effect directly influences 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. 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 strength [1]. The mechanical properties of the MR fluids can be used in the construction of magnetically controlled devices such as the MR fluid rotary brake, or clutch. To design the MR fluid brake for a given specification, one must establish the relationship between the torque developed by MR fluids and the parameters of the structure and the magnetic field strength. In this paper the fundamental design method of the cylindrical MR brake is investigated theoretically. A 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 torque transmitted by the MR fluid within the brake. An engineering expression for the torque is derived to provide the theoretical foundation in the design of the brake. Based on this equation, after algebraic manipulation, the volume and thickness of the annular MR fluid within the brake is yielded.

II. Operational Principle

An MR fluid brake is a device to transmit torque by the shear stress of MR fluid. A MR rotary brake has the property that its braking torque changes quickly in response to an external magnetic field strength. The operational principle of the cylindrical MR brake is shown in fig. 1. The MR fluid fills the working gap between the fixed outer cylinder and the rotor. The rotor rotates at a rotational speed of o. 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 the rotor. However, in the course of operation, a magnetic flux path is formed when electric current is put through the solenoidal coil. As a result, the particles are gathered to form chain-like structures, in 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 brake can be achieved by utilizing the shear force of the MR fluid. The braking torque values can be adjusted continuously by changing the external magnetic field strength.

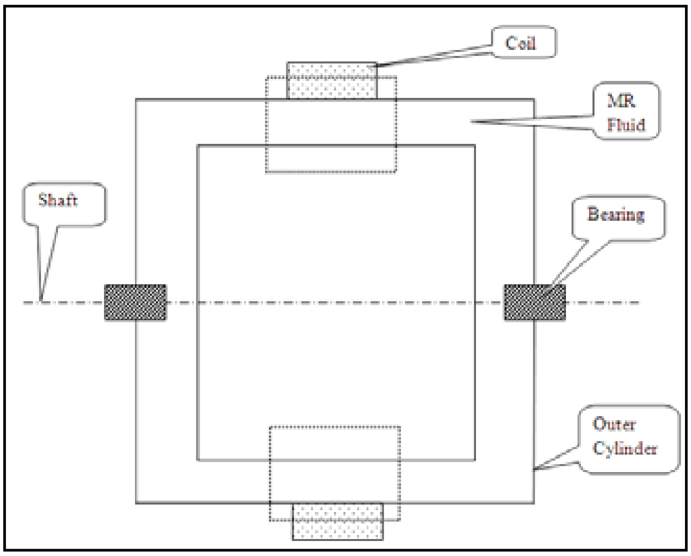

Fig. 1: Cylindrical Brake

III. Properties of MR Fluids

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 additives. The magnetizable particles in MR fluids induce polarization upon the application of an external magnetic field, which results in the MR effect of the MR fluids. The carrier fluid serves as a dispersed medium and ensures the homogeneity particles in the fluid. The additives include stabilizers and surfactants. The stabilizers serve to keep the particles suspended in the fluid, whilst the surfactants are adsorbed on the surface of the magnetic particles to enhance the polarization induced in the suspended particles upon the application of a magnetic field. In the absence of an applied magnetic field, the particles in MR fluid disperse randomly in the carrier fluid. MR fluid flows freely through the working gap between the fixed outer cylinder and the rotor. MR fluid exhibits a Newtonian-like behavior, where the shear stress of MR fluids can be described as

$$\tau = \eta . \gamma \qquad (1)$$

In which τ is the shear stress, η the viscosity of the MR fluid with no applied magnetic field, and γ the shear rate. When the magnetic field is applied, the behavior of the controllable fluid is often represented as a Bingham fluid having variable yield strength. In this model, the constitutive equation is derived by the least-squares method [1]:

$$\tau = \tau_B + \eta . \gamma \qquad (2)$$

Where τ_B is the yield stress developed in response to the applied magnetic field. Its value is dependent upon the magnetic induction field B.

IV. Magnetic Circuit Design

It consists of two configuration of magnetic circuit design for brakes. MR Fluid filled air gap configuration corresponds to the situation where an electromagnet is used to control the apparent viscosity of the MR-fluid as shown in following figure. When no current is applied to the coil, the MR-fluid apparent viscosity is minimum. The equivalent Kirchhoff's voltage law gives:

$$NI = \left(\Re_{MR} + \Re_{iron}\right)\phi \tag{3}$$

$$\phi = \frac{NI}{\Re_{MR} + \Re_{iron}} = \frac{NI}{\left({g_{MR}}/{\mu_{MR} A_{MR}}\right) + \left({l_{iron}}/{\mu_{iron} A_{iron}}\right)} \tag{4}$$

Which is equivalent to

$$H_{MR} = \frac{\phi}{\mu_{MR} A_{MR}} = \frac{NI}{g_{MR} + l_{iron}\left({\mu_{MR}}/{\mu_{iron}}\right)\left({A_{MR}}/{A_{iron}}\right)} \tag{5}$$

But $\mu_{iron} \approx 1000\,\mu_{MR}$,

Consequently, provided that length of iron is not too large and that the MR-fluid and soft-steel core sections are in the same range, therefore equation (4) is reduces as

$$\phi = \frac{NI}{\Re_{MR}} \tag{6}$$

Which is equivalent to

$$H_{MR} = \frac{NI}{g_{MR}} \tag{7}$$

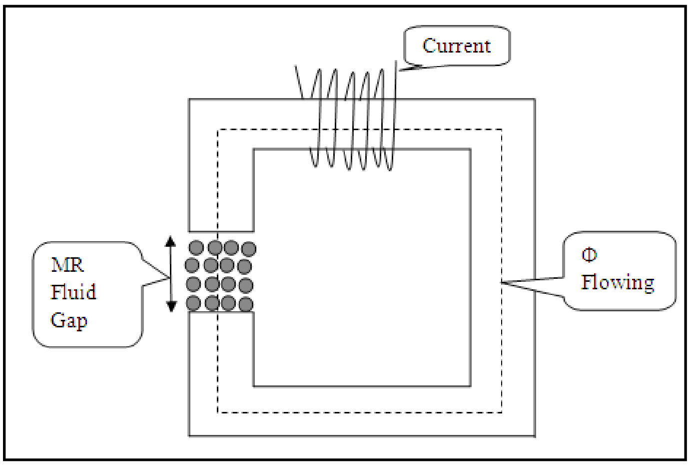

Fig. 2: Magnetic Core with MR Fluid Filled Gap

V. Analysis of Magnetorheological Brake

The design of MR fluid brake is to establish the relationship between the torque and the parameters of the structure and the magnetic field strength. Fig. 3 shows the flow of the MR fluid in the MR brake. When the magnetic field is applied, the braking torque T developed by the MR fluid can be calculated by

$$T = 2\pi r^2 \times w \times \tau \tag{8}$$

Where w is the effective width of the MR effect developed by the MR fluid, and r the radius of the annular MR fluid. The shear stress τ is proportional to the shear rate γ as described by Eq. (9). The shear rate γ can be calculated by

$$\gamma = r\frac{d\omega_r}{dr} \tag{9}$$

Where ω_r is the rotational speed in the MR fluid at radius r.

The differential of the rotational speed or can be obtained by Equation (8) and (9) as follows:

$$d\omega_r = \frac{1}{\eta}\left(\frac{T}{2\pi \times w \times r^3} - \frac{\tau_B}{r}\right)dr \tag{10}$$

Integrating Eq. (10) and applying the boundary conditions of the MR fluid brake: $r = r_1$ at $\omega_r = \omega$, and $r = r_2$ at $\omega_r = 0$; the braking torque T developed by the MR fluid can be calculated, to yield

$$T = \frac{4\pi \times \tau_B \times r_1^2 \times r_2^2 \times \ln\left(\frac{r_2}{r_1}\right)}{\left(r_2^2 - r_1^2\right)} + \frac{4\pi \times \eta \times r_1^2 \times r_2^2 \times \omega}{\left(r_2^2 - r_1^2\right)} \tag{11}$$

Where r_1 and r_2 are the radius of the rotor and the outer cylinder, respectively, and ω is the rotational speed of the rotor. As shown in Fig. 3, the thickness h of the annular MR fluid between the rotor and outer cylinder can be given by

$$h = r_2 - r_1 \tag{12}$$

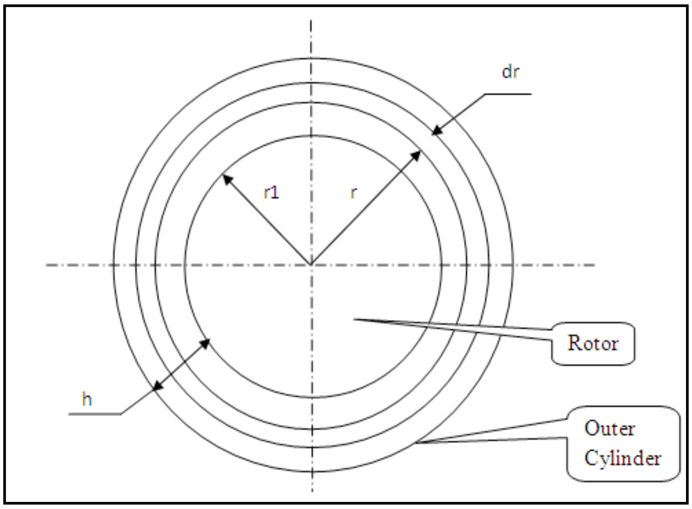

Fig. 3: The Analysis of MR Brake

If it is assumed that the thickness is much smaller than the radius of the rotor $\left(\frac{h}{r_1} \le 1\right)$, Eqs. (11) and (12) can be manipulated mathematically to yield:

$$T = 2\pi \times w \times \tau_B \times r_1^2 + \frac{2\pi \times \eta \times w \times r_1^3 \times \omega}{h} \tag{13}$$

Eq. (13) shows that the braking torque developed in the cylindrical MR fluid brake can be divided into a magnetic- field-dependent induced yield stress component τ_B and a viscous component τ_H:

$$T = 2\pi \times w \times \tau_B \times r_1^2 \tag{14}$$

$$T_\eta = \frac{2\pi \times \eta \times w \times r_1^3 \times \omega}{h} \tag{15}$$

The total torque T is the sum of τ_B and τ_h, i.e.

$$T = T_B + T_\eta \tag{16}$$

Thickness and width of the MR fluid

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

$$V = 2\pi \times \int_{r_1}^{r_2} r \times dr \qquad (17)$$

Eq. (17) can be manipulated mathematically to yield

$$V = 2\pi \times r_1 \times w \times h \qquad (18)$$

Equations (14)–(18) can be further manipulated to yield

$$V = \left(\frac{\eta}{\tau_B^2}\right)\left(\frac{T_B}{T_\eta}\right)(T_B \times \omega) \qquad (19)$$

Equation (19) gives the minimum active MR fluid volume that is necessary within the brake in order to achieve the desired control torque ratio $\left(\frac{T_B}{T_\eta}\right)$ at a given rotational speed ω, and the specified controllable torque T_B. Equations (14) and (15) can be manipulated algebraically to derive the thickness of the annular MR fluid as follows:

$$h = \left(\frac{\eta}{\tau_B}\right)\left(\frac{T_B}{T_\eta}\right)(r_1 \times \omega) \qquad (20)$$

Equation (20) provides geometric constraints for the MR fluid brake based on the MR fluid material properties $\left(\frac{\eta}{\tau_B}\right)$, the desired control torque ratio $\left(\frac{T_B}{T_\eta}\right)$ at a given rotational speed ω, and the radius r_1 of the rotor.

VI. Conclusions

The geometric design method of a cylindrical MR fluid brake is investigated theoretically in this paper. The braking torque developed by the MR fluid within the brake under different magnetic field strength conditions has been analyzed. The engineering design calculations of the volume, thickness and width of the annular MR fluid within the brake are derived. When the required mechanical power level, the rotational speed of the rotor, and the desired control torque ratio are specified, the parameters of the thickness and width of the fluid in the brake can be calculated from the equations obtained.

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