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Effect of Temperature on the Performance of Squeeze Film Damper Lubricated With Magnetorheological Fluid

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Abstract*—Modern machines demands high speed of rotation and thus requires provision of damping externally to the rotor system to reduce large force small amplitude vibrations. Magnetorheological fluid squeeze film dampers are new kind of dampers used in such applications. The viscosity of these fluids can be readily varied by changing the magnetic field intensity to reduce the vibrations. Magnetorheological fluids squeeze film dampers usually provide variable stiffness and damping at a particular excitation frequency by varying the coil current. This paper examines the performance of such dampers under the influence of temperature which changes due to the coil current flowing through the magnet, wide operating range of the rotor system. The analysis is conducted for every 10ºC change in the temperature as mentioned in the earlier work and viscosity change and its effect on the performance of the damper is evaluated theoretically. The stiffness and damping characteristics decrease with increase in temperature. The results are plotted and it provides information on the effect of temperature effect on the performance of Magnetorheological fluid squeeze film dampers.

Index Terms*—Squeeze film damper, Temperature change, Stiffness and dynamic characteristics, Magnetorheological fluid, Speed.

I. INTRODUCTION

Modern gas turbines produces large amount of power in a relatively small size unit generally accomplished through the use of high speed shafts which allows these high energy densities and flow rates to be transmitted. Along with high speeds, high inertial loads and problems with shaft whirl, vibration and rotor dynamic instability surfaces. These vibrations are dampened using squeeze film dampers externally. But the damping effect varies with the rotor speed; experimental evidence shows that in order to dissipate energy at the critical speeds, the rotor displacement in the damper has to be significant, meaning that viscosity must be low where as in non critical conditions, higher values are required. Electrorheological and magnetorheological fluids are successfully used in these dampers to achieve variation in the viscosity of the fluid dynamically.

These fluids behave as solids as long as the shear stress is lower than a threshold value which depends on the field strength, as quasi-Newtonian fluids if the shear stress is higher. The change induced in the yield shear stress produces a variation in their apparent viscosity and hence stiffness and damping characteristics. Magnetorheological fluids are suspension micro ferrous particles in a carrier fluid in which the viscosity can be varied by applying the different magnetic field. In this paper the effect of temperature on the change in the viscosity of the fluid is considered and the effect of temperature on the performance characteristics of squeeze film damper is studied theoretically. Constant strain rate model is used for the analysis and the results obtained were plotted in order to help the designers to consider the effect of temperature.

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II. MATHEMATICAL MODELING

Magnetorheological fluid (MR) is a controllable fluid because of its ability to change from free-flowing, linear viscous liquids to semi-solids having controllable yield strength in milliseconds when exposed to an external magnetic field. The suspended particles in the MR fluids become magnetized and align themselves, like chains, along the direction of the magnetic field, thereby increasing the yield stress of the fluid when subjected to magnetic field intensity.

A simple Bingham visco-plasticity model is used to describe the essential field-dependent fluid characteristics. In this model, the total shear stress τ is given by

$$\tau = \tau_o(H)\, Sgn(\dot{\gamma}) + \eta\,\dot{\gamma} \qquad (1)$$

Where τ_o = yield stress caused by the applied field [pa], H = magnitude of the applied magnetic field [A/m]. $\dot{\gamma}$ = shear strain rate [s^{-1}] and η = field independent plastic viscosity [pa.s], defined as the slope of the post-yield shear stress versus shear strain rate. The fluid post-yield viscosity is assumed to be a constant in the Bingham model. Because MR fluids exhibit shear thinning effect as shown in Figure (1)

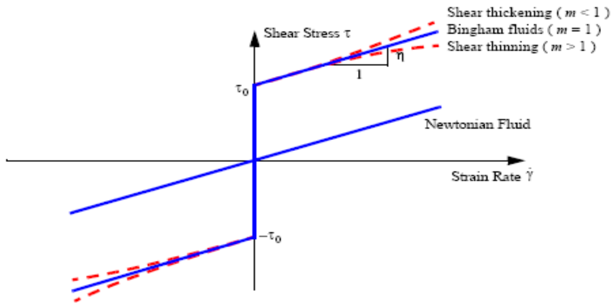

Figure 1: Visco-plasticity model for MR Fluids

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The Herschel-Bulkley visco-plasticity model can be employed to accommodate this effect. In this model, the constant post-yield plastic viscosity in the Bingham model is replaced with a power law model dependent on shear strain rate. Therefore,

$$\tau = \left(\tau_o(H) + K|\dot{\gamma}|^{\frac{1}{m}}\right) Sgn\dot{\gamma} \tag{2}$$

where m, K = fluid parameters and m, K > 0.
Comparing equation (2) and (1), the Bulkley plastic viscosity of the Herschel Bulkley model is

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

The above equation indicates that the equivalent plastic viscosity η_e decreases as the shear strain rate $\dot{\gamma}$ increases when m > 1, (Shear thinning). The Herschel-Bulkley model reduces to the Bingham model when m = 1, therefore, η_e=K. It is possible to obtain a relation between the viscosity, shear strain rate and the intensity of the applied magnetic field using Rayleigh's method of dimensional analysis. After applying the dimensional analysis one can obtain

$$\eta_{eH} = K|\dot{\gamma}|^{-1}(H)^2 \tag{4}$$

This is the incremental viscosity produced due to the application of the field. The total viscosity η_t if the sum of the field dependent and field independent viscosities, that is

$$\eta_t = K|\dot{\gamma}|^{\frac{1}{m}-1} H^2 + K|\dot{\gamma}|^{\frac{1}{m}-1}$$

$$= \left[K|\dot{\gamma}|^{\frac{1}{m}-1}\right](1+H^2)$$

$$= \eta_e\left(1+MH^2\right) = \text{(N-s/m}^2\text{)} \tag{5}$$

This is the total viscosity of the MR fluid under the action of the magnetic field. Viscosity is proportional to the square of the magnetic field intensity and hence the yield stress $\tau_y \alpha H^2$ and it is reasonable to consider the magnification factor obtained due to the effect of the magnetic field. It is assumed M=1 in the analysis.

2.1 Pressure developed in the film

The pressure developed in the film sustains the load, besides damping the vibration imposed on the foundation. Assuming a long bearing that is, the length in the z-direction is infinitely long, the differential equation for the bearing reduces to

$$\frac{\partial^2 p}{\partial x^2} = \frac{-12\eta V}{C^3} \tag{6}$$

Integrating twice and employing the boundary conditions that pressure is zero at the ends,

$$P = 0 \text{ at } \quad x = \frac{\pm B}{2}$$

The pressure is given by the formula-

$$p = \frac{3\eta V}{2C^3}(B^2\text{-}4x^2) = \text{(N/m}^2\text{)} \tag{7}$$

The maximum pressure occurs at the centre of the bearing.

2.2 Load capacity of the squeeze film

The load capacity is given by

$$W = L\int_{-B/2}^{B/2} P dx$$

$$W = \frac{\eta VLB^3}{C^3} = \text{(N)} \tag{8}$$

The volume rate of flow of the fluid is

$$V' = \frac{-LC^3}{12\eta}\frac{\partial p}{\partial x} = LxV = (\text{m}^3/\text{s}) \tag{9}$$

The flow rate increases from zero at the centre of the bearing to a maximum value of ½ LBV at edge of the bearing.

2.3 Dynamic characteristics

The dynamic characteristics are the stiffness and damping characteristics. They vary in accordance with the vibration levels imposed on the system. The stiffness is the first differential of load capacity i.e.

$$K = \frac{-\partial W}{\partial C} = \frac{-\partial}{\partial C}\left[\frac{\eta VLB^3}{C^3}\right]$$

$$K = \frac{3\eta VLB^3}{C^4}$$

$$K = \frac{3W}{C} = \text{(N/m)} \tag{10}$$

It is directly proportional to the load capacity and inversely proportional to the clearance of the damper. The damping coefficient is the damping force per unit velocity of the damper *i.e.*

$$\frac{\partial W}{\partial V} = \frac{\eta LB^3}{C^3} = \text{(N-s/m)} \tag{11}$$

2.4 Damping and Stiffness characteristics evaluation

The theoretical squeeze film damping and stiffness characteristics can be obtained using the constant strain rate viscosity model developed. A constant strain rates of 2s $^{-1}$ and 4s $^{-1}$ are assumed for analysis. The damper specification and relevant MR fluid data used for the analysis have been outlined in Tables 1 and 2.

Table 1. Specifications of the damper

Diameter (D, mm)	118
Length(L, mm)	20 & 28
Excitation Velocity(ω, mm/s)	100
Clearance,(C, mm)	0.5 & 0.75
Eccentricity ratio, n	0.05 & 0.1

Table 2. Specifications of the MR Fluid – MRF132LD

Manufacturer	Lord Corporation USA
Viscosity, η_e	0.94
Fluid Parameters	
m	2.86
K	4.202

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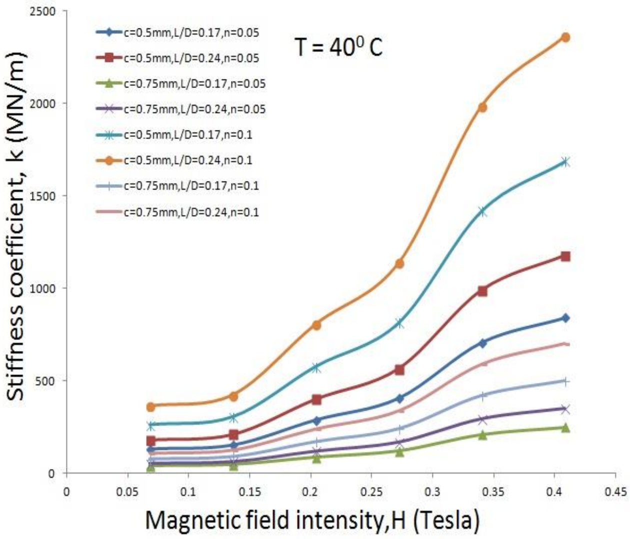
2.5 Effect of temperature

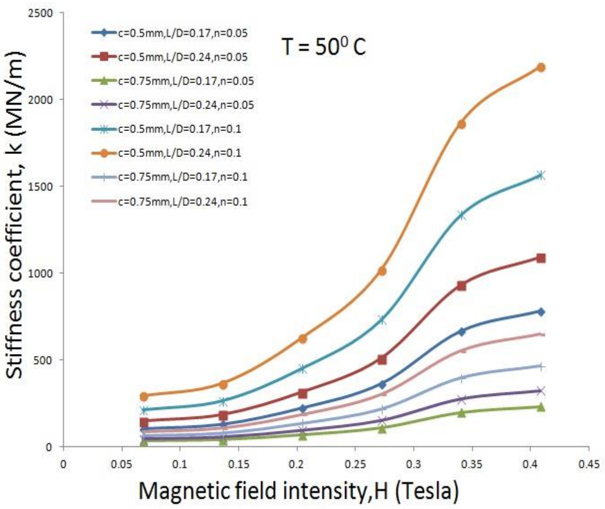
The changes in the temperature of the magnetorheological fluid due to heat dissipated from the magnetic coil, wide range of operating conditions and frictional effects, directly affects the performance of the squeeze film damper. The temperature decreases the viscosity of the fluid and hence affects the performance characteristics of the squeeze film damper [4]. At a particular temperature, the viscosity characteristics with reference to the shear strain rate is used to evaluate the dynamic characteristics like damping and stiffness coefficients of the squeeze film damper.

III. RESULTS AND DISCUSSIONS

The effect of temperature on the stiffness and damping characteristics of the magnetorheological fluid squeeze film damper with orbital motion is presented in this section. The damper and fluid specifications given in the Tables 1 and 2 are used to evaluate the dynamic characteristics of the damper. Figure 2 (a), (b) & (c) shows the effect of temperature on the stiffness characteristics of the damper for a constant shear strain rate of 2 s^{-1} for different temperatures of 40 °C, 50 °C and 60 °C as a function of magnetic field intensity.



(a)



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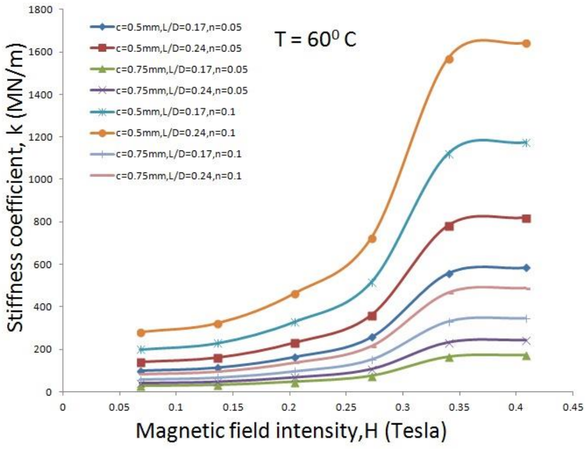
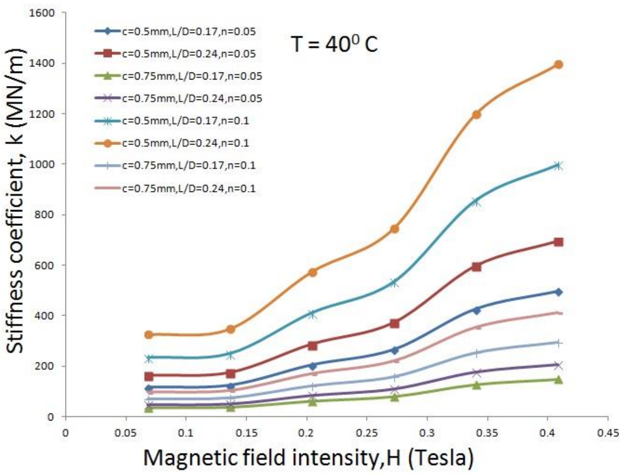


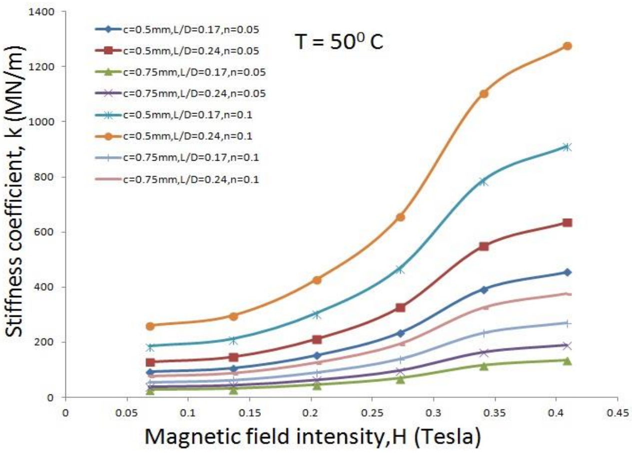
(c)

Figure 2. Stiffness coefficient as a function of magnetic field intensity for different temperatures at a shear strain rate of 2 s^{-1}

Figure 3 (a), (b) & (c) illustrates the effect of temperature on the stiffness characteristics of the damper for a constant shear strain rate of 4 s^{-1} for different temperatures of 40 °C, 50 °C and 60 °C as a function of magnetic field intensity.



(a)



(b)

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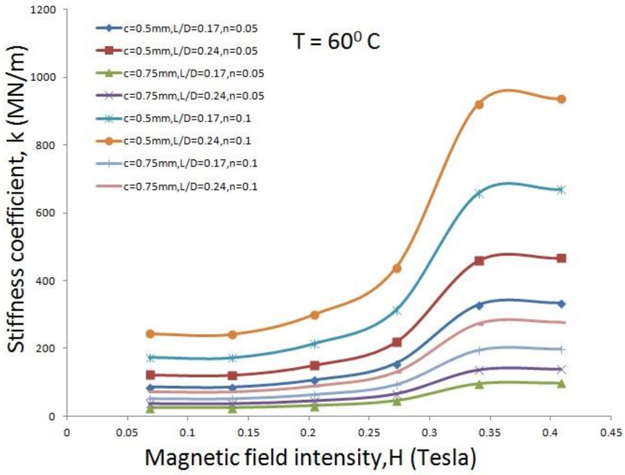
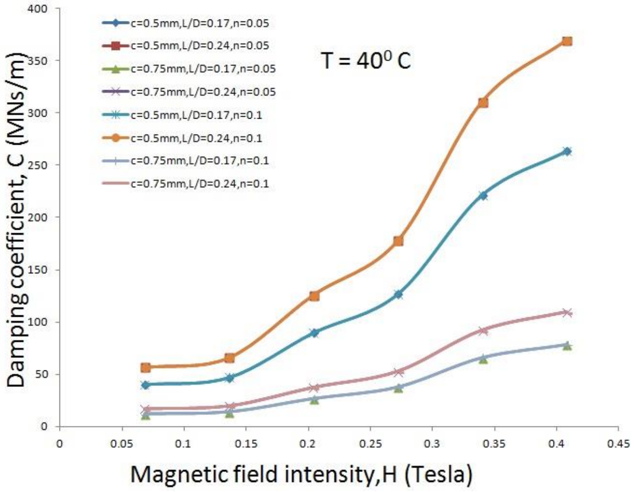


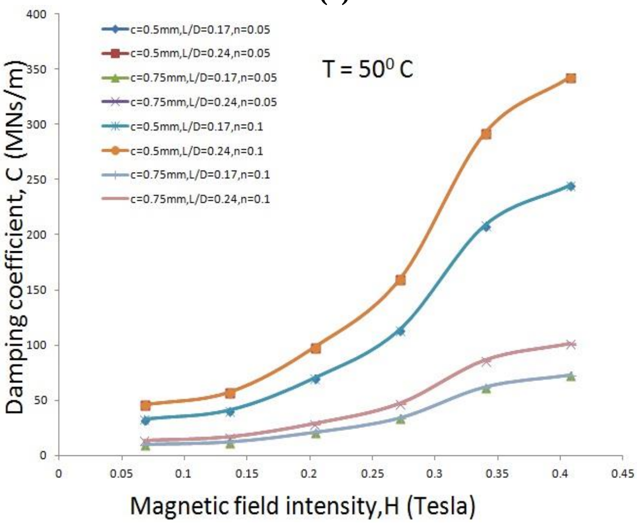
(c)

Figure 3. Stiffness coefficient as a function of magnetic field intensity for different temperatures at a shear strain rate of 4 s^{-1}

Figure 4 (a), (b) & (c) describes the effect of temperature on the damping characteristics of the damper for a constant shear strain rate of 2 s^{-1} for different temperatures of 40 °C, 50 °C and 60 °C as a function of magnetic field intensity.



(a)



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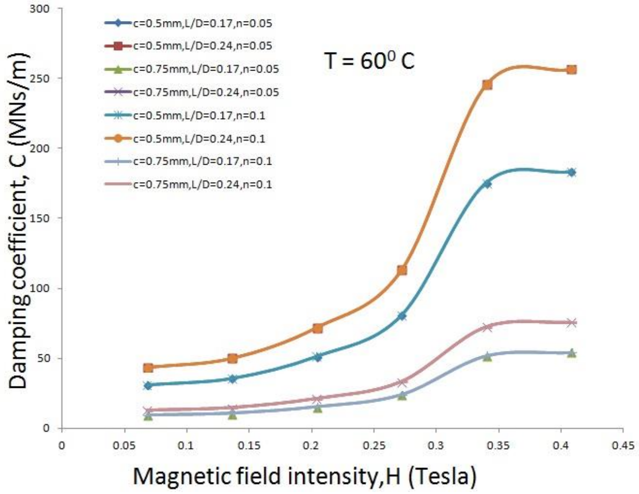
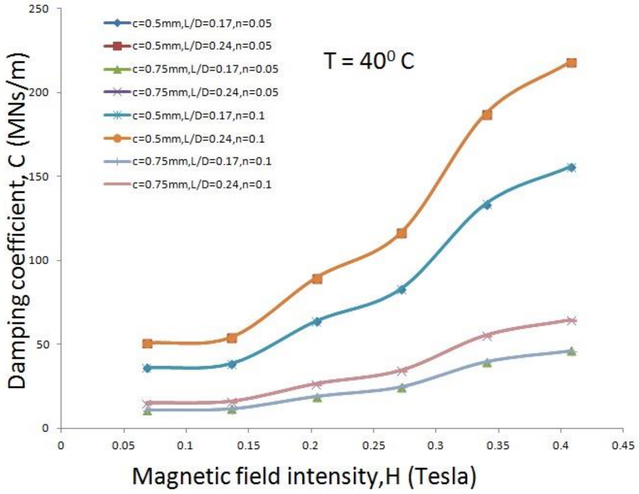


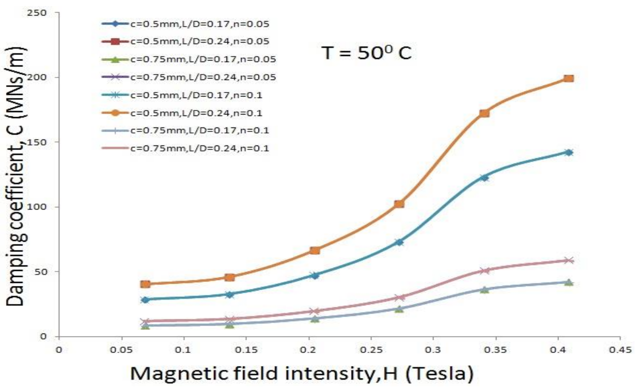
(c)

Figure 4. Damping coefficient as a function of magnetic field intensity for different temperatures at a shear strain rate of 2 s^{-1}

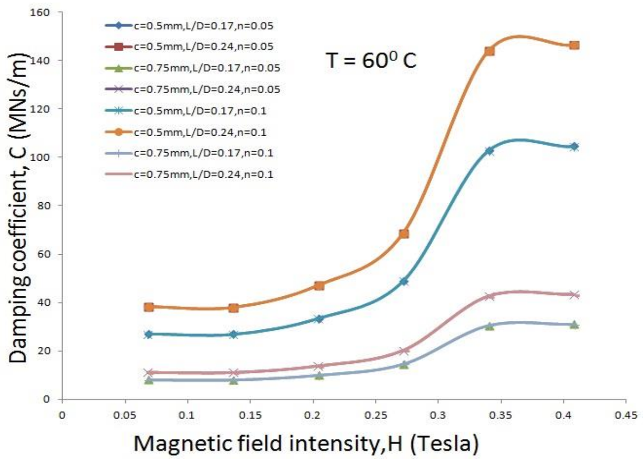
Figure 5 (a), (b) & (c) shows the effect of temperature on the damping characteristics of the damper for a constant shear strain rate of 4 s^{-1} for different temperatures of 40 °C, 50 °C and 60 °C as a function of magnetic field intensity.



(a)



(b)



(c)

Figure 5. Damping coefficient as a function of magnetic field intensity for different temperatures at a shear strain rate of 4 s^{-1}

It is clear from the results that the dynamic characteristics for different temperatures decreases as the viscosity of the fluid decreases with increases in shear strain rates.

IV. CONCLUSIONS

The magnetorheological fluid viscosity is highly depending on the shear strain rates and the magnetic field intensities. The dynamic characteristics decreases with increase in shear strain rate but gets improved when magnetic field intensity is increased. These characteristics tend to deteriorate when the temperature is increased as the viscosity decreases due to rise in temperature. Thus, the damping and stiffness coefficients of the damper can be enhanced by increasing the magnetic field intensity. These characteristics increase with decrease in clearance and increase in L/D ratio & eccentricity ratio of the damper.

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