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Analysis of Two-Layered Journal Bearing Lubricated with Ferrofluid

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Abstract. The present study investigates the load capacity and friction coefficient for a two-layered journal bearing lubricated with ferrofluid. A modified Reynolds equation for a two-layered ferrofluid is derived using displaced infinitely long wire magnetic field model. Reynolds boundary conditions are used to obtain nondimensional pressure and shear stress expressions. Nondimensional load capacity and coefficient of friction are analyzed under the influence of lubricant layer's thickness, viscosities, magnetic field intensity and distance ratio parameter. Ferrofluid lubrication under the influence of magnetic field has potential to enhance load carrying capacity and reduce coefficient of friction for two-layered journal bearing.

1 Introduction

Ferrofluids are stable colloidal suspension comprising ferromagnetic particles dispersed within a carrier fluid. Lubrication is an important application of ferrofluids. Journal bearings lubricated with ferrofluids enhance load carrying capacity. Osman et al. [1] derived modified Reynolds equation applicable for external applied magnetic field. Osman et al. [2] investigated the influence of ferrofluid on the static and dynamic characteristics of the finite hydrodynamic journal bearing under an applied magnetic field. Hsu et al. [3] investigated the characteristics of short journal bearing under the combined effects of non-Newtonian power law ferrofluid and bearing surface roughness.

A two-layered film consists of two immiscible fluid layers of different viscosities that share the clearance space between the bearing and journal surfaces. Szeri [4] analyzed the journal bearing with two-layered film bearing that combines the advantages of high viscosity with low viscosity lubricant. Tichy [5] developed a modified Reynolds equation for analysis of journal bearing with surface layers of higher viscosity. Rao et al. [6] investigated the generation of load support and consequent reduction in friction in a two-layered lubricant film journal bearing under the influence of partial slip configuration.

The purpose of this study is to investigate the generation of load support and consequent reduction in friction in a two-layered film journal bearing lubricated with ferrofluid. Results of nondimensional load capacity and coefficient of friction in one dimensional journal bearing lubricated with ferrofluid under steady state are analyzed for different values of magnetic field intensity (α) and eccentricity ratio (ε).

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2 Analysis

A one-dimensional analysis of two-layered journal bearing lubricated with ferrofluid is considered in the analysis. Figure 1 shows the schematic of two-layered film journal bearing configuration. The nondimensional film thickness for the plain journal bearing is expressed as $H = (1 + \varepsilon \cos\theta)$.

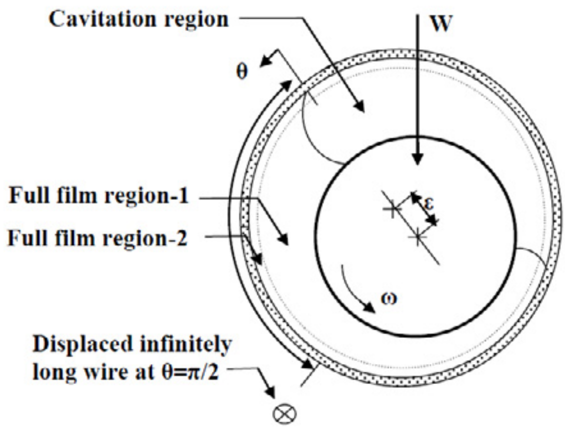


Figure 1 Geometry of two-layered film journal bearing with displaced infinitely long wire

The nondimensional magnetic field intensity using the displaced infinitely long wire magnetic field model is represented as [1]

$$H_m = \left[1 + K^2 - 2K\cos\left(\frac{\pi}{2} - \theta\right)\right]^{-0.5} \tag{1}$$

Using the magnetic force as a body external force [1], the momentum equations of two-layered journal bearing lubricated with ferrofluid are simplified considering pressure variation only along the sliding direction. Using the equation of continuity for steady flow and the condition of equality of shear stress at the interface, the non-dimensional pressure gradient is expressed as

$$\frac{dP}{d\theta} = \frac{6\Delta_s}{\Delta_p H^2} - \frac{12Q}{\Delta_p H^3} + F_m \tag{2}$$

where $F_m = \alpha H_m \frac{dH_m}{d\theta}$, $\Delta_p = \left[\gamma^3 + \frac{(1-\gamma)^3}{\beta} + \frac{3\gamma(1-\gamma)}{1-\gamma+\beta\gamma}\right]$, $\Delta_s = \left[\frac{1-\gamma^2+\beta\gamma^2}{1-\gamma+\beta\gamma}\right]$.

The non-dimensional pressure in the two-layered film journal bearing lubricated with ferrofluid can be written as

$$P(0 \le \theta \le \theta_r) = P\big|_{\theta=0} + \int_0^\theta \frac{6\Delta_s}{\Delta_p H^2} d\theta - \int_0^\theta \frac{12Q}{\Delta_p H^3} d\theta + \int_0^\theta \alpha H_m \frac{dH_m}{d\theta} d\theta \tag{3}$$

Substituting the Reynolds pressure boundary condition at rupture in Eq. (3) and Reynolds pressure gradient boundary condition at rupture in Eq. (2), results in

$$Q = \frac{\int_0^{\theta_r} \frac{6\Delta_s}{\Delta_p H^2} d\theta + \int_0^{\theta_r} \alpha H_m \frac{dH_m}{d\theta} d\theta}{\int_0^{\theta_r} \frac{12}{\Delta_p H^3} d\theta} \quad \text{and} \quad Q = \left(\frac{\Delta_s H}{2} + \frac{\Delta_p H^3 \alpha H_m \frac{dH_m}{d\theta}}{12}\right) \tag{4}$$

Equation (4) is simultaneously solved by the Newton-Raphson iterative procedure to determine the unknowns Q and θ_r.

The nondimensional load capacity is expressed as

$$W = \sqrt{W_\varepsilon^2 + W_\phi^2} \quad \text{where} \quad W_\varepsilon = -\int_0^{\theta_r} P\cos\theta d\theta, \quad W_\phi = \int_0^{\theta_r} P\sin\theta d\theta \quad (5)$$

The nondimensional shear stress at Y=0 in the journal bearing lubricated with ferrofluid is

$$\Pi\big|_{Y=0}\left(0 \le \theta \le \theta_r\right) = \left(\frac{1-\gamma^2+\beta\gamma^2}{1-\gamma+\beta\gamma}\right)\left(\frac{3\Delta_s}{\Delta_p H} - \frac{6Q}{\Delta_p H^2}\right) + \left(\frac{\beta}{1-\gamma+\beta\gamma}\right)\frac{1}{H} \quad (6)$$

The nondimensional friction coefficient is calculated as

$$C_f = \left(\frac{R}{C}\right)\frac{f}{w} = \frac{F}{W} \quad \text{where} \quad F = \int_0^{\theta_r} \Pi d\theta \quad (7)$$

3 Results and Discussion

The parameters used in the analysis of two-layered lubricant film journal bearing lubricated with ferrofluid are: ε=0.1-0.5; α=0, 0.05, 0.1, 0.15; K=1.1, 1.2, 1.3, 1.4; β=10; γ=0.9.
The variation of nondimensional load capacity (W) with two-layered lubricant film journal bearing lubricated with ferrofluid is shown in Figs. 2a-2b. The variation of nondimensional load capacity (W) with eccentricity ratio (ε) and distance ratio parameter (K) are presented for different values of magnetic field intensity (α) and eccentricity ratio (ε) for γ=0.9 and β=10. The nondimensional load capacity (W) increases with increase in magnetic field intensity (α) for eccentricity ratios (ε) of 0.1-0.5. The nondimensional load capacity (W) is higher at lower eccentricity ratios (ε) of 0.1-0.3 for the displaced infinitely long wire magnetic field model. The nondimensional load capacity increases with increase in magnetic field intensity (α) due to increase of pressure around the location of wire (θ=π/2). For the case of journal bearing eccentricity ratios (ε) of 0.1-0.5, the nondimensional load capacity (W) decreases with increase in distance ratio parameter (K) from 1.1-1.2. The magnetic effect decreases with increase in distance ratio parameter (K).

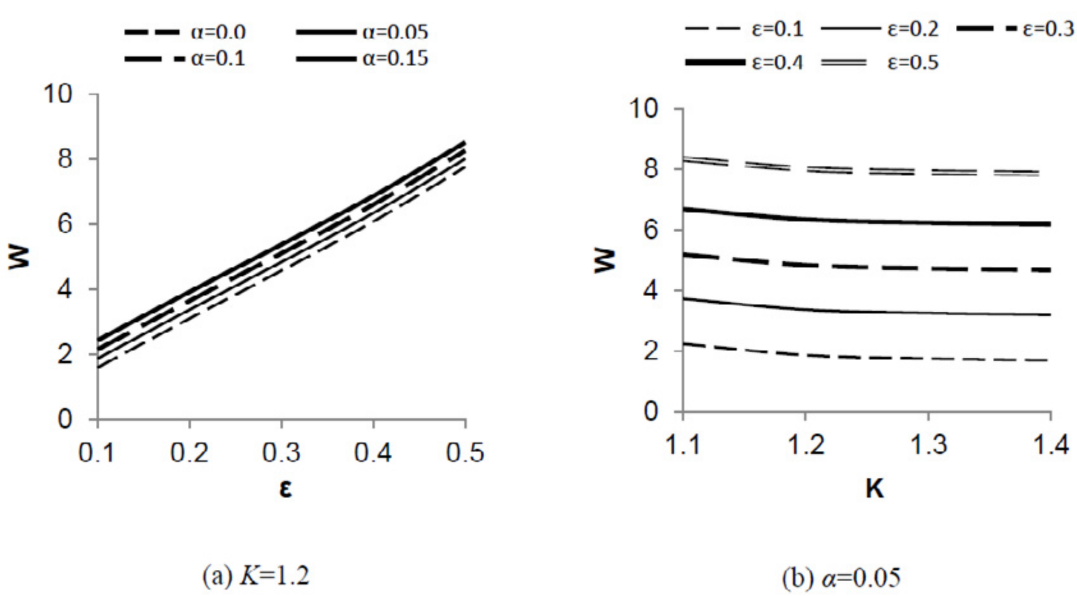
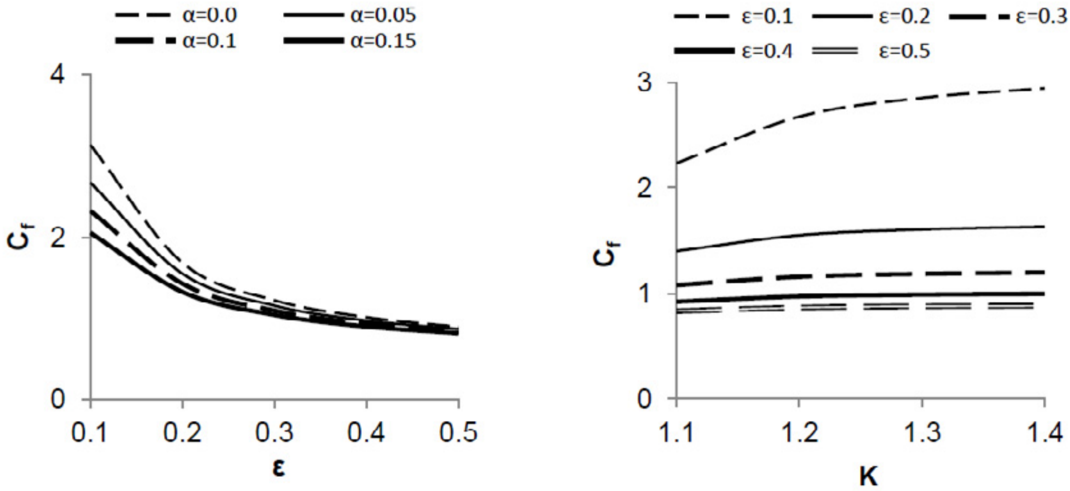


Figure 2 Nondimensional load capacity (γ=0.9, β=10)

The coefficient of friction (C_f) in the two-layered lubricant film journal bearing lubricated with ferrofluid is shown in Figs. 3a-3b for γ=0.9 and β=10. In the case of two-layered lubricant film journal bearing eccentricity ratios (ε) of 0.1-0.3, the coefficient of friction (C_f) decreases with increase in magnetic field intensity (α=0.05-0.15). At low eccentricity ratio (ε=0.1), the coefficient of friction (C_f) considerably decreases for lower distance ratio parameter (K=1.1).



(a) K=1.2 (b) α=0.05

Figure 3 Coefficient of friction (γ=0.9, β=10)

4 Conclusion

The present study investigates the influence of ferrofluids on improvement in load capacity and reduction in friction coefficient for a two-layered lubricant film journal bearing. A two-layered journal bearing lubricant film of different Newtonian dynamic viscosities that adheres to journal and bearing surfaces is presented in the analysis. The nondimensional pressure and shear stress expressions are obtained using the Reynolds boundary conditions considering the displaced infinitely long wire magnetic field model. The conclusions based on the analysis presented in this paper are:

- Under the influence of ferrofluids for a two-layered journal bearing (ε=0.1-0.3), the nondimensional load capacity (W) increases with increase in magnetic field intensity (α=0.05-0.15).
- Under the influence of ferrofluids for a two-layered journal bearing (ε=0.1-0.3), the coefficient of friction (C_f) decreases with increase in magnetic field intensity (α=0.05-0.15). The coefficient of friction (C_f) also decreases for lower distance ratio parameter (K=1.1).

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Nomenclature

C	Radial clearance, m
f	Friction force, N; $F = fC/\mu_1 URL$
f_m	Magnetic force in circumferential direction; $F_m = f_m C^2/\mu_1 U$
h	Film thickness, m; $H=h/C$
h_m	Magnetic field intensity; $H_m=h_m/h_{mo}$
h_{mo}	Characteristic magnetic field intensity
K	Distance ratio parameter; $K=R_o/R$
L	Length of the journal bearing, m
p	Pressure distribution, N/m^2; $P = pC^2/\mu_1 UR$
q	Volume flow rate per unit length along film thickness, m^2/s; $Q = q/UC$
R	Journal radius, m
R_o	Displacement of infinitely long wire location from bearing center, m
u	Velocity component along x direction, m/s
w	Static load, N; $W = wC^2/\mu_1 UR^2 L$
W_ε, W_ϕ	Nondimensional radial and tangential static load for journal bearing
x	Coordinate along circumferential (x) direction, m; $\theta=x/R$
X_m	Susceptibility of ferrofluid
y	Coordinate along radial direction, m; $Y=y/h$
α	Magnetic field intensity; $\alpha = \mu_o X_m h_{mo}^2 C^2/\mu_1 UR$
β	Dynamic viscosity ratio of lubricant attached to bearing and journal; $\beta=\mu_2/\mu_1$
γ	Lubricant layer thickness ratio attached to journal; $\gamma=y_i/h$
ε	Journal bearing eccentricity ratio
μ_1, μ_2	Lubricant viscosity adjacent to the journal and bearing surface respectively, Ns/m^2
μ_o	Permeability of free space or air, $\mu_o=4\pi \times 10^{-7}$ AT/m
θ	Angular coordinate measured from the direction of maximum film thickness in journal bearing
θ_r	Extent of outlet film measured from the position of maximum film thickness
τ	Shear stress component, N/m^2; $\Pi = \tau C/\mu_1 U$
ω	Angular velocity of journal bearing, rad/s

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