Jurnal Mekanikal
June 2015, Vol 38, 01-06

FERROFLUID LUBRICATED PARTIAL POROUS LAYERED JOURNAL BEARING ANALYSIS

T. V. V. L. N. Rao, A. M. A. Rani, T. Nagarajan, F. M. Hashim

Department of Mechanical Engineering,
Universiti Teknologi PETRONAS
32610 Bandar Seri Iskandar, Perak Darul Ridzuan,
Malaysia

ABSTRACT

Analysis of non-porous and partial porous layered regions on the bearing surface using ferrofluid lubrication is presented. Modified Brinkman model is used in the analysis of fluid flow in the partial porous region. Displaced infinitely long wire magnetic field model is applied for Ferrofluid lubricated journal bearing analysis. Non-dimensional load capacity and coefficient of friction are evaluated under the influence of extent of non-porous film region, permeability of porous media, porous layer thickness, magnetic field intensity and distance ratio parameter. A partial porous layered journal bearing lubricated with ferrofluid increases the load carrying capacity and reduces the coefficient of friction.

Keywords : *Partial Porous layer, Load capacity, Coefficient of friction, Ferrofluid, Magnetic field*

NOMENCLATURES

C	Radial clearance, m
f	Friction force, N; $F = fC/\mu URL$
f_m	Magnetic force $F_m = f_m C^2/\mu U$
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	Permeability parameter, m^2; $K = k/C^2$
K_r	Distance ratio parameter; $K = R_o/R$
L	Length of the journal bearing, m
p	Pressure, N/m^2; $P = pC^2/\mu UR$
q	Volume flow rate, m^2/s; $Q = q/UC$
R	Journal radius, m
R_o	Displacement of infinitely long wire
w	Static load, N; $W = wC^2/\mu UR^2L$
W_ε, W_ϕ	Non-dimensional radial and tangential static load
x, y	Coordinate along circumferential and radial directions, m; $\theta = x/R$, $Y = y/h$
X_m	Susceptibility of ferrofluid
α	Magnetic field coefficient; $\alpha = \mu_o X_m h_{mo}^2 C^2/\mu UR$
δ	Thickness porous layer, m; $\Delta = \delta/C$
ε	Journal bearing eccentricity ratio
μ	Lubricant viscosity, Ns/m^2
μ_o	Permeability of free space or air, $\mu_o = 4\pi \times 10^{-7}$ AT/m
θ_p, θ_r	Extent of non-porous film region and outlet film measured from the position of maximum film thickness
τ	Shear stress component, N/m^2; $\Pi = \tau C/\mu U$
ω	Angular velocity of journal bearing, rad/s

---

*Corresponding author: tadimalla_v@petronas.com.my

1.0 INTRODUCTION

The performance of hydrodynamic contacts are enhanced by considering the effects of both lubricant additives as porous layer on bearing surfaces and ferrofluids which are stable colloidal suspension comprising of ferromagnetic particles dispersed within a carrier fluid. Tichy [1] developed porous media model for thin film lubricant microstructure. Li and Chu [2] developed couple stress fluid lubricated hydrodynamic contacts model using thin film porous media based on Brinkman-extended Darcy equations. Decrease in permeability of porous layer increases the resistance to fluid flow in the porous region which results in increase in bearing load capacity. Elsharkawy [3] evaluated the performance of hydrodynamic contacts with additives in lubricants using thin porous media model and couple stress fluid model respectively. Osman et al. [4-5] investigated the effect of ferrofluid lubrication on the static and dynamic performance characteristics of hydrodynamic journal bearings. The magnetic field models investigated for the analyses [5] are: displaced infinitely long wire model, concentric finite wire model, and displaced finite wire model. Rao et al. [6] investigated load capacity and coefficient of friction in a porous layered journal bearing lubricated with ferrofluid.

The present study investigates the influence of bearing adsorbent partial porous layer on the non-dimensional load capacity and coefficient of friction in one dimensional ferrofluid lubricated journal bearing.

2.0 ANALYSIS

A one-dimensional analysis of partial porous layered journal bearing lubricated with ferrofluid is presented. Figure 1 shows the schematic of partial porous layered film journal bearing configuration with displaced infinitely long wire.

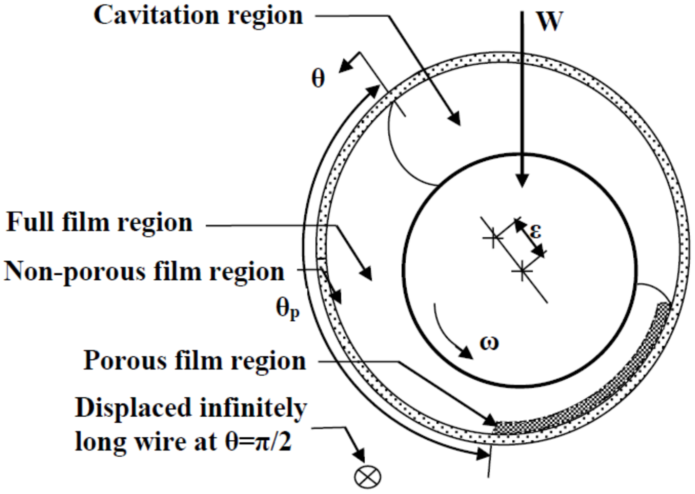


Figure 1: Geometry of partial porous layered journal bearing with displaced infinitely long wire

Using the displaced infinitely long wire magnetic field model, the non-dimensional magnetic field intensity is represented as [5]

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

Using the equation of continuity for steady flow and the condition of equality of shear stress at the interface, the non-dimensional pressure gradient for non-porous and partial porous layered exit region is expressed as

$$\frac{dP}{d\theta}\left(0 \le \theta \le \theta_p\right) = \frac{G_{1p} - Q}{G_{2p}} + F_m \qquad \frac{dP}{d\theta}\left(\theta_p \le \theta \le \theta_r\right) = \frac{G_1 - Q}{G_2} + F_m \tag{2}$$

where $G_{1p} = \frac{H}{2}$, $G_{2p} = \frac{H^3}{12}$, $G_1 = F_1 H_1^* + \frac{1}{2}\left(F_1 + 1\right)\left(H - \Delta\right)$,

$$G_2 = F_2 H_1^* + \frac{1}{2} F_2 \left(H - \Delta\right) + \frac{1}{12}\left(H - \Delta\right)^3 + K\left(\Delta - 2H_1^*\right),\; F_m = \alpha H_m \frac{dH_m}{d\theta},$$

$$F_1 = \frac{1}{\left(H - \Delta\right)\left[\frac{1}{\sqrt{K}}\coth\left(\frac{\Delta}{\sqrt{K}}\right) + \frac{1}{\left(H - \Delta\right)}\right]},\; F_2 = \frac{H_1^* + \frac{1}{2}\left(H - \Delta\right)}{\frac{1}{\sqrt{K}}\coth\left(\frac{\Delta}{\sqrt{K}}\right) + \frac{1}{\left(H - \Delta\right)}},\; H = \left(1 + \varepsilon\cos\theta\right),$$

$$H_1^* = \sqrt{K}\left[\coth\left(\frac{\Delta}{\sqrt{K}}\right) - \operatorname{csch}\left(\frac{\Delta}{\sqrt{K}}\right)\right]$$

The non-dimensional pressure in the non-porous and partial porous layered journal bearing lubricated with ferrofluid can be written as

$$P\left(0 \le \theta \le \theta_p\right) = \int_0^\theta \frac{G_{1p}}{G_{2p}} d\theta - Q\int_0^\theta \frac{1}{G_{2p}} d\theta + \int_0^\theta \alpha H_m \frac{dH_m}{d\theta} d\theta \tag{3}$$

$$P\left(\theta_p \le \theta \le \theta_r\right) = P\big|_{\theta=\theta_p} + \int_{\theta_p}^{\theta} \frac{G_1}{G_2} d\theta - Q\int_{\theta_p}^{\theta} \frac{1}{G_2} d\theta + \int_{\theta_p}^{\theta} \alpha H_m \frac{dH_m}{d\theta} d\theta \tag{4}$$

Using the Reynolds pressure boundary conditions, results in

$$Q = \frac{\int_0^{\theta_p} \frac{G_{1p}}{G_{2p}} d\theta + \int_{\theta_p}^{\theta_r} \frac{G_1}{G_2} d\theta + \int_0^{\theta_r} \alpha H_m \frac{dH_m}{d\theta} d\theta}{\int_0^{\theta_p} \frac{1}{G_{2p}} d\theta + \int_{\theta_p}^{\theta_r} \frac{1}{G_2} d\theta} \quad \text{and} \quad Q = \left(G_1 + G_2 F_m\right)\big|_{\theta=\theta_r} \tag{5}$$

Equation (5) is solved by the Newton-Raphson method to determine Q and θ_r.

The non-dimensional load capacity is expressed as

$$W = \sqrt{W_\varepsilon^2 + W_\phi^2} \quad \text{where} \quad W_\varepsilon = -\int_0^{\theta_r} P\cos\theta d\theta, \quad W_\phi = \int_0^{\theta_r} P\sin\theta d\theta \tag{6}$$

The non-dimensional shear stress at Y=0 in the in the non-porous and partial porous layered journal bearing lubricated with ferrofluid is

$$\Pi\big|_{Y=0}\left(0 \le \theta \le \theta_p\right) = \frac{1}{H} + \left(\frac{G_{1p} - Q}{G_{2p}}\right)\frac{H}{2} \tag{7}$$

$$\Pi\big|_{Y=0}\left(\theta_p \le \theta \le \theta_r\right) = \frac{1}{H - \Delta}\left(1 - F_1\right) + \left(\frac{G_1 - Q}{G_2}\right)\left[\frac{1}{2}\left(H - \Delta\right) + \frac{1}{\left(H - \Delta\right)} F_2\right] \tag{8}$$

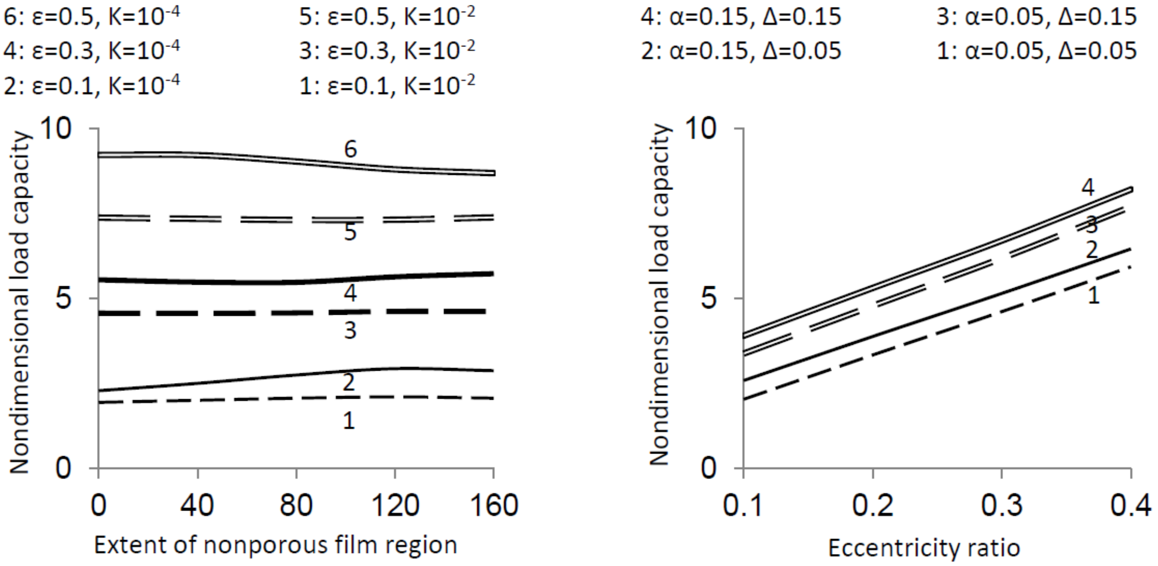
The non-dimensional friction coefficient is calculated as

$$C_f = \left(\frac{R}{C}\right)\frac{f}{w} = \frac{F}{W} \qquad \text{where} \quad F = \int_0^{\theta_r} \Pi \, d\theta \tag{9}$$

3.0 RESULTS AND DISCUSSION

The non-dimensional load capacity (W) and coefficient of friction (C_f) in one-dimensional ferrofluid lubricated journal bearing are analyzed. The parameters used in the analysis are: eccentricity ratio (ε) = 0.1-0.5; magnetic field coefficient (α) = 0.05, 0.1, 0.15; non-dimensional permeability of porous layer (K) = 10^{-2}, 10^{-4}; non-dimensional thickness of porous layer (Δ) = 0.05, 0.1, 0.15; distance ratio parameter (K_r) = 1.2; and extent of non-porous film region measured from the position of maximum film thickness (θ_p) = 0, 40°, 80°, 120°, 160°.

The variation of non-dimensional load capacity (W) with extent of non-porous film region measured from the position of maximum film thickness (θ_p) and eccentricity ratio (ε) are shown in Figure 2a and 2b. The non-dimensional load capacity (W) increases with the increase in extent of non-porous film region measured from the position of maximum film thickness (θ_p = 0.0-160°) at low eccentricity ratios (ε = 0.1, 0.3) and non-dimensional permeability of porous layer ($K = 10^{-2}, 10^{-4}$). The increase in non-dimensional load capacity (W) with extent of non-porous film region (θ_p) is higher at low non-dimensional permeability of porous layer ($K = 10^{-4}$). The non-dimensional load capacity (W) increases with the increase in eccentricity ratio (ε = 0.1-0.4) for various magnetic field coefficients (α = 0.05, 0.15) and non-dimensional thickness of porous layer (Δ = 0.05, 0.15). The non-dimensional load capacity (W) increases significantly with increase in both magnetic field coefficient and non-dimensional thickness of porous layer at high eccentricity ratios.



(a) α=0.1, Δ=0.1

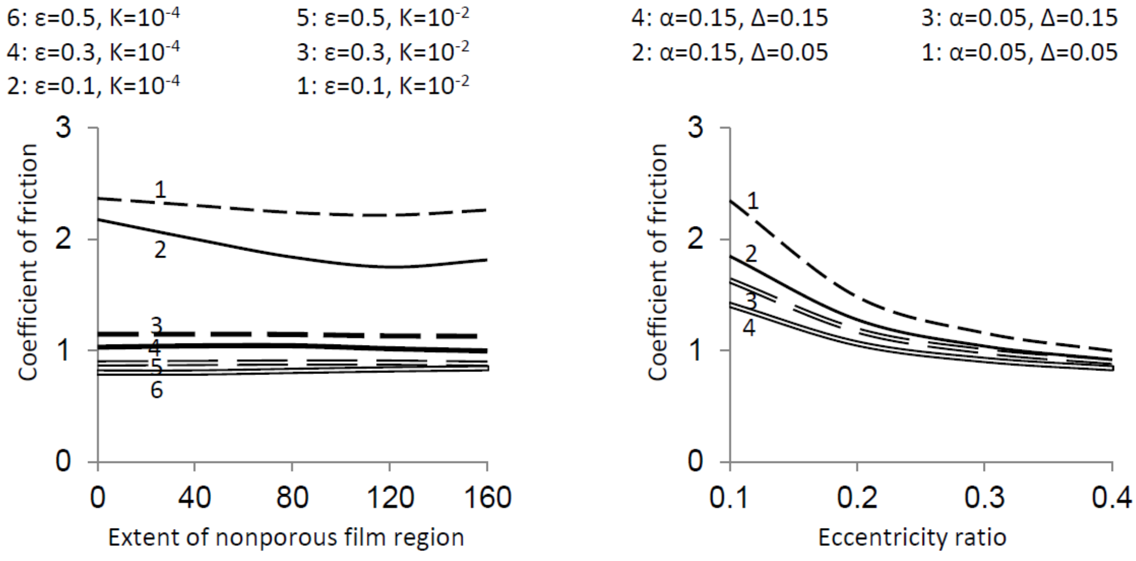
(b) θ_p=120°, $K=10^{-4}$

Figure. 2 Non-dimensional load capacity (K_r=1.2)

The coefficient of friction (C_f) in partial porous layered film journal bearing lubricated with ferrofluid is shown in Figure 3a and 3b. As shown in Figure 3a, at low eccentricity ratio (ε = 0.1) and low non-dimensional permeability of porous layer ($K = 10^{-4}$), the coefficient of friction (C_f)

decreases with the extent of non-porous film region measured from the position of maximum film thickness (θ_p = 0.0-160°).

Figure 3b shows that the coefficient of friction (C_f) decreases considerably with increase in both magnetic field coefficient (α = 0.05, 0.15) and non-dimensional thickness of porous layer (Δ = 0.05, 0.15) at low eccentricity ratio (ε = 0.1) and low non-dimensional permeability of porous layer ($K = 10^{-4}$).



(a) α=0.1, Δ=0.1

(b) θ_p=120°, K=10^{-4}

Figure 3 Coefficient of friction (K_r=1.2)

4.0 CONCLUSIONS

The present study investigates the influence of ferrofluid lubricated partial porous bearing adsorbent layer using displaced infinitely long wire magnetic field model and modified Brinkman model. The expressions for non-dimensional pressure and shear stress are derived for long journal bearing using Reynolds boundary conditions. The conclusions based on the present study of partial porous layered ferrofluid journal bearing are:

- The non-dimensional load capacity (W) increases with increase in extent of non-porous film region measured from the position of maximum film thickness (θ_p = 0°-160°) and decrease in non-dimensional permeability of porous layer ($K = 10^{-2}$-10^{-4}) at low eccentricity ratios. The non-dimensional load capacity (W) increases with increase in magnetic field coefficient (α = 0.05-0.15) and non-dimensional thickness of porous layer (Δ = 0.05-0.15).
- At low eccentricity ratio (ε = 0.1), the coefficient of friction (C_f) decreases with increase in magnetic field coefficient (α), decrease in non-dimensional permeability of porous layer (K), increase in non-dimensional thickness of porous layer (Δ) and increase in extent of non-porous film region measured from the position of maximum film thickness (θ_p).

The bearing performance is significantly improved at low eccentricity ratios under the influence of ferrofluid lubricated bearing adsorbent partial porous layer.

ACKNOWLEDGEMENTS

This research work is funded by Exploratory Research Grant Scheme of Ministry of Education (ERGS-MOE) Malaysia under grant 15-8200-153. The authors greatly appreciate the support provided by Universiti Teknologi PETRONAS for this research.

REFERENCES

1. Tichy, J.A., 1995. A Porous Media Model for Thin Film Lubrication, *ASME Journal of Tribology* 117, 16-21.

2. Li, W-L. and Chu, H-M., 2004. Modified Reynolds Equation for Couple Stress Fluids – A Porous Media Model, *Acta Mechanica* 171, 189-202.

3. Elsharkawy, A.A., 2005. Effects of Lubricant Additives on the Performance of Hydrodynamically Lubricated Journal Bearings, *Tribology Letters* 18, 63-73.

4. Osman, T.A., Nada, G.S. and Safar, Z.S., 2001. Static and Dynamic Characteristics of Magnetized Journal Bearings Lubricated with Ferrofluid, *Tribology International* 34, 369-380.

5. Osman, T.A., Nada, G.S. and Safar, Z.S., 2001. Effect of Using Current-Carrying-Wire Models in the Design of Hydrodynamic Journal Bearings Lubricated with Ferrofluid, *Tribology Letters* 11, 61-70.

6. Rao, T.V.V.L.N., Rani, A.M.A., Nagarajan, T. and Hashim, F.M., 2015. Analysis of Porous Layered Journal Bearing Lubricated with Ferrofluid, *Applied Mechanics and Materials 819*, 474-478.