ANALYSIS OF GROOVED JOURNAL BEARING WITH PARTIAL SLIP SURFACE

T.V.V.L.N. Rao¹, A.M.A. Rani², T. Nagarajan² and F.M. Hashim³

Mechanical Engineering Department
Universiti Teknologi PETRONAS
31750 Tronoh, Perak Darul Ridzuan
MALAYSIA

Email: tadimalla_v@petronas.com.my

ABSTRACT

Design of devices with hydrodynamic lubrication of grooved surfaces with partial slip is possible due to the research efforts in the areas of micro electro mechanical systems (MEMS). The present study examines the effects of slip/no-slip configuration regions on improvement in load capacity and reduction in friction coefficient for journal bearing. The classical Reynolds equation governing the pressure distribution in a hydrodynamic bearing is based on the assumption of no-slip of fluid over the two surfaces with relative sliding motion. In the present work, hydrodynamic grooved journal bearing with partial slip surface is considered and the analysis is carried out using modified classical Reynolds equation considering the partial slip on the bearing surface. The nondimensional pressure and shear stress expressions are derived for the following case: journal bearing with groove immediately followed by the region of partial slip/no-slip configuration. Reynolds boundary conditions are used in the analysis of grooved convergent one dimensional journal bearing to predict nondimensional load capacity and coefficient of friction. Analysis of grooved concentric journal bearing under steady state is also carried out using partial slip conditions. Partial slip of bearing surfaces has a potential to generate load carrying capacity even for concentric journal bearing.

Keywords: Grooved journal bearing, Partial slip surface, Load capacity, Coefficient of friction

1. INTRODUCTION

The classical Reynolds equation is based on the boundary condition assumption of no-slip of fluid over the two surfaces with relative sliding motion. However, recent experimental studies have shown that slip occurs under smooth and microgeometrical conditions (Craig et al., 2001; Zhu and Garnick, 2001, 2002). Spikes (2003a, 2003b) analyzed the influence of wall slip on the hydrodynamic properties of half-wetted bearing. Wu et al. (2006) presented the load capacity of convergent, parallel and divergent slider bearing with mixed slip surface. Wall slip is usually described by slip length model at low shear rate and in the case of the slip length model (Navier condition), slip velocity is proportional to the shear stress at the solid surface. The numerical analysis of slider (Fortier and Salant 2004) and journal (Salant and Fortier 2005) bearing with heterogeneous slip/no-slip bearing surface using modified slip length model yield high load support and low friction. Rao (2010) analyzed the nondimensional pressure and shear stress distribution for a single-grooved slider and journal bearing with partial slip on the stationary surface.

A growing interest is given to the textured hydrodynamic lubricated contacts since the concept of texturing bearing surfaces results in increased load or reduced friction. Based on theoretical studies, Tønder (2001) presented that introducing variable roughness profile at the inlet of a sliding surface contact can generate higher load capacity. Fowel et al. (2007) have analyzed the textured slider bearing performance considering surface texture geometry parameters such as texture depth, width, number of textures, and location of textures. Cupillard et al. (2008) showed an improvement in the hydrodynamic performance due to the texture in the converging gap of journal bearing.

In the present paper, grooved hydrodynamic journal bearing with partial slip is analyzed for the influence of slip configuration on the generation of load support and consequent reduction in friction. Partial slip is considered on the stationary surface of journal bearing. A modified Reynolds equation has been obtained. Nondimensional pressure and shear stress in the single-grooved journal bearing with partial slip under steady state are deduced. Reynolds boundary conditions are used to solve the nondimensional pressure distribution in the journal bearing. Results of load capacity and coefficient of friction in the single grooved one dimensional journal bearing with partial slip under steady state are analyzed.
2. ANALYSIS OF GROOVED JOURNAL BEARING WITH PARTIAL SLIP

Considering that pressure in the journal bearing is a function of sliding direction \((x)\), the momentum equation is simplified as

\[
dp{dx} = \mu \frac{du}{dy} \frac{d^2u}{dy^2} \tag{1}
\]

The boundary conditions for velocity are: Navier slip boundary conditions are imposed on the part of bearing surface. On the other part of the plain and grooved bearing surface, and on the journal surface, no slip conditions are imposed. The boundary conditions for velocity at the journal surface and at the bearing surface are

At \(y = 0, u = U\) and at \(y = h, u = -\mu \frac{du}{dy}\) \tag{2}

Integrating the Eq. (1) for velocity component along \(x\) direction and satisfying the boundary conditions in Eq. (2)

\[
u = \frac{1}{2\nu} \left[ y^2 - \frac{y(h+2a\mu)}{h+a\mu} \right] \frac{dp}{dx} + U \left(1 - \frac{y}{h+a\mu}\right) \tag{3}
\]

The equation of continuity across the film is

\[q_x = \int_0^h y dy \tag{4}\]

Integrating the equation of continuity across the film, and substituting Eqs (3) in (4), yields the modified classical Reynolds equation for partial slip surface as

\[
\frac{d}{dx} \left[ \frac{h^3(h+4a\mu)}{12\mu(h+a\mu)} \right] = \frac{U}{2} \frac{d}{dx} \left[ \frac{h(h+2a\mu)}{h+a\mu} \right] \tag{5}
\]

The nondimensional form of modified classical Reynolds equation for partial slip surface is

\[
\frac{d}{d\theta} \left[ \frac{H^3(H+4A)}{12(H+A)} \right] = \frac{1}{2} \frac{d}{d\theta} \left[ \frac{H(H+2A)}{H+A} \right] \tag{6}
\]

The nondimensional film thickness for the plain journal bearing is expressed in Eq. (7) and the nondimensional film thickness in the grooved journal bearing is expressed as \(H + H_g\).

\[H = (1 + \varepsilon \cos \theta) \tag{7}\]

The shear stress is expressed as

\[\tau_{xy} = -\mu \frac{du}{dy} \tag{8}\]

The shear stress in the journal bearing at \(y=0\) is obtained as

\[\tau_{xy} \big|_{y=0} = \frac{1}{2} \left[ \frac{h(h+2a\mu)}{h+a\mu} \right] \frac{dp}{dx} + \mu \frac{U}{h+a\mu} \tag{9}\]

The nondimensional shear stress in the journal bearing at \(y=0\) is obtained as

\[\Pi \big|_{y=0} = \frac{1}{2} \left[ \frac{h(h+2A)}{H+A} \right] \frac{dp}{d\theta} + \frac{1}{H+A} \tag{10}\]

2.1 Convergent Grooved Journal Bearing with Slip/No-slip Configuration

The schematic of convergent grooved journal bearing with slip/no-slip configuration is shown in Fig. 1.

![Fig. 1 Geometry of grooved journal bearing with slip/no-slip configuration](image)

The slip/no-slip configuration is composed of a number of successive regions of slip and no-slip regions on the bearing surface. The angular extent of successive regions of slip and no-slip regions are \(\theta_{1,2} - \theta_{1,1} = \cdots = \theta_{n,2} - \theta_{n,1} = \theta_s\) and \(\theta_{1,3} - \theta_{1,2} = \cdots = \theta_{n,3} - \theta_{n,2} = \theta_n\) respectively.

The boundary conditions of slip and no-slip region 1 respectively are

\[P|_{\theta=0} = 0, P|_{\theta=\theta_{1,2}} = P_{1,2}\] and \[P|_{\theta=\theta_{1,3}} = P_{1,3}\] \tag{11}

Integrating the Eq. (6), yields the nondimensional pressure profiles of slip and no-slip region 1 as

\[\frac{dp}{d\theta} (0 \leq \theta \leq \theta_{1,2}) = \frac{6(6+2A)}{H^2(H+4A)} - \frac{12(6+2A)}{H^3(H+4A)} \tag{12}\]

\[\frac{dp}{d\theta} (\theta_{1,2} \leq \theta \leq \theta_{1,3}) = \frac{6}{H^2} - \frac{12Q}{H^3} \tag{13}\]

Integrating the Eqs. (12-13) and substituting the boundary conditions given in Eqs. (11), yields the nondimensional pressure profiles of slip and no-slip region 1 as
The boundary conditions in the groove region are

\[ P(\theta = \theta_r) = P(\theta = \theta_\theta), \quad P(\theta = \theta_\beta) = P(\theta = \theta_\beta) \quad (20) \]

Integrating the Eq. (19) and substituting the boundary conditions given in Eqs. (20), yields the nondimensional pressure profile for groove region as

\[ P(\theta \leq \theta \leq \theta_\beta) = P(\theta = \theta_\theta) + 6 \int_{\theta_\beta}^{\theta} \frac{1}{H^2} d\theta - 12Q \int_{\theta_\beta}^{\theta} \frac{1}{H^3} d\theta \quad (21) \]

Integrating the Eq. (6), yields the nondimensional pressure gradient profiles for exit region as

\[ \frac{dP}{d\theta}(\theta \leq \theta \leq \theta_r) = \frac{6}{H^2} - \frac{12Q}{H^3} \quad (22) \]

Integrating the Eq. (22) and substituting the boundary condition for exit region \( P(\theta = \theta_r) = P(\theta_r) \), yields the nondimensional pressure profile for exit region as

\[ P(\theta \leq \theta \leq \theta_r) = P(\theta = \theta_\theta) + 6 \int_{\theta_\beta}^{\theta} \frac{1}{H^2} d\theta - 12Q \int_{\theta_\beta}^{\theta} \frac{1}{H^3} d\theta \quad (23) \]

The Reynolds boundary conditions for film rupture are

\[ P(\theta = \theta_r) = 0 \quad \text{and} \quad \frac{dP}{d\theta}(\theta = \theta_r) = 0 \quad (24) \]

Substitution of the Reynolds boundary conditions for nondimensional pressure at film rupture in Eq. (23) and simplifying using the nondimensional pressure in Eqs. (14), (15), (17), (18), (21) results in Q as

\[ \frac{Q}{H^2} = \int_0^{\theta_\beta} \frac{1}{H^2} d\theta + \int_{\theta_\beta}^{\theta_\theta} \frac{1}{H^2} d\theta + \int_{\theta_\theta}^{\theta_\beta} \frac{1}{H^2} d\theta + \int_{\theta_\beta}^{\theta_\theta} \frac{1}{H^2} d\theta + \int_{\theta_\theta}^{\theta_\beta} \frac{1}{H^2} d\theta + \int_{\theta_\beta}^{\theta_\theta} \frac{1}{H^2} d\theta + \int_{\theta_\theta}^{\theta_\beta} \frac{1}{H^2} d\theta + \int_{\theta_\beta}^{\theta_\theta} \frac{1}{H^2} d\theta \quad (25) \]

Substituting the pressure gradient boundary condition given in Eq. (24) in the expression for nondimensional pressure gradient in Eq. (22), results in

\[ Q|_{\theta = \theta_r} = 0.5H|_{\theta = \theta_r} \quad (26) \]

The Newton-Raphson iterative procedure is used to solve simultaneously both \( \theta_r \) and \( Q|_{\theta = \theta_r} \), using Eqs. (25) and (26).

The radial and tangential nondimensional load capacity obtained by integration of nondimensional pressure along and perpendicular to line of centers are expressed as

\[ W_c = -\int_0^{\theta_\beta} P \cos \theta \, d\theta, \quad W_\phi = \int_0^{\theta_\beta} P \sin \theta \, d\theta \quad (27) \]

The nondimensional load capacity is expressed as

\[ W = \sqrt{W_c^2 + W_\phi^2} \quad (28) \]

The nondimensional shear stress of slip and no-slip region \( I \) is expressed as
Similarly, the nondimensional shear stress of slip and no-slip region \( n \) is expressed as
\[
\Pi(\theta_{n1} \leq \theta \leq \theta_{n2}) = -\frac{6Q}{H^2} + \frac{4}{H} \tag{31}
\]
\[
\Pi(\theta_{n2} \leq \theta \leq \theta_{n3}) = -\frac{6Q}{H^2} + \frac{4}{H} \tag{32}
\]
The nondimensional shear stress for groove region is
\[
\Pi(\theta_1 \leq \theta \leq \theta_2) = -\frac{6Q}{(H+nH_p)^2} + \frac{4}{(H+nH_p)} \tag{33}
\]
The nondimensional shear stress for exit region is
\[
\Pi(\theta_2 \leq \theta \leq \theta_\infty) = -\frac{6Q}{H^2} + \frac{4}{H} \tag{34}
\]
The nondimensional friction force on the journal surface is obtained by integrating the shear stress along the journal surface as
\[
F = \int_0^{\theta_\infty} \Pi \, d\theta \tag{35}
\]
The nondimensional friction coefficient is calculated as
\[
C_f = \left( \frac{R}{L} \right) \frac{f}{W} = \frac{F}{W} \tag{36}
\]
\[\]
2.2 Concentric Grooved Journal Bearing with Slip/No-slip configuration

The nondimensional pressure profiles of a concentric journal bearing for slip and no-slip region \( l \) respectively are
\[
P(0 \leq \theta \leq \theta_{l1}) = P|_{\theta=0} + 6\theta \left( \frac{1+2A}{1+4A} - 2Q \right) \tag{36}
\]
\[
Q = \frac{(\begin{array}{c} 2(1+2A) \\ (1+4A) \end{array})\theta_{l1} + (\theta_{l1}-\theta_{l2}) + \cdots + (\begin{array}{c} 2(1+2A) \\ (1+4A) \end{array})(\theta_{l2}-\theta_{l1}) + (\theta_{l3}-\theta_{l2}) + \frac{1}{H_p} (\theta_{g}-\theta_t) + (2\pi-\theta_g)}{2(1+2A)(\theta_{l1}+2(\theta_{l1}-\theta_{l2}) + \cdots + (\begin{array}{c} 2(1+2A) \\ (1+4A) \end{array})(\theta_{l2}-\theta_{l1}) + 2(\theta_{l3}-\theta_{l2}) + \frac{2}{H_p} (\theta_{g}-\theta_t) + 2(2\pi-\theta_{l3})} \tag{43}
\]
The net load support in the bearing is obtained by integration of nondimensional pressure. The nondimensional load capacity is expressed in Eq. (28). Integrating the nondimensional shear stress over the bearing surface yields the nondimensional friction force as
\[
P(\theta_{l1} \leq \theta \leq \theta_{l2}) = P|_{\theta=\theta_{l1}} + 6(\theta - \theta_{l1})(1 - 2Q) \tag{37}
\]
Similarly, the nondimensional pressure profiles of a concentric journal bearing for slip and no-slip region \( n \) are expressed as
\[
P(\theta_{n1} \leq \theta \leq \theta_{n2}) = P|_{\theta=\theta_{n1}} + 6(\theta - \theta_{n1})(1 - 2Q) \tag{38}
\]
\[
P(\theta_{n2} \leq \theta \leq \theta_{n3}) = P|_{\theta=\theta_{n2}} + 6(\theta - \theta_{n2})(1 - 2Q) \tag{39}
\]
The nondimensional pressure profiles of a concentric journal bearing for groove region is
\[
P(\theta_1 \leq \theta \leq \theta_2) = P|_{\theta=\theta_1} + \frac{6}{H_p} (\theta - \theta_1)(H_p - 2Q) \tag{40}
\]
The boundary conditions for the exit region for a concentric journal bearing are
\[
P|_{\theta=\theta_g} = P_g \quad \text{and} \quad P|_{\theta=2\pi} = 0 \tag{41}
\]
Integrating the Eq. (22) and substituting the boundary conditions given in Eqs. (41), yields the nondimensional pressure profile for exit region as
\[
P(\theta_g \leq \theta \leq 2\pi) = P|_{\theta=\theta_g} + 6(\theta - \theta_g)(1 - 2Q) \tag{42}
\]
Substitution of the boundary conditions for nondimensional pressure in Eq. (42) and simplifying using the nondimensional pressure in Eqs. (36)-(40) results in \( Q \) as
\[
F = \int_0^{2\pi} \Pi \, d\theta = \left( -\frac{6Q(1+2A)}{(1+4A)} + \frac{4(1+3A)}{(1+4A)} \right) \theta_{l1} + \left( -6Q + 4 \right) (\theta_{l1} - \theta_{l2}) + \cdots + \left( -\frac{6Q(1+2A)}{(1+4A)} \right) (\theta_{l2} - \theta_{l1}) + (\theta_{l3} - \theta_{l2}) + \left( \frac{6Q}{H_p} + \frac{4}{H_p} \right) (\theta_g - \theta_t) + (2\pi - \theta_g) \tag{44}
\]
3. RESULTS AND DISCUSSION

A grooved journal bearing with slip/no-slip configuration. The parameters used in the analysis are: journal eccentricity ratio ($\varepsilon$)=0.0, 0.2, 0.4, 0.6 and 0.8; extent of slip region on the bearing surface measured from the position of maximum film thickness for journal bearing ($\theta_t$)=40°, 80°, 120° and 160°; angular extent of groove region for journal bearing immediately followed by partial slip ($\theta_g$)=40°, 80°, 120° and 160°; slip to no-slip region ratio in the grooved journal bearing with slip/no-slip configuration ($\gamma$)=0.2, 0.4, 0.6 and 0.8; number of slip regions in the journal bearing with slip/no-slip configuration ($n$)=2, 4, 6 and 8; nondimensional depth of groove ($H_g$)=1, 2, 3, 4. The non-dimensional slip coefficient ($A$) is zero in no-slip regions.

Figures 2a-2d show the non-dimensional load capacity ($W$) of grooved journal bearing with slip/no-slip configuration. Using the parameters considered in the study, the non-dimensional load capacity ($W$) in the case of grooved concentric journal bearing ($\varepsilon$ =0.0) is higher for higher value of slip to no-slip region ratio ($\gamma$) of 0.8. The non-dimensional load capacity ($W$) in the case of grooved concentric journal bearing ($\varepsilon$ =0.0) increases with increase in slip to no-slip region ratio ($\gamma$). In the case of grooved concentric journal bearing with slip/no-slip configuration ($\varepsilon$ =0.0), the non-dimensional load capacity ($W$) decreases with (i) increase in extent of slip region on the bearing surface ($\theta_t$) and (ii) increase in nondimensional depth of groove ($H_g$). For the case of grooved convergent journal bearing with slip/no-slip configuration at higher eccentricity ratio ($\varepsilon$ =0.8), the non-dimensional load capacity ($W$) increases with (i) increase in extent of slip region on the bearing surface ($\theta_t$), (ii) decrease in nondimensional depth of groove ($H_g$), and (iii) decrease in slip to no-slip region ratio ($\gamma$).
Fig. 2 Nondimensional load capacity of grooved journal bearing with slip/no-slip configuration

Fig. 3 Coefficient of friction of grooved journal bearing with slip/no-slip configuration

Figures 3a-3d show the coefficient of friction ($C_f$) of grooved journal bearing with slip/no-slip configuration. For the parameters considered in the study for grooved concentric journal bearing ($\varepsilon = 0.0$), minimum coefficient of friction ($C_f$) is obtained for higher slip to no-slip region ratio ($\gamma$). Using the parameters analyzed in the study for concentric journal bearing ($\varepsilon = 0.0$), the coefficient of friction ($C_f$) decreases with (i) decrease in extent of slip region on the bearing surface ($\theta_t$), (ii) increase in slip to no-slip region ratio ($\gamma$), and (iii) decrease in nondimensional depth of groove ($H_g$). The variation in coefficient of friction ($C_f$) is not significant for convergent journal bearing eccentricity ratios of 0.6
and 0.8, while the coefficient of friction \((C_f)\) decreases with increase in eccentricity ratio from 0.2 to 0.4.

4. CONCLUSION

The present study examines an approach on improvement in load capacity and reduction in friction coefficient for grooved journal bearing, using slip/no-slip configuration. The conclusions based on the analysis presented in this paper are:

- In the case of grooved concentric \((\varepsilon = 0.0)\) journal bearing with slip/no-slip configuration, the non-dimensional load capacity \((W)\) is higher for higher slip to no-slip region ratio \((\gamma)\).
- For the case of grooved concentric journal bearing with slip/no-slip configuration \((\varepsilon = 0.0)\), the coefficient of friction \((C_f)\) is significantly affected for higher values of slip to no-slip region ratio \((\gamma)\) and lower values of extent of slip region on the bearing surface \((\theta)\).

The analysis of hydrodynamic grooved journal bearing is carried out using modified classical Reynolds equation considering the partial slip on the bearing surface. Bearing surfaces with partial slip has a potential to generate load carrying capacity even for concentric journal bearing. Partial slip on the concentric bearing surface increase the load capacity and reduce the friction coefficient.

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NOMENCLATURE

\(C\) Radial clearance, m

\(f\) Friction force, N; \(F = fC/\mu URL\) for journal bearing

\(h, H\) Film thickness, m; \(H = h/C\) for journal bearing

\(h_g, H_g\) Depth of groove, m; \(H_g = h_g/C\) for journal bearing

\(H_p\) Nondimensional film thickness at groove for concentric journal bearing

\(L\) Length of the journal bearing, m

\(n\) Number of slip regions in the journal bearing with slip/no-slip configuration

\(p\) Pressure distribution, N/m²; \(P = pC^2/\mu UR\) for journal bearing

\(R\) Journal radius, m

\(p\) Pressure distribution, N/m²; \(P = pC^2/\mu UR\) for journal bearing
Volume flow rate per unit length along film thickness, \( m^2/s; \ Q = q/UC \) for journal bearing

Journal radius, m

Velocity component along x direction, m/s

Journal velocity along \( \theta \) direction, m/s

Static load, N; \( W = wC^2/\mu UR^2L \) for journal bearing

Nondimensional radial and tangential static load for journal bearing

Coordinate along x direction, m; \( \theta = x/R \) for journal bearing

Coordinate along y direction, m; \( Y = y/C \) for journal bearing

slip coefficient; \( A = a\mu/C \)

Journal bearing eccentricity ratio

Fluid viscosity, \( \text{Ns/m}^2 \)

Angular coordinate measured from the direction of maximum film thickness in journal bearing

Angular extent of groove region for journal bearing immediately followed by partial slip

Angular extent of successive regions of slip region for journal bearing with slip/no-slip configuration

Angular extent of successive regions of no-slip region for journal bearing with slip/no-slip configuration

Extent of slip region on the bearing surface measured from the position of maximum film thickness for journal bearing

Angular extent of film rupture for journal bearing

Slip to no-slip ratio in the grooved journal bearing with slip/no-slip configuration; \( \gamma = \theta_s/\theta_{sn} \)

Shear stress component, \( \text{N/m}^2 \); \( \Pi = \tau C/\mu U \) for journal bearing

Angular velocity of journal bearing, rad/s

Extent of outlet film in journal bearing measured

Slip region on the bearing surface

No-slip region on the bearing surface

Along the radial direction

Along the tangential direction