Computational Model for Radial Plain Bearing with Non-Circular Bearing Surface Profile and Fusible Coating on Shaft Surface

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Abstract. The paper presents a study based upon: a Newtonian fluid flow equation (“thin layer”), a continuity equation, and an equation of the molten-profile radius for a shaft coated with a fusible metal alloy; considering a mechanical energy dissipation rate formula, the authors produced an asymptotic and accurate automodel solution for the zero approximation (melting ignored) and first approximation (adjusted for melting) of a radial plain bearing featuring a fusible metal coating and a bearing profile adapted to the specific friction parameters. The paper further presents analytical dependencies describing the molten surface radius, velocity and pressure fields for zero and first approximation. Besides, it determines the key operating parameters of the frictional couple, the bearing capacity, and the friction. It also shows how the parameters arising from the melting of the surface affect the bearing capacity and friction where the bearing surface profile is adapted to the specific conditions of friction.

1. Introduction
Many papers cover computational modeling of radial plain bearings with a fusible coating [1-13]. However, lubrication of the molten coating is not a self-sustained process. For the lubrication process in plain bearings to sustain itself, one of the contact areas need a fusible coating, and a lubricant must be present all the time, which can be done by either feeding the lubricant continually, or having a porous surface in the other contact area [14-26] and using a nonstandard bearing profile.

This paper presents a computational model of a radial plain bearing featuring a nonstandard bearing profile of the bearing sleeve and a fusible coating on the shaft surface; this model enables a self-sustained process and hydrodynamic flow.

2. Statement of problem
The paper dwells upon a steady motion of Newtonian fluid between an eccentrically placed shaft and a bearing. The bearing features a non-circular bearing surface profile and is stationary; the shaft has a fusible surface coating and rotates at the angular velocity Ω. In polar coordinates as shown in Fig. 1 r', θ, with the pole being in the center of the shaft, the equations of: (i) the profile of the fusible-coating shaft C₁, (ii) the molten-surface shaft C₀, (iii) the bearing sleeve with an adapted bearing surface profile C₂; and (iv) the bearing sleeve will be written as

C₁ : r' = r₀, C₀ : r' = r₀ − λjθ, C₂ : r' = η(1 + H) − d' sin θ, C₃ : r' = η(1 + H),

(1)
where \( H = \varepsilon \cos \theta - \frac{1}{2} \varepsilon^2 \sin^2 \theta + \ldots \), \( \varepsilon = \frac{e}{r_0} \), \( r_0 \) is the radius of the coated shaft; \( r_1 \) is the sleeve radius; \( e \) is the eccentricity; \( \varepsilon \) is the relative eccentricity; \( \lambda f(\theta) \) is the function that defines the profile of the molten shaft surface profile; \( a' H \omega \) is the disturbance amplitude and the parameter of the adapted sleeve profile, respectively.

![Figure 1. Computational Model.](image)

The initial fundamental equations are the motion equation for the incompressible Newtonian fluid, the continuity equation, and an equation that describes the radius of the molten shaft surface coating profile as adjusted for the mechanical energy dissipation rate:

\[
\frac{\partial \nu'}{\partial r^*} = 0, \quad \mu \frac{\partial^2 \nu_0}{\partial \theta^2} = \frac{dp'}{d\theta} + \frac{\partial \nu_r'}{\partial r'} + \frac{v_r'}{r'} \frac{\partial}{\partial \theta} = 0; \\
\frac{d\lambda f(\theta) \Omega L'}{d \theta} = 2\mu \int_{r_0 - \lambda f(\theta)}^{r_0 + \lambda f(\theta)} \left( \frac{\partial \nu_0}{\partial r'} \right)^2 dr',
\]

where \( \nu_0, \nu_r' \) are the components of the lubricant velocity vector; \( p' \) is the hydrodynamic pressure; \( \mu \) is the coefficient of dynamic viscosity; \( L' \) is the specific heat of melting per unit volume.

The equation system (2) is soluble under the following boundary conditions:

\[
\nu_0 = 0, \quad \nu_r' = 0 \quad \text{at} \quad r' = r_0 (1 + H) - a' \sin \omega \theta; \\
\nu_r' = 0, \quad \nu_0 = \Omega \left( r_0 - \lambda f(\theta) \right) \quad \text{at} \quad r' = r_0 - \lambda f(\theta); \\
p'(0) = p'(2\pi) = p_g, \quad r_0 - \lambda f(\theta) = h^*_0 \quad \text{at} \quad \theta = 0, \quad \theta = 2\pi.
\]

The following formulas enable a transition to dimensionless variables:

\[
r' = \left( r_0 - \lambda f(\theta) \right) + \delta r; \quad \delta = r_0 - \left( r_0 - \lambda f(\theta) \right); \quad \nu_r' = \Omega \delta u, \quad \nu_0 = \Omega \nu \left( r_0 - \lambda f(\theta) \right); \\
p' = p^* p; \quad p^* = \frac{\mu \Omega (r_0 - \lambda f(\theta))^2}{\delta^2}.
\]

Substitute (4) in the system of differential equations (2) and (3) to obtain
where \( \eta = \frac{e}{\delta}; \quad \eta_l = \frac{\eta'}{\delta}; \quad \Phi(\theta) = \lambda f' (\theta). \)

\[
\begin{align*}
&u = 0, \quad v = 1 \text{ at } r = r_0 - \Phi(\theta); \\
&u = 0, \quad v = 0 \text{ at } r = 1 + \eta \cos \theta - \eta_l \sin \omega \theta = h(\theta); \\
&p(0) = p(2\pi) = \frac{p_g}{p}.
\end{align*}
\]

With \( K \) being the small parameter that derives from the melt and the energy dissipation rate, find the function \( \Phi(\theta) \) as

\[
\Phi(\theta) = -K\Phi_1(\theta) - K^2\Phi_2(\theta) - K^3\Phi_3(\theta) - ...
\]

Boundary conditions for the dimensionless velocity components \( u \) and \( v \) for the profile \( r = -\Phi(\theta) \) can be written as

\[
\begin{align*}
&v(0-H(\theta)) = v(0) - \left( \frac{\partial v}{\partial r} \right)_{r=0} \cdot H(\theta) - \left( \frac{\partial^2 v}{\partial r^2} \right)_{r=0} \cdot H'(\theta) - ... = 0; \\
u(0-H(\theta)) = u(0) - \left( \frac{\partial u}{\partial r} \right)_{r=0} \cdot H(\theta) - \left( \frac{\partial^2 u}{\partial r^2} \right)_{r=0} \cdot H'(\theta) - ... = 0.
\end{align*}
\]

Find asymptotic solution of the differential equations (5) with adjustment for the boundary conditions (6) and (8) as follows

\[
\begin{align*}
v(r, \theta) &= v_0(r, \theta) + K\Phi_1(r, \theta) + K^2v_2(r, \theta) + ...; \\
u(r, \theta) &= u_0(r, \theta) + K\Phi_1(r, \theta) + K^2u_2(r, \theta) + ...; \\
\Phi(\theta) &= -K\Phi_1(\theta) - K^2\Phi_2(\theta) - K^3\Phi_3(\theta) - ...; \\
p(0) &= p_0(0) + Kp_1(0) + K^2p_2(0) + K^3p_3(0) ...
\end{align*}
\]

Substitute (9) in the system of differential equations (5)–(6) to obtain

– for zero approximation:

\[
\begin{align*}
&\frac{\partial^2 v_0}{\partial r^2} = \frac{dp_0}{d\theta}, \quad \frac{\partial v_0}{\partial r} + \frac{\partial u_0}{\partial r} = 0; \\
v_0 = 0, \quad u_0 = 0 \text{ at } r = 1 + \eta \cos \theta - \eta_l \sin \omega \theta; \\
v_0 = 1, \quad u_0 = 0 \text{ at } r = r_0 - \Phi(\theta); \quad p_0(0) = p_0(2\pi) = \frac{p_g}{p};
\end{align*}
\]
– for the first approximation:

\[
\frac{\partial^2 v_1}{\partial r^2} = \frac{dp_1}{d\theta}; \quad \frac{\partial v_1}{\partial \theta} + \frac{\partial u_1}{\partial r} = 0; \quad \frac{d\Phi_1(\theta)}{d\theta} = -K \int_0^{\phi(\theta)} \left( \frac{\partial v_0}{\partial r} \right) dr; \tag{12}
\]

\[
v_1 = \left( \frac{\partial v_0}{\partial r} \right)_{r=0} \cdot \Phi; \quad u_1 = \left( \frac{\partial u_0}{\partial r} \right)_{r=0} \cdot \Phi; \tag{13}
\]

\[
p_1(0) = p_1(2\pi) = 0; \quad \Phi(0) = \Phi(2\pi) = h_0^*; \tag{14}
\]

Find the exact automodel solution for zero approximation as

\[
v_0 = \frac{\partial \psi_0}{\partial r} + V_0(r, \theta); \quad u_0 = \frac{\partial \psi_0}{\partial \theta} + U_0(r, \theta); \quad \psi_0(r, \theta) = \tilde{\psi}_0(\xi); \quad \xi = \frac{r}{h(\theta)}; \tag{15}
\]

\[
V_0(r, \theta) = \tilde{\psi}_0(\xi) \cdot h'(\theta). \tag{16}
\]

Substitute (14) in the system of differential equations (10) with adjustment for the boundary conditions (11) to obtain the following system of differential equations:

\[
\frac{d\tilde{\psi}_0^\prime}{d\theta} = \tilde{C}_2, \quad \tilde{v}_0^\prime = \tilde{C}_1, \quad \tilde{u}_0^\prime(\xi) - \xi \tilde{v}_0^\prime(\xi) = 0; \quad \frac{dp_0}{d\theta} = \frac{\tilde{C}_1}{h^2(\theta)} + \frac{\tilde{C}_2}{h^3(\theta)}; \tag{17}
\]

\[
\tilde{\psi}_0^\prime(0) = 0, \quad \tilde{v}_0^\prime(1) = 0, \quad \tilde{u}_0^\prime(1) = 0; \quad \tilde{v}_0^\prime(1) = 0; \quad \tilde{u}_0(0) = 0; \quad \tilde{v}_0(0) = 1; \quad \frac{1}{0} \int_0^{\tilde{v}_0(\xi)} d\xi = 0. \tag{18}
\]

Direct integration will return

\[
\tilde{\psi}_0(\xi) = \frac{\tilde{C}_2}{2} (\xi^2 - \xi), \quad \tilde{v}_0(\xi) = \frac{\tilde{C}_1}{2} \left( 1 + \frac{\tilde{C}_2}{2} \right) \xi + 1, \quad \tilde{C}_1 = 6. \tag{19}
\]

From \( p_0(0) = p_0(2\pi) = \frac{p g}{p} \) obtain the following

\[
\tilde{C}_2 = -\tilde{C}_1 \left( 1 + \frac{\eta_1}{2\pi \omega} (\cos 2\pi \omega - 1) \right). \tag{20}
\]

Taking (18) into account for hydrodynamic pressure:

\[
p_0 = 6 \left( \eta_1 \sin \theta + \frac{\eta_1}{\omega} (\cos \omega \theta - 1) \right) - \frac{\eta_1}{2\pi \omega} (\cos 2\pi \omega - 1) + \frac{p g}{p}. \tag{21}
\]

To define \( \Phi_1(\theta) \) in the context of (11), obtain the following equation

\[
\frac{d\Phi_1(\theta)}{d\theta} = h(\theta) \int_0^{\tilde{\psi}_0(\xi)} \left( \frac{\tilde{v}_0(\xi)}{h^2(\theta)} + \frac{\tilde{v}_0(\xi)}{h(\theta)} \right) d\xi. \tag{22}
\]

Solve Eq. (20) to obtain
\[ \Phi_1(\theta) = \theta - \eta \sin \theta - \frac{\eta_i}{\omega} \cos \omega \theta + h_i^*; \]  
\[ \Phi = \sup_{\theta \in [0,2\pi]} \Phi_1(\theta). \]

Then for the first approximation, obtain
\[ v_i = \frac{\partial \psi_1}{\partial r} + V_i(r, \theta); \quad u_i = -\frac{\partial \psi_1}{\partial \theta} + U_i(r, \theta); \]
\[ \psi_1(r, \theta) = \tilde{\psi}_1(\xi); \quad \xi = \frac{r}{h(\theta) + \Phi}; \]
\[ V_i(r, \theta) = \tilde{v}(\xi); \quad U_i(r, \theta) = -\tilde{u}_i(\xi) \cdot h'(\theta). \]  
(22)

Substitute (22) in the system of differential equations (12)–(13), obtain the following system of differential equations:
\[ \ddot{\tilde{\psi}}_1 = \tilde{C}_2, \quad \ddot{\tilde{v}}_1 = \tilde{C}_1, \quad \ddot{\tilde{u}}_i(\xi) - \xi \ddot{\tilde{v}}_1(\xi) = 0; \quad \frac{dp_i}{d\theta} = \frac{\tilde{C}_1}{(h(\theta) + \Phi)^2} + \frac{\tilde{C}_2}{(h(\theta) + \Phi)^3}; \]
(23)
\[ \ddot{\tilde{\psi}}_1(0) = 0; \quad \ddot{\tilde{v}}_1(1) = 0; \quad \ddot{\tilde{u}}_i(1) = 0; \quad \ddot{\tilde{v}}_1(0) = 0; \quad \ddot{\tilde{u}}_i(0) = 0; \quad \ddot{\tilde{v}}_1(0) = M; \quad \int_0^1 \tilde{v}_1(\xi) d\xi = 0. \]
(24)

Direct integration will return
\[ \tilde{\psi}_1(\xi) = \frac{\tilde{C}_2}{2}(\xi^2 - \xi), \quad \tilde{v}_1(\xi) = \frac{\tilde{C}_1}{2} + \left( \frac{\tilde{C}_1}{2} - M \right) \xi + M, \quad \tilde{C}_1 = 6M. \]
(25)

From \( p_1(0) = p_1(2\pi) = 0 \), find
\[ \tilde{C}_2 = -6M \left( 1 + \frac{\tilde{\eta}_i}{2\pi \omega} (\cos 2\pi \omega - 1) \right) (1 + \Phi), \]
(26)

where \( \tilde{\eta} = \frac{\eta}{1 + \Phi}, \quad \tilde{\eta}_i = \frac{\eta_i}{1 + \Phi}; \)
\[ M = \sup_{\theta \in [0,2\pi]} \left( \frac{\partial \psi_0}{\partial r} \right)_{r=0} \cdot \Phi = \sup_{\theta \in [0,2\pi]} \left[ -1 + 4\eta \cos \theta + 2\eta_i \sin \omega \theta + \frac{3\eta_i}{2\pi \omega} (\cos 2\pi \omega - 1) \right] \cdot \Phi. \]

Adjusting for (26) for \( p_1 \):
\[ p_1 = 6M \frac{\tilde{\eta}_1 \sin \theta + \frac{\tilde{\eta}_1}{\omega} (\cos \omega \theta - 1) - \frac{\tilde{\eta}_1}{2\pi \omega} (\cos 2\pi \omega - 1)}{(1 + \Phi)^2}. \]
(27)

Taking into account (10), (12), (19), and (27), obtain the following for the bearing capacity and the friction
\[ R_\chi = p^* \int_0^{2\pi} \left[ p_0 - \frac{p}{p} + \frac{K p_1}{p} \right] \cos \theta d\theta = 0; \]
Now run numerical analysis in the tested range of parameters and plot the graphs of the key triboparameters, see Fig. 2.

\begin{align*}
R_j &= p^2 \mu_0 \left[\left(\rho_0 - \rho + K \rho_1\right) \sin \theta d\theta = \frac{\mu_0 K}{\omega^2} \left[\eta \pi - \frac{\eta_1}{\omega} \left(\cos 2 \pi \omega - 1\right) + KM \left(\pi \eta + \frac{\eta_1}{\omega} \left(\cos 2 \pi \omega - 1\right)\right)\right] \right] \; ; \\
L_{TP} &= \mu \left[\left.\frac{\partial K_0}{\partial r}\right|_{r=0} + K \left.\frac{\partial K_1}{\partial r}\right|_{r=0}\right] d\theta = \mu \left[\left(-2 \pi + \frac{\eta_1}{\omega} \left(\cos 2 \pi \omega - 1\right) + K \left(2 \pi - \frac{2 \eta_1}{\omega} \left(\cos 2 \pi \omega - 1\right)\right)\right) \cdot \Phi\right] . \quad (28)
\end{align*}

Figure 2. How the adapted profile parameter \( \omega \) and the melting-attributable thermal parameter \( K \) affect the bearing force \((a)\) and the friction \((b)\).

3. Conclusions
For the experimental testing, we had a plain bearing with a fusible coating: Wood’s alloy, see Table. Experiments were run to find the coefficient of friction that would shed light onto whether the bearing would showcase hydrodynamic friction when lubricated with lubricant of Newtonian rheology and with a melting fusible coating. We also detected temperatures and transition from hydrodynamic friction to boundary friction. Experimental investigations showed the melting of fusible coating to have a greater effect on the coefficient of friction compared to the rheology of liquid lubricants.

Table 1. Theoretical vs. experimental investigations: a comparison

| No.   | Theoretical investigations | Experimental investigations |
|-------|---------------------------|-----------------------------|
|       | non-coated                | coated                      | Wood’s alloy-coated        |
| 1     | 0.0050                    | 0.0025                      | 0.0026                     |
| 2     | 0.0048                    | 0.0024                      | 0.0027                     |
| 3     | 0.0049                    | 0.0022                      | 0.0029                     |
| 4     | 0.0045                    | 0.0026                      | 0.0030                     |
| 5     | 0.0047                    | 0.0027                      | 0.0028                     |
Based on the models derived in the theoretical section, we ran experiments that helped outline the potential applications of the developed tribosystem.

Experiments determined the triboparameters that shed light on the duration of hydrodynamic friction and on the reliability of the theoretical computational models and the numerical analysis data.

This study produced novel multiparametric equations for the key operating parameters (bearing capacity and friction) of a radial plain bearing as affected by the rheology of a Newtonian lubricant or molten coating.

The paper further evaluates how the melting of the coating affects the parameters of variable factors.

Improved computational models of radial plain bearings help control the ratio of bearing capacity and friction coefficient by varying the coating.

Theoretical and experimental results show satisfactory convergence, which proves the conclusions of theoretical investigations.

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