Mathematical model of a journal bearing with low-melting and porous coating in its structure on different contacting surfaces with incomplete filling of operating clearance

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Abstract. The authors consider the development of a mathematical design model of an infinite journal bearing lubricated with a lubricant with Newtonian rheological properties and a melt of a low-melting metal alloy covering the surface of the bearing bush, as well as a porous coating on the surface of the shaft, taking into consideration the dependence of the viscosity characteristics of the lubricant, the melt and the permeability of the porous coatings on the pressure with incomplete filling of the operating clearance. The authors found asymptotic solution of the system of differential equations with respect to the parameter $K$ due to the melt and the rate of dissipation of mechanical energy and the exact self-similar solution for the zero approximation without regard for the melt and the first approximation taking into consideration the melt. This solution was found according to the equation of motion of a viscous incompressible fluid for a thin layer, the equations of continuity, Darcy equation and the equation determining, taking into account the expression for the rate of dissipation of mechanical energy, the profile of the molten contour of the bearing bush with regard to the dependence of the permeability of the porous coating, the viscosity of the lubricant depending on pressure. As a result, the fields of velocities and pressures in the lubricating and porous layers were determined taking into consideration the dependence of the lubricant viscosity and the permeability of the porous coating on pressure, as well as the function $\Phi_1(0)$, reasoned by the melt of the bearing bush surface. In addition, the main performance characteristics were determined: load-bearing capacity and friction force.

1. Introduction

It is well-known that modern machines are designed in view of the increase in static and shock loads, which are determined by latest engineering research. Furthermore, it is known that one of the most important elements of slide bearings is the lubricant. In our opinion, one of the methods to solve operational problems is the use a low-melting metal alloy as a lubricant that covers the surface of the bearing bush and a porous coating on the surface of the shaft, taking into consideration the dependence of the rheological properties of the lubricant, the melt and the permeability of the porous coating on pressure. Using a melt as a lubricant has been considered in many publications [1-5].

There are also a lot of works [6-10] that discuss the hydrodynamic calculation of sliding bearings taking into consideration the damping properties and the dependence of viscosity on pressure, as well as the non-Newtonian properties of lubricants. However, in these works there is no simultaneous consideration of the dependence of the viscosity of the applied lubricant and the permeability of the
porous layer on pressure. A distinctive feature of this work is the development of a mathematical design model of a journal bearing with a porous coating of the journal shaft and a low-melting metal coating of the bearing bush surface, taking into consideration the dependence of the viscosity of the lubricant, the melt and the permeability of the porous layer on pressure, which provides a hydrodynamic friction mode with incomplete filling of the operating clearance.

2. Problem statement
In this article the authors consider the movement of a lubricant in the clearance of a journal bearing, the surface of the bearing bush of which is coated with a low-melting metal alloy, and the neck shaft – with a porous layer.

The rotational speed of the neck journal is \( \Omega \), and the bearing bush is stationary. All the heat during rotation goes to melting the surface of the bearing bush coating material covered with a fusible metal coating.

The dependence of the rheological properties of a liquid lubricant and the material permeability is set in the form:

\[
\mu' = \mu_0 e^{\alpha p'}, \quad K' = K_0 e^{\alpha p'}
\]  

(1)

In the coordinate system that we have set, the equations of the contours of the neck journal, the neck journal with a porous layer, the bearing bush with a fusible metal coating are written in the form:

\[
C_0 : r' = r_0 - \tilde{H}; \quad C_1 : r' = r_1; \quad C_2 : r' = r_1 (1+H) + \lambda' f(\theta),
\]  

(2)

Figure 1. Functional diagram

The initial equation is a system of dimensionless equations of motion of the lubricant, Darcy's law, the equation of continuity and the equation that determines the profile of the molten contour of the bearing bush coated with a low-melting metal alloy with an accuracy of terms \( O(\xi^{-1}) \). This equation takes into account the expression for the rate of dissipation of mechanical energy. It is presented in the following form:

\[
\frac{\partial p}{\partial r} = 0; \quad \frac{\partial^2 \nu}{\partial r^2} = e^{-\nu} \frac{dp}{d\theta}; \quad \frac{\partial u}{\partial r} + \frac{\partial \nu}{\partial \theta} = 0; \quad \frac{\partial^2 P}{\partial r^2} + \frac{1}{r} \frac{\partial P}{\partial r} + \frac{1}{r^2} \frac{\partial^2 P}{\partial \theta^2} = 0, \quad \frac{d\Phi(\theta)}{d\theta} = K \int_{r_1} \left( \frac{\partial \nu}{\partial r} \right)^2 \, dr; \quad (3)
\]

where \( K = \frac{2\mu\Omega\eta_0}{L\delta} \), \( \eta = \frac{e}{\delta} \), \( \eta_0 = \frac{\lambda'}{\delta} \), \( \Phi(\theta) = \eta_0 f(\theta) \).

The boundary conditions for equation (3) are as follows:

\[
u = 0, v = 0 \text{ at } r = 1 + \eta_0 \cos \theta + \Phi(\theta), \quad u \bigg|_{r=0} = M \frac{\partial P}{\partial r} \bigg|_{r=\frac{r_1}{\pi}} \bigg|_{\nu = \frac{\nu_0}{\pi}} = 0, \quad v(0) = 1, \quad p = P \text{ at } r' = \frac{r_0}{\tilde{H}}, \quad \frac{\partial P}{\partial r'} \bigg|_{r' = \frac{r_1}{\pi}} = 0,
\]  

(4)
\[ P(\theta) = P(\theta_{1}) = 0 \]  

where \( \tilde{M} = -\frac{k^{2} \eta_{0}^{2}}{H^{3}} \), \( \theta_{1} \) and \( \theta_{2} \) – respectively, the slope ratios of the beginning and end of the free surface of the lubricant.

The relationship between dimensionless and dimensional quantities is as follows:

- in the lubricating layer:

\[ \nu'_{r} = \Omega \delta u, \nu'_{\vartheta} = \Omega \nu_{0} \nu, r' = r_{0} + \delta r, \delta = \eta_{1} - \eta_{0}, p' = \tilde{p} p, \mu' = \mu_{0} \mu, \alpha' = \frac{\alpha}{\tilde{p}}. \]  

- in the porous layer:

\[ P' = p'' P, r' = \tilde{H} r, k' = \tilde{k} \]  

Let us introduce the notation, let \( z = e^{\nu_{0} p} \). Differentiating both sides of the equality, we get:

\[ e^{\nu_{0} p} \frac{dP}{d\theta} = -\frac{1}{\alpha} \frac{dz}{d\theta} \]

Then equation (3) will take the following form:

\[ \frac{dP}{dr} = 0, \frac{\partial^{2} \nu}{\partial r^{2}} = -\frac{1}{\alpha} \frac{d\nu}{d\theta}, \frac{\partial u}{\partial \theta} + \frac{\partial \nu}{\partial r} = 0, \frac{\partial^{2} P}{\partial r^{2}} + \frac{1}{r} \frac{\partial P}{\partial r} - \frac{1}{r^{2}} \frac{\partial^{2} P}{\partial \theta^{2}} = 0, z \frac{d\Phi(\theta)}{d\theta} = K \int_{\pi}^{1} \left( \frac{\partial \nu}{\partial r} \right)^{2} dr \]

With the corresponding boundary conditions:

\[ u = 0, \nu = 0 \text{ at } r = 1 + \eta \cos \theta + \Phi(\theta), u \mid_{r = 0} = \tilde{M} \frac{dP}{d\theta} \mid_{r = \pi}, \nu (0) = 1, P \text{ at } r' = r_{0}, \frac{dP}{dr} \mid_{r = \pi} = 0, \]

\[ z(\theta_{1}) = z(\theta_{2}) = 1 \]

Taking the function \( \Phi(\theta) \) as a small parameter \( K \) due to the melt, we find:

\[ \Phi(\theta) = K \Phi_{1}(\theta) + K^{2} \Phi_{2}(\theta) + K^{3} \Phi_{3}(\theta) + \ldots = H(\theta) \]

Boundary conditions on the contour are:

\[ \nu (1 + \eta \cos \theta + H(\theta)) = \nu (1 + \eta \cos \theta) + \frac{\partial \nu}{\partial r} \mid_{r = 1 + \eta \cos \theta} \cdot H(\theta) + \frac{\partial^{2} \nu}{\partial r^{2}} \mid_{r = 1 + \eta \cos \theta} \cdot H^{2}(\theta) + \ldots = 0; \]

\[ u (1 + \eta \cos \theta + H(\theta)) = u (1 + \eta \cos \theta) + \frac{\partial u}{\partial r} \mid_{r = 1 + \eta \cos \theta} \cdot H(\theta) + \frac{\partial^{2} u}{\partial r^{2}} \mid_{r = 1 + \eta \cos \theta} \cdot H^{2}(\theta) + \ldots = 0 \]

Asymptotic transformation of equations (8):

\[ \nu (r, \theta) = v_{0}(r, \theta) + K_{1} \nu_{1}(r, \theta) + K^{2} v_{2}(r, \theta) + \ldots; \]

\[ u (r, \theta) = u_{0}(r, \theta) + K_{1} u_{1}(r, \theta) + K^{2} u_{2}(r, \theta) + \ldots; \]

\[ \Phi(\theta) = -K \Phi_{1}(\theta) + K^{2} \Phi_{2}(\theta) + K^{3} \Phi_{3}(\theta) + \ldots; \]

\[ z(\theta) = z_{0}(\theta) + K_{1} z_{1}(\theta) + K^{2} z_{2}(\theta) + K^{3} z_{3}(\theta) + \ldots \]

Substituting (12) into (8) taking into consideration (9), we get:

excluding melting:

\[ \frac{\partial^{2} v_{0}}{\partial r^{2}} = -\frac{1}{\alpha} \frac{d\nu_{0}}{d\theta}, \frac{\partial u_{0}}{\partial \theta} + \frac{\partial v_{0}}{\partial r} = 0, \frac{\partial^{2} P_{0}}{\partial r^{2}} + \frac{1}{r} \frac{\partial P_{0}}{\partial r} + \frac{1}{r^{2}} \frac{\partial^{2} P_{0}}{\partial \theta^{2}} = 0 \]

with boundary conditions:

\[ u_{0} = 1, v_{0} = 1 \text{ at } r = 0, \nu_{0} = 0, u_{0} = 0 \text{ at } r = 1 + \eta \cos \theta, u_{0} \mid_{r = 0} = \tilde{M} \frac{dP}{d\theta} \mid_{r = \pi}, P_{0} = P_{2} \text{ at } r' = r_{0}, \frac{dP_{0}}{dr} \mid_{r = \pi} = 0, \]

\[ z_{0}(\theta_{1}) = z_{0}(\theta_{2}) = 1 \]

including melting:
\[ \frac{\partial^2 v_1}{\partial r^2} = -\frac{1}{a} \frac{dz_0}{d\theta} \frac{\partial u_1}{\partial \theta} + \frac{\partial v_1}{\partial \theta} = 0, \quad \frac{\partial^2 P}{\partial r^2} + \frac{1}{r} \frac{\partial P}{\partial r} + \frac{1}{r^2} \frac{\partial^2 P}{\partial \theta^2} = 0, \quad z_0 \frac{\partial \Phi(\theta)}{\partial \theta} = \int_{0}^{\eta} \left( \frac{\partial v_1}{\partial r} \right)^2 \, dr. \]  

(15)

with boundary conditions:

\[ v_1 \left|_{r=0} = \left( \frac{\partial v_1}{\partial r} \right) \cdot \Phi(0); \quad u_1 \left|_{r=0} = \left( \frac{\partial u_1}{\partial r} \right) \cdot \Phi(0); \quad v_1 = 0, u_1 = 0 \right. \] at \( r = 1 + \eta \cos \theta, \)

\[ u_1 \left|_{r=0} = \frac{\partial P}{\partial r} \right|_{r=0} = 0, \quad P_1 = P_1 \] at \( r^* = \frac{r_0}{H} \) \( \frac{\partial P}{\partial r} \left|_{r=0} = 0 \right. \)

\[ \zeta_1(\theta) = \zeta_1(\theta_0) = 0, \quad K \Phi(0) = K \alpha, \quad \Phi(\theta) = \Phi(\theta_0) = \bar{u} \]  

(16)

3. Exact solution

We are looking for the exact solution for the zero approximation:

\[ v_0 = \frac{\partial \psi_0}{\partial r} + V_o (r, \theta), \quad u_0 = -\frac{\partial \psi_0}{\partial r} + U_o (r, \theta). \psi_0 (r, \theta) = \psi_0 (\xi), \quad \xi = \frac{r}{h(\theta)}, \]  

(17)

\[ V_o (r, \theta) = \tilde{v}(\xi), \quad U_o (r, \theta) = -\tilde{u}(\xi) \cdot h'(\theta), \quad h(\theta) = 1 + \eta \cos \theta. \]

Substituting (17) into (13) - (14), we get:

\[ \psi_0^{\omega} = \tilde{C}_2, \quad v_0^{\omega} = \tilde{C}_1, \quad \tilde{u}_0^{\omega}(\xi) + \tilde{\xi}\tilde{v}_0^{\omega}(\xi) = 0, \quad \frac{dz_0}{d\theta} = -a \left( \frac{\tilde{C}_1}{h^2(\theta)} + \frac{\tilde{C}_2}{h^3(\theta)} \right). \]  

(18)

and boundary conditions:

\[ u_0 \left|_{r=0} = \frac{\partial P}{\partial r} \right|_{r=0} = 0, \quad \psi_0^{\omega} (0) = 0, \quad \psi_0^{\omega} (1) = 0, \quad \tilde{u}_0^{\omega} (0) = 0, \quad \tilde{v}_0^{\omega} (0) = 1, \quad \int_{0}^{\eta} \tilde{v}_0^{\omega}(\xi) \, d\xi = 0, \]  

(19)

Integrating (18), we have:

\[ \tilde{v}_0^{\omega}(0) = \frac{\tilde{C}_2}{2} (\xi^2 - \xi), \quad \tilde{v}_0^{\omega}(\xi) = \frac{\tilde{C}_2}{2} \left( 1 + \frac{\tilde{C}_1}{2} \right) \xi + 1, \quad z_0 = -a \left[ \tilde{C}_1 (0 - 2\eta \sin \theta) + \tilde{C}_2 (0 - 3\eta \sin \theta) \right] + 1 \]  

(20)

From \( z_0(0) = z_0(2\pi) = 1 \) the following expression is obtained:

\[ \tilde{C}_2 = -\tilde{C}_1 \left( 1 + \frac{\eta}{\theta_2 - \theta_1} (\sin \theta_2 - \sin \theta_1) \right) \]  

(21)

Substituting the value \( \tilde{C}_2 \) into equation (20) for \( z_0 \), we get:

\[ z_0 = 1 - a\eta \tilde{C}_1 \left[ \sin \theta - \sin \theta_0 - \frac{\theta - \theta_0}{\theta_2 - \theta_1} (\sin \theta_2 - \sin \theta_1) \right] \]  

(22)

Using the asymptotic expansion to determine \( P \), we approach to the following approximate equation:

\[ 1 - a\eta + \frac{a^2 p^2}{2} - 1 + a\eta \tilde{C}_1 \left[ \sin \theta - \sin \theta_0 - \frac{\theta - \theta_0}{\theta_2 - \theta_1} (\sin \theta_2 - \sin \theta_1) \right] = 0 \]  

(23)

In order to find the hydrodynamic pressure, we solve equations (23) accurate to \( O(\eta^3) \) as a result, we get:

\[ P_0 = \frac{1}{2} a\eta \tilde{C}_1 \left[ \sin \theta - \sin \theta_0 - \frac{\theta - \theta_0}{\theta_2 - \theta_1} (\sin \theta_2 - \sin \theta_1) \right] \]  

(24)
Considering expression (24), the Darcy equation will have the form:

\[ P \left( r, \theta \right) = R \left( r \right) C \frac{\eta}{2} \left[ \sin \theta - \sin \theta \right] \left( \frac{\partial \theta}{\partial x} - \frac{\partial \theta}{\partial y} \right) \left( \sin \theta - \sin \theta \right) \] (25)

Substituting (25) into the Darcy equation to determine the function, let us pass to the following differential equation:

\[ R' \left( r \right) + \frac{R'}{r} = 0 \] (26)

and boundary conditions:

\[ \frac{dP}{dr} \bigg|_{r = \eta_H} = 0, \quad R \left( \frac{\eta_H}{H} \right) = 1 \] (27)

Direct integration (26) taking into consideration (27) for the function \( R \left( r \right) \) allows us to get the equation:

\[ R \left( r \right) = \frac{\eta_H r}{2 \eta_H^2 - 2 \eta_H + H^2} \] (28)

Taking into consideration the expression

\[ \tilde{M} \frac{dP}{dr} \bigg|_{r = \eta} = \int_0^1 \psi \left( \xi \right) d\xi \] (29)

For \( \tilde{C}_i \) we use:

\[ \tilde{C}_i = 6 \left[ 1 - \frac{2 \eta_H}{2 \eta_H^2 - 2 \eta_H + H^2} \left( \frac{\sin \theta - \sin \theta}{(\theta - \theta) \cos \theta} \right) \right] \] (30)

Then for \( P_0 \) we get:

\[ P_0 = 3 \eta \left[ 1 - \frac{2 \eta_H}{2 \eta_H^2 - 2 \eta_H + H^2} \left( \frac{\sin \theta - \sin \theta}{(\theta - \theta) \cos \theta} \right) \right] \] (31)

For \( \Phi (\theta) \) we have:

\[ \frac{d\Phi \left( \theta \right)}{d\theta} = \frac{1}{z_0 h(\theta)} \left[ \psi \left( \xi \right) \left( \frac{\eta_H}{h(\theta)} \right)^2 \right] \] (32)

Taking into account \( K \Phi \left( \theta \right) = K \Phi \left( \theta \right) = K \tilde{a} \), we get:

\[ \Phi \left( \theta \right) = \frac{1}{12} \int \left[ \tilde{C}_z \left( \theta - \phi \sin \theta \right) + \tilde{C}_z \left( \theta - \phi \sin \theta \right) + \tilde{C}_z \left( \theta - \phi \sin \theta \right) \right] d\xi \] (33)

We find the solution for the first approximation using:

\[ v_1 = \frac{\partial \psi}{\partial r} + V_1 \left( r, \theta \right); \quad u_i = -\frac{\partial \psi}{\partial \theta} + U_i \left( r, \theta \right); \quad \psi_i \left( r, \theta \right) = \tilde{\psi}_i \left( \xi \right); \quad \xi = \frac{r}{h(\theta)}; \quad V_1 \left( r, \theta \right) = \tilde{V}_1 \left( \xi \right); \quad U_i \left( r, \theta \right) = \tilde{U}_i \left( \xi \right) \cdot h(\theta) \] (34)

Substituting (34) in (15) - (16), we get:

\[ \tilde{\psi}_i' = \tilde{C}_z; \quad \tilde{\psi}_i = \tilde{C}_z; \quad \tilde{U}_i' \left( \xi \right) + \tilde{\psi}_i' \left( \xi \right) = 0; \quad \frac{d}{d\theta} \left( \frac{\tilde{C}_z}{h^2(\theta)} + \frac{\tilde{C}_z}{h^2(\theta)} \right) = 0 \] (35)

and boundary conditions:

\[ \tilde{\psi}_i \left( 0 \right) = 0, \quad \tilde{\psi}_i \left( 1 \right) = 0, \quad \tilde{U}_i \left( 1 \right) = 0, \quad \tilde{v}_i \left( 1 \right) = 0; \quad \frac{dP}{dr} \bigg|_{r = \eta} = 0 \]
\[ u_{\xi} = \frac{\partial P}{\partial r} \left( \frac{r}{r'} \right) \left( \frac{r'}{r} \right) \]

Integrating (35), we have:

\[ \psi (\xi) = \frac{C}{2} (\xi^2 - \xi), \quad \psi (\xi) = \frac{C}{2} + M \left( \xi + M \right). \]

From \( z_1 (\theta_1) = \xi_1 (\theta_2) = 0 \), we get

\[ R = \frac{M \Omega r^2}{3 \eta (1 + MK)} \int_{0}^{\theta_2} \left[ 1 - N \left( 1 - \frac{S}{\cos \theta} \right) \right] \sin \theta - \sin \theta_1 (\theta - \theta_1) : \cos \theta d \theta = \]

\[ \left( 1 - 6\tilde{M} \frac{H^2 (2r - \tilde{H})}{r_1 (2r_1^2 - 2\tilde{H}r_1 + r_1^2)} \right) \frac{\sin (\theta_2 + \theta_1) \cdot \sin (\theta_2 - \theta_1) - \sin \theta_1 \sin \theta_2 + \sin^2 \theta_1 - (\sin \theta_2 - \sin \theta_1) \times \sin \theta_2 + \cos \theta_2 - \cos \theta_1}{\theta_2 - \theta_1} \right) - 6\tilde{M} \frac{H^2 (2r - \tilde{H})}{r_1 (2r_1^2 - 2\tilde{H}r_1 + r_1^2)} \frac{(\sin \theta_2 - \sin \theta_1)^2}{2} \]

\[ R = \frac{\mu \Omega r^2}{3 \eta (1 + MK)} \int_{0}^{\theta_2} \left[ 1 - N \left( 1 - \frac{S}{\cos \theta} \right) \right] \sin \theta - \sin \theta_1 (\theta - \theta_1) : \cos \theta d \theta = \]

\[ + \frac{\sin \theta_2 - \sin \theta_1}{\theta_2 - \theta_1} \left[ \frac{\cos \theta_2 - \theta_1 \cos \theta_1 - (\sin \theta_2 - \sin \theta_1) \times \sin \theta_2 - \sin \theta_1 \times \frac{\sin \theta_2 - \sin \theta_1}{\theta_2 - \theta_1} \times \frac{1 - 6\tilde{M} \frac{H^2 (2r - \tilde{H})}{r_1 (2r_1^2 - 2\tilde{H}r_1 + r_1^2)} \frac{(\sin \theta_2 - \sin \theta_1)^2}{2} \right] \]

\[ L_{\theta} = \mu \frac{\partial}{\partial \theta} \int_{0}^{\theta_2} \left[ \frac{\partial \psi}{\partial \theta} \right] d \theta = \frac{\mu \Omega r^2}{6} \left[ -2(\theta_2 - \theta_1) + \eta (2 + \tilde{C}_1 + 2K\tilde{C}_1) (\sin \theta_2 - \sin \theta_1) + KM \right] \]

As a result of the numerical analysis, graphs were built:
5. Conclusion
The theoretical design models and their numerical analysis obtained as a result of the research showed a significant contribution of the parameter (α) characterizing the dependence of the viscosity of the lubricant and the porous layer on pressure as well as parameters (K) that is determined by the melting of an easily fusible metal coating. (H) which characterizes the thickness of the porous coating on the surface of the neck journal on the performance characteristics of the plain bearing. A large reduction in frictional force and an increase in bearing capacity have been proven. Tribotechnical design models were approximately refined in terms of bearing capacity by 22%, in terms of friction force by 25%.

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