Mathematical Model of Micropolar Lubricant Considering Viscosity-Pressure Dependence

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Abstract. In the study, based on the micropolar fluid flow equation for a “thin layer”, the continuity equation, the equation describing the profile of the molten contour of the guide coated with a low-melting metal alloy, and the equation for the mechanical energy dissipation rate, asymptotic and exact self-similar solution has been found for the zero (without considering the melting) and first (considering the melting) approximation of wedge-shaped support with the slider support profile adapted to the friction conditions and the low-melting metal coating of the guide surface. The research has taken into account the pressure dependence of the lubricant rheological properties and the melt having micropolar properties in the laminar flow regime. Analytical dependencies have been obtained for the molten surface profile of the low-melting metal coating of the guide and the field of velocities and pressure for the zero and first approximations. Also, the basic performance characteristics of the friction pair under consideration have been determined: the bearing capacity and the friction force. The impact of parameters determined by the coating melt, adapted to the support profile friction conditions, and the parameter characterizing the pressure dependence of the lubricant viscosity on the bearing capacity and friction force has been estimated.

1. Introduction
A sufficient number of publications [1-13] consider developing a design model of thrust plain bearings with a low-melting coating on movable and fixed contact surfaces. However, the surface melt lubrication is not a self-sustaining process. To provide self-sustaining lubrication of journal bearings, not only the presence of low-melting coatings on one of the working contact surfaces but also the constant availability, i.e., constant supply of lubricant [14-26] or an adapted profile of the bearing surface is required.

The study provides a design mathematical model of the hydrodynamic lubricant flow regime and a coating melt with micropolar rheological properties in the running clearance of wedge-shaped sliding support with an adapted profile of the bearing surface of the slider, considering the viscosity-pressure dependence.

2. Research objective
The steady-state flow of an incompressible liquid and a coating melt in the running clearance of wedge-shaped sliding support has been considered. In this case, the wedge-shaped sliding support with a non-standard support profile is fixed, and the thrust ring with a low-melting coating moves at the velocity $u^*$ (Fig. 1).
The design scheme is built in the coordinate system $x'y'y'$. The contours of an inclined slider with a non-standard support profile and a molten coating of the guide surface are described as follows:

$$y' = h_0 + x'\tan\alpha, \quad y' = h_0 + x'\tan\alpha - \alpha'\sin\alpha x' = h'(x'),$$
$$y' = -\lambda'y'(x').$$

(1)

where $\alpha'$ is the angle between the inclined slider and the $Ox$ axis; $h_0$ is the lubricating layer thickness in the initial section; $\alpha'$ and $\omega'$ are the disturbance range and the adapted slider profile parameter, respectively.

The pressure dependence of the lubricant viscosity is set in the form:

$$\mu = \mu_0 p', \quad \kappa' = \kappa_0 p', \quad y' = \gamma_0 p'.$$

(2)

The basic equations are the well-known micropolar lubricant flow equation for a “thin layer”, the continuity equation, and the equation describing the profile of the molten coating contour, considering the mechanical energy dissipation rate:

$$\frac{1}{2} \left( 2\mu + \kappa \right) \frac{d^2 u'}{dy'^2} + \kappa \frac{\partial v'}{\partial y'} = \frac{dp'}{dx'},$$

$$\gamma \frac{d^2 \omega'}{dy'^2} - 2\kappa \omega' - \kappa' \frac{\partial v'}{\partial y'} = 0, \quad \frac{\partial v'}{\partial y'} \frac{\partial v'}{\partial x'} = 0,$$

$$\frac{d\lambda'}{dx'} \left( h'(x') \right) \cdot L' = -2\mu \left\{ \frac{\partial u'}{\partial y'} \left( \frac{\partial u'}{\partial y'} \right)^2 \right\} dy'.$$

(3)

With commonly accepted simplifications, the boundary conditions for this problem will have the form:

$$u' = -u^*, v' = 0, \quad v' = 0 \text{ at } y = -\eta f'(x');$$
$$u' = 0, \quad v' = 0, \quad v' = 0 \text{ at } y = h'(x');$$
$$p(0) = p(L) = p_0.$$

(4)
To pass to dimensionless variables, we apply the standard technique:

\[ u' = \frac{u}{h_0}, \quad v' = \frac{v}{v_0}, \quad \nu' = \frac{\nu}{\mu}, \quad p' = \frac{p}{\mu h_0^2}; \quad y' = h_0 y; \]

\[ N^2 = \frac{\kappa}{2\mu + \kappa}; \quad \nu'_I = \frac{2h_0^2}{\nu_0^2}; \quad \nu_0^2 = \frac{\gamma}{4\mu}; \quad \nu' = \mu_0 \mu; \]

\[ \varepsilon = \frac{h_0}{L}; \quad \nu' = \frac{u}{2h_0}; \quad \nu = \frac{2(h_0 + \nu_0^2)h^*_l}{2h_0^2}; \quad x' = Lx; \quad \bar{a} = \frac{a}{p}; \quad \bar{v}' = \bar{a} L. \] 

(5)

Considering (5) in the system of equations (3) and boundary conditions (4), as a result, we obtain a system of equations with boundary conditions:

\[ \frac{\partial^2 u}{\partial y^2} + N^2 \frac{\partial \nu}{\partial y} = e^{-\alpha p} \frac{\partial p}{\partial x}, \quad \nu = \frac{1}{2N_0 h} (y^2 - h), \quad \frac{\partial u}{\partial y} + \frac{\partial \nu}{\partial y} = 0, \quad \frac{\partial \Phi}{\partial x} = -K \frac{\partial^2 \nu}{\partial y^2}; \]

\[ \nu = 0, \quad v = 0, \quad u = 0 \text{ at } y = 1 + \eta x - \eta_1 \sin \alpha x; \]

\[ \nu = 0, \quad v = 0, \quad u = -1 \text{ at } y = -\Phi(x); \]

\[ p(0) = p(1) - \frac{P_0}{p}. \] 

(6)

(7)

(8)

(9)

Introduce the notation \( z = e^{-\alpha p} \). When differentiating both sides of the equality, equations (8) with boundary conditions (9) will take the form:

\[ \frac{\partial^2 u}{\partial y^2} + N^2 \frac{2y - h}{2N_0 h} = -\frac{1}{\alpha} \frac{dz}{dx}, \quad \nu = \frac{1}{2N_0 h} \left(y^2 - h \right), \quad \frac{\partial u}{\partial y} + \frac{\partial \nu}{\partial y} = 0, \quad \frac{\partial \Phi}{\partial x} = -K \frac{\partial^2 \nu}{\partial y^2}; \]

\[ \nu = 0, \quad v = 0, \quad u = 0 \text{ at } y = 1 + \eta x - \eta_1 \sin \alpha x; \]

\[ \nu = 0, \quad v = 0, \quad u = -1 \text{ at } y = -\Phi(x); \]

\[ p(0) = p(1) - \frac{P_0}{p} e^{-\alpha p}. \] 

(10)

(11)

Similarly to the previous problems, the asymptotic solution of system (10) considering (11) can be written as follows:

\[ v(x, y) = \frac{v_0}{\Phi(x)} + K \nu(x, y) + \nu^2(x, y) + \ldots; \]

where \( K = \frac{2\mu^\prime L}{\eta_0 L}; \quad \eta = \frac{\mu^\prime a}{h_0}; \quad \eta_1 = \frac{a}{h_0}. \)
\[ u(x, y) = u_0(x, y) + Ku_1(x, y) + K^2u_2(x, y) + \ldots; \]
\[ \Phi(x) = -K\Phi_1(x) - K^2\Phi_2(x) - K^3\Phi_3(x) - \ldots; \]
\[ z(x) = z_0 + Kz_1(x) + K^2z_2(x) + K^3z_3(x) - \ldots. \]  
(12)

Considering (12), from (10), we obtain a system of equations with boundary conditions:

- for zero approximation:
\[ \frac{\partial^2 u_0}{\partial y^2} + \frac{N^2}{2N'h}(2y - h) = -\frac{1}{\alpha} \frac{\partial u_0}{\partial x} + \frac{\partial \psi_0}{\partial y} = 0, \]
\[ v_0 = 0, \quad u_0 = 0 \quad \text{at} \quad y = 1 + \eta x - \eta_1 \sin \alpha; \]
\[ v_0 = 0, \quad u_0 = -1, \quad v_0 = 0 \quad \text{at} \quad y = \Phi(x) = 0; \]
\[ z_0(0) = z_0(1) = e^{\frac{-a\rho}{p}} ; \]
(13)

- for the first approximation:
\[ \frac{\partial^2 u_1}{\partial y^2} + \frac{1}{\alpha} \frac{\partial u_1}{\partial x} + \frac{\partial \psi_0}{\partial y} = 0, \]
\[ \frac{d\Phi_1(x)}{dx} = K \frac{\psi_0}{\Phi(0)} \frac{\partial \psi_0}{\partial y} dy; \]
\[ v_1 = \left( \frac{\partial \psi_0}{\partial y} \right)_{y=0} \cdot \Phi; \quad u_1 = \left( \frac{\partial \psi_0}{\partial y} \right)_{y=0} \cdot \Phi; \]
\[ v_1 = 0, \quad v_1 = 0, \quad u_1 = 0 \quad \text{at} \quad y = h(x) + \Phi; \]
\[ z_1(0) = z_1(1) = 1; \quad \Phi(0) = \Phi(1) = h^*; \]
(14)

A self-similar solution to systems (13) and (14) will be sought in the form
\[ u_0 = \frac{\partial \psi_0}{\partial x} + U_0(x, y); \quad v_0 = \frac{\partial \psi_0}{\partial y} + V_0(x, y); \quad \psi_0(x, y) = \tilde{\psi}_0(\xi); \quad \xi = \frac{y}{h(x)}; \]
\[ V_0(x, y) = -\tilde{v}(\xi) \cdot h'(x); \quad U_0(x, y) = \tilde{u}_0(\xi); \quad \frac{dz_0}{dx} = -\alpha \left( \frac{\tilde{C}_1}{h'(x)} + \frac{\tilde{C}_2}{h''(x)} \right). \]
(15)

Considering (17), from (13) and (14), we obtain a system of equations with boundary conditions:
\[ \tilde{\psi}_0^* = \tilde{C}_2, \quad \tilde{\nu}_0^* = \tilde{C}_1 - \frac{N^2}{2N'h}(2\xi - 1); \quad \tilde{u}_0^* + \xi \tilde{v}_0^* = 0; \quad \frac{dz_0}{dx} = -\alpha \left( \frac{\tilde{C}_1}{h'(x)} + \frac{\tilde{C}_2}{h''(x)} \right); \]
\[ \tilde{\psi}_0(0) = 0, \quad \tilde{\nu}_0(1) = 0, \quad \tilde{\nu}_0(1) = 0, \quad \tilde{v}_0(0) = 0, \quad \tilde{v}_0(1) = 0; \]
\[ \tilde{u}_0(0) = 1, \quad \tilde{v}_0(0) = 0, \quad 0 \frac{d\tilde{a}_0(\xi)}{d\xi} = 0; \]
(16)

Solving (18) and (19), we obtain the calculation formulas
\[ \tilde{\psi}_0(\xi) = \frac{\tilde{C}_2}{2} \left( \xi^2 - \tilde{C}_1 \right), \quad \tilde{C}_1 = 6; \]
(20)

\[ \tilde{u}_0(\xi) = \frac{\xi^2}{2} - \frac{N^2}{2N'h} \left( \frac{\xi^3}{3} - \frac{\xi^2}{2} \right) - \left( \frac{N^2}{12N'h} + \frac{\tilde{C}_1}{2} + 1 \right) \xi + 1. \]

Considering \( z_0(0) = z_0(1) = e^{\frac{-a\rho}{p}} \), from the fourth equation of system (18), up to for, we obtain the equation for \( \tilde{C}_2 \) accurate to \( O(\eta^3) \):
Considering (21), for \( z_0 \), we get:

\[
\hat{z}_2 = -6 \left( 1 + \frac{n}{2} + \frac{n}{\omega} (\cos \omega - 1) \right).
\]  

(21)

For the function determining the molten contour of the support ring, considering (20), we obtain:

\[
z_0 = -6\alpha \left( \frac{n}{2} (x^2 - x) + \frac{n}{\omega} (\cos \omega x - 1) - \frac{n_1 x}{\omega} (\cos \omega - 1) \right) + e^{-\frac{u_0}{\rho}}.
\]  

(22)

A self-similar solution to (15) and (16) will be sought in the same way as for (13) and (14). As a result, we obtain the calculation formulas for the field of velocities and pressure:

\[
\tilde{\psi}'(\tilde{\xi}) = \tilde{C}_1 \left( \tilde{\xi}^2 \right), \quad \tilde{C}_1 = 6M; \quad \tilde{\alpha}_1(\tilde{\xi}) = \tilde{C}_1 \frac{\tilde{\xi}^2}{2} - \left( \tilde{C}_1 + M \right) \tilde{\xi} + M;
\]  

(23)

\[
\frac{dz_1}{dx} = -\alpha \left( \frac{\tilde{C}_1}{(h(x) + \Phi)^2} + \frac{\tilde{C}_2}{(h(x) + \Phi)^2} \right);
\]  

(24)

A self-similar solution to (15) and (16) will be sought in the same way as for (13) and (14). As a result, we obtain the calculation formulas for the field of velocities and pressure:

\[
\tilde{C}_2 = -6M \left( 1 + \frac{1}{2} \tilde{n} + \frac{\tilde{n}_1}{\omega} (\cos \omega - 1) \right) \left( 1 + \Phi \right),
\]  

(25)

where

\[
\tilde{n} = \frac{n}{1 + \Phi}; \quad \tilde{n}_1 = \frac{n_1}{1 + \Phi};
\]

\[
M = \sup_{x \in [0,1]} \left( \frac{\partial h_0}{\partial y} \right)_{y=0} \cdot \Phi_1(x) = \sup_{x \in [0,1]} \left[ -2\eta \frac{\eta_0}{\omega} (\cos \omega + 1) + \frac{N^2}{4N_1} (1 + \eta_1 - \eta \sin \omega) \right] \Phi.
\]  

(26)

Considering (26), for \( z_1 \), we get:

\[
z_1 = -6\alpha M \left( 1 + \Phi \right)^2 \left( \frac{\eta_1}{2} (x^2 - x) + \frac{\tilde{n}_1}{\omega} (\cos \omega x - 1) \right) - \frac{n_1 x}{\omega} (\cos \omega - 1) + 1.
\]  

(27)

Therefore, for \( z = z_0 + Kz_1 \), we get the following equation:

\[
z = -6\alpha A + e^{-\frac{u_0}{\rho}} - 6\alpha KM \cdot B + 1,
\]  

(28)
where \( A = \left( \frac{\eta \left( x^2 - x \right)}{\omega} + \frac{\eta_1}{\omega} \left( \cos \omega x - 1 \right) - \frac{\eta_1 x}{\omega} \left( \cos \omega - 1 \right) \right) ; \)

\[ B = \frac{\tilde{\eta} \left( x^2 - x \right) + \frac{\eta_1}{\omega} \left( \cos \omega x - 1 \right) - \frac{\eta_1 x}{\omega} \left( \cos \omega - 1 \right)}{(1 + \Phi)^2}. \]

Applying the Taylor method for the functions \( e^{-x^2} \) and \( e^{-\frac{\omega x}{p}} \), with an accuracy to \( O(\alpha^3) \), \( O\left( \frac{p a}{p^3} \right) \), for the hydrodynamic pressure, we obtain

\[ p = \frac{p a}{p^3} - 6 \left( A + KMB \right) \left( 1 + \alpha \frac{p a}{p^3} - \frac{\alpha^2}{2} \left( \frac{p a}{p^3} \right)^2 \right). \]  \( \text{(29)} \)

Considering (13), (15), and (29), for the bearing capacity and friction force, we obtain:

\[ W = p \int_0^{\frac{1}{2}} \left( \frac{p a}{p^3} - \frac{p a}{p^3} \right) dx = \frac{3 \left( 2 \mu_0 + \kappa_0 \right) L^2 u^2}{b_0} \times \]

\[ \times \left( 1 + KM \left( 1 + \alpha \frac{p a}{p^3} - \frac{\alpha^2}{2} \left( \frac{p a}{p^3} \right)^2 \right) \right) \times \]

\[ \times \left( - \frac{\eta_1}{12} \frac{\eta_1}{\omega} \left( \sin \omega \frac{1}{2} \cos \omega \frac{1}{2} \right) \right) + \]

\[ \frac{KM}{(1 + \Phi)^2} \left( - \frac{\tilde{\eta}}{12} \frac{\eta_1}{\omega} \left( \sin \omega \frac{1}{2} \cos \omega \frac{1}{2} \right) \right) \right); \]

\[ L_{\text{fr}} = \int_0^1 \left[ \frac{\partial u_a}{\partial y} \right]_{y=0} + K \frac{\partial u_t}{\partial y} \left|_{y=0} \right. \right] dx = \]

\[ \left( 2 \mu_0 + \kappa_0 \right) \left( 1 - \alpha \rho - \frac{\alpha^2}{2} \right) \times \]

\[ \times \left[ 1 - \frac{\eta_1}{\omega} \cos \omega - 1 + \frac{N^2}{4 N_1} \left( 1 + \frac{\eta_1}{\omega} \cos \omega - 1 \right) \right] - \]

\[ - \Phi K \left( - \frac{N^2}{4 N_1} \left( 1 - \frac{\eta_1}{\omega} \cos \omega - 1 \right) + \frac{N^2}{4 N_1} \right). \]  \( \text{(30)} \)

The above models of thrust plain bearings with a low-melting coating of the support ring surface and an adapted profile of a slider with an inclined contact surface, working in a hydrodynamic regime on a liquid lubricant and a metal melt have shown that \( K, N^2, N_1, \alpha, \) and \( \omega \) parameters contribute significantly to the tribological characteristics of bearings. These models have been considered to account the pressure dependence of the viscosity of lubricants and the coating melt having micropolar rheological properties. Considering the above factors, the authors obtained the bearing capacity of the sliding support exceeds that of standard journal bearings by 19-21 %. Thereat, the friction coefficient decreases by 14–16 %.

In an experimental study, wedge-shaped sliding support with a low-melting metal coating made of Wood's alloy has been considered (see table). Based on the experimental results, the friction coefficient has been determined. This allows suggesting the occurrence of a hydrodynamic friction mode when the bearing operates with both a lubricant with micropolar properties and low-melting
Wood's alloy coating of the guide surface. The temperature and the transition from the hydrodynamic friction regime to the boundary one have also been determined. The analysis of experimental studies has shown that the Wood's alloy low-melting coating melt affects the friction coefficient 2.5–4 times more intensively than the rheological properties of the liquid lubricants applied. Experimental studies have confirmed the reliability of the theoretical models developed and the data of their numerical analysis in the considered range of design and operational parameters of wedge-shaped sliding supports with Wood's alloy low-melting metal coatings as a result of satisfactory convergence of theoretical and experimental results.

| Item No. | Friction coefficient | Theoretical study | Experimental study |
|----------|----------------------|-------------------|-------------------|
| Thrust without low-melting coating | Thrust bearing with Wood's alloy low-melting metal coating |
| 1        | 0.0044               | 0.0026            | 0.0028            |
| 2        | 0.0045               | 0.0025            | 0.0031            |
| 3        | 0.0048               | 0.0024            | 0.0034            |
| 4        | 0.0049               | 0.0023            | 0.0035            |
| 5        | 0.0052               | 0.0024            | 0.0037            |

3. Summary
Theoretical studies have shown that a low-melting metal coating of the guide surface, considering the pressure dependence of the general rheological properties of both the lubricant applied and the low-melting metal coating melt with micropolar properties, results in the bearing capacity increase by ≈5–8 % with a higher α parameter characterizing the pressure dependence of viscosity, and the friction coefficient decreases by 8–9 %.

Based on the design models obtained in the theoretical part, an experimental study was performed, which allowed determining the area of prospective exploitation of the tribosystem developed.

As a result of experimental studies, tribological characteristics have been determined, which allow obtaining the duration of the hydrodynamic friction regime, the reliability of the theoretical design models developed, and the data of their numerical analysis.

4. Conclusion
New multivariable equations have been developed for the main performance characteristics (bearing capacity and friction force) of wedge-shaped sliding support, considering the rheological properties of a micropolar lubricant the melt of the guide surface coated with a low-melting metal alloy.

The impact of variables determined by the melt of the guide surface coated with a low-melting metal alloy and the pressure dependence of the lubricant viscosity have been estimated.

The refined design models of wedge-shaped sliding support obtained allow adjusting the ratio of bearing capacity to the friction coefficient by varying the low-melting metal coating on the guide surface.

To support the theoretical conclusions, satisfactory convergence of theoretical and experimental study results has been established.
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