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Simulation Model of Radial Bearing, Taking into Account the Dependence of Viscosity Characteristics of Micro-Polar Lubricant Material on Temperature

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Abstract

This work tells about method of formation of exact self-similar solution of the problem of hydrodynamic calculation of the infinite radial sliding bearing with the adapted profile of the supporting surface, taking into account the dependence of the viscosity characteristics of the micro-polar lubricant on temperature during the adiabatic process. Analytical dependence is obtained for the bearing capacity and frictional force based on the equations of motion of the micro-polar liquid for the case of a "thin layer", taking into account the viscosity characteristics of temperature, continuity and expression for the energy dissipation rate. The effect of parameters characterizing the dependence of viscosity on temperature and the adapted profile on the bearing capacity and the friction force is estimated.

Keywords: radial bearing, micro-polar liquid lubricant, dependence of viscosity characteristics on temperature, adapted profile.

INTRODUCTION

It is known, at present the micro-polar liquid lubricant is widely used as the model of hydrodynamic tribosystem of sliding bearings. Therefore, the development of methods for the calculation of sliding bearings operating on the micro-polar liquid lubricant requires consideration of the dependence of viscosity not only on pressure, but also on the dependence of viscosity characteristics on temperature. The significant drawback of the existing methods for calculation of sliding bearings operating on the micro-polar liquid lubricant is that, in most cases, the dependence of viscosity on pressure and temperature [1] - [7] is not taken into account at all, or this dependence is taken into account only on pressure [8]-[11]. Analysis of the examined works on the micro-polar lubricant shows that today there are a number of important but unsolved problems that significantly impede the expansion of the practical application of this highly effective lubricant.

STATEMENT OF PROBLEMS.

The steady motion of a viscous micro-polar liquid lubricant in the working gap of a radial bearing under conditions of adiabatic process is considered. The bearing with the adapted profile of the support surface is stationary, and the shaft rotates at angular velocity Ω (See Fig. 1).

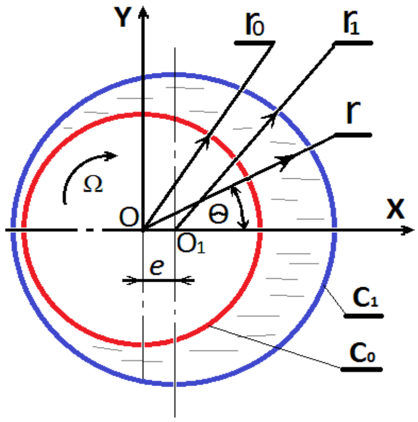

Figure 1. Simulation Scheme

It is assumed that there is a complete filling of the working gap with the lubricating material. In addition, we assume that the viscosity characteristics of the micro-polar lubricant depend on the temperature according to the exponential law:

$$\mu' = \mu_0 e^{-\beta' T'}, \qquad \kappa' = \kappa_0 e^{-\beta' T'}, \qquad \gamma' = \gamma_0 e^{-\beta' T'}. \tag{1}$$

Here μ' is the coefficient of dynamic viscosity of lubricant;

κ' и γ' are viscosity coefficients of micro-polar lubricant;

μ_0 is characteristic viscosity of a Newtonian lubricant; κ_0 и γ_0 are characteristic viscosity of micro-polar lubricant; T' is temperature, β' is experimental constant value.

The equation of the shaft contours and the bearing bush in the polar coordinate system r', θ in the center of the shaft are as follows:

$$r' = r_0, \quad r' = r_1 + e\cos\theta - a\sin\omega\theta, \tag{2}$$

where r_0 is the pin radius; r_1 is the bearing radius; e is eccentricity; $\frac{e}{\delta}, \frac{a}{\delta}$ is small quantity of the same order $(\delta = r_1 - r_0)$; a, ω are parameters of the contact profile to be determined.

LEGEND

μ_0 – characteristic viscosity of a Newtonian lubricant, Ns/m^2 ;

κ' и γ' — viscosity coefficients of micro-polar lubricant, Ns/m^2;

κ_0 и γ_0 — characteristic viscosity of micro-polar lubricant, Ns/m^2;

p' – hydrodynamic pressure, Pa;

T' –temperature, $^\circ C$;

β' – constant experimental value,

μ' – lubricant dynamic viscosity coefficient, Ns/m^2 ;

r_0 – shaft radius, m;

r_1 – bearing radius, m;

e – eccentricity;

δ – radial gap, m;

ω, a – parameters, characterizing the adapted profile of the bearing;

u', v' – components of lubricating material's velocity vector;

T_0 – characteristics temperature, $^\circ C$;

β – parameter, characterizing the dependence of viscosity on temperature;

υ' — micro-particles rotation rate, m/ s ;

Q – lubricant consumption per unit time, $\frac{m^3}{s}$;

C_p – heat capacity at constant pressure, J/kg·degrees;

h – oil film thickness, m;

Ω – angle speed, s^{-1};

η – eccentricity ratio of bearing bush;

η_1 – eccentricity ratio of adapted profile of the bearing.

BASIC EQUATIONS AND BOUNDARY CONDITIONS.

The system of dimensionless equations of motion of the micro-polar liquid for the case of a "thin layer" with allowance for (1), and also the continuity equation are taken as initial equations:

$$\frac{\partial^2 u}{\partial r^2} + N^2 \frac{\partial \upsilon}{\partial r} = \frac{1}{e^{-\beta T}} \frac{dp}{d\theta},$$

$$\frac{\partial^2 \upsilon}{\partial r^2} = \frac{\upsilon}{N_1} + \frac{1}{N_1}\frac{\partial u}{\partial r}, \qquad \frac{\partial u}{\partial r} + \frac{\partial v}{\partial \theta} = 0. \tag{3}$$

Dimensional values $u', v', \upsilon', p', r', \mu', \kappa', \gamma', \beta', T'$ are connected with non-dimensional $u, v, \upsilon, p, r, \mu, \kappa, \gamma, \beta, T$ by the following correlations:

$$u' = u\Omega r_0; \quad v' = \Omega\delta v; \quad v' = v^* v; \quad p' = p^* p;$$
$$\mu' = \mu_0\mu; \quad \kappa' = \kappa_0\kappa; \quad \gamma' = \gamma_0\gamma; \quad T' = T_0 T; \quad r' = r_0 + \delta r;$$
$$\upsilon^* = \frac{r_0\Omega}{2\delta}; \quad p^* = \frac{r_0^2\Omega(2\mu_0 + \kappa_0)}{2\delta^2}; \quad \delta = r_1 - r_0; \quad \beta = \beta' T_0;$$
$$N^2 = \frac{\kappa_0}{2\mu_0 + \kappa_0}; \quad N_1 = \frac{2l^2\mu_0}{\kappa_0\delta^2}; \quad l^2 = \frac{\gamma_0}{4\mu_0}. \tag{4}$$

Here u', v' are components of the speed vector; υ' is micro-particles rotation rate, T_0 is characteristic temperature.

As can be seen from the system (3), in addition to the usual dimensionless parameters encountered in the Newtonian fluid theory, other parameters are also introduced for a micro-polar liquid. Interaction parameter $N \to 0$ at $\kappa_0 \to 0$.

Dimensionless parameter N_1 depends on parameter l, having the dimension of length, and it can be treated as characteristics, depending on the size of the molecules of the lubricant. The system of equations (3) up to $O\left(\frac{\delta}{r_0}\right)$ is solved under the following boundary conditions:

$$u = 0, \quad v = 0, \quad \upsilon = 0 \quad \text{при} \quad r = h(\theta) = 1 + \eta\cos\theta - \eta_1\sin\omega\theta;$$
$$u = 1, \quad v = 0, \quad \upsilon = 0 \quad \text{при} \quad r = 0;$$
$$p(0) = p(2\pi) = \frac{p_a}{p^*}; \quad \eta = \frac{e}{\delta}; \quad \eta_1 = \frac{a}{\delta}. \tag{5}$$

We average the second equation of the system (3) for the thickness of the lubricating layer. We get:

$$\frac{1}{h}\int_0^h \frac{\partial^2 \nu}{\partial r^2}dr = \frac{1}{N_1 h}\int_0^h \nu dy + \frac{1}{N_1 h}\int_0^h \frac{\partial u}{\partial r}dr. \quad (6)$$

We seek the solution of (6) in the form:

$$\upsilon = A_1(\theta)r^2 + A_2(\theta)r + A_3(\theta). \quad (7)$$

It follows from the boundary conditions (5) that

$$A_3 = 0; \qquad A_2 = -A_1 h. \quad (8)$$

Taking into account (8) for υ we get the following expression:

$$\upsilon = A_1(\theta)\cdot\left(r^2 - rh\right). \quad (9)$$

Adding (9) to (6) up to $O\left(\eta\cdot\frac{1}{N_1}\right), O\left(\eta_1\cdot\frac{1}{N_1}\right), O\left(\frac{1}{N_1^2}\right)$,

we get:

$$\upsilon = -\frac{1}{2N_1}\left(r^2 - rh\right), \qquad \frac{\partial\upsilon}{\partial y} = -\frac{1}{2N_1}(2r - h). \quad (10)$$

Taking into account (10) the equation system (3) in the approximation we adopted is transformed to the following form:

$$\frac{\partial^2 u}{\partial r^2} - \frac{N^2}{2N_1}(2r - h) = e^{\beta T}\frac{dp}{d\theta},$$

$$\upsilon = -\frac{1}{2N_1}\left(r^2 - rh\right),$$

$$\frac{\partial u}{\partial r} + \frac{\partial v}{\partial\theta} = 0. \quad (11)$$

PRECISE SELF-SIMILAR SOLUTION.

Precise self-similar solution (11) with boundary condition (5) will be found as:

$$u = \frac{\partial\psi}{\partial r} + U(r,\theta), \quad v = -\frac{\partial\psi}{\partial\theta} + V(r,\theta),$$

$$V(r,\theta) = -\tilde{v}(\xi)h_0', \quad U(r,\theta) = \tilde{u}(\xi), \quad \xi = \frac{r}{h(\theta)},$$

$$\psi(r,\theta) = \tilde{\psi}(\xi), \quad e^{\beta T}\frac{dp}{d\theta} = \frac{\tilde{C}_1}{h^2(\theta)} + \frac{\tilde{C}_2}{h^3(\theta)}, \quad \upsilon(\xi) = -\frac{1}{2N_1}\left(\xi^2 - \xi\right). \quad (12)$$

Taking into account (12) from the system (11), we get:

$$\tilde{\psi}'''(\xi) = \tilde{C}_2, \qquad \tilde{u}''(\xi) = \tilde{C}_1 + \frac{N^2}{2N_1}(2\xi - 1),$$

$$\tilde{u}'(\xi) + \xi\tilde{v}'(\xi) = 0, \qquad \upsilon(\xi) = -\frac{1}{2N_1}\left(\xi^2 - \xi\right),$$

$$\frac{dp}{d\theta} = e^{-\beta T}\left(\frac{\tilde{C}_1}{h^2(\theta)} + \frac{\tilde{C}_2}{h^3(\theta)}\right). \quad (13)$$

The boundary conditions (5) will be as follows:

$$\tilde{\psi}'(0) = 0, \quad \tilde{\psi}'(1) = 0; \qquad \tilde{u}(0) = 1, \qquad \tilde{v}(0) = 0,$$

$$\tilde{u}(1) = 0, \qquad \tilde{v}(1) = 0, \qquad \int_0^1 \tilde{u}(\xi)d\xi = 0. \quad (14)$$

Solving the problem (13) — (14) by the direct integration, we get:

$$\tilde{\psi}'(\xi) = \frac{\tilde{C}_2}{2}\left(\xi^2 - \xi\right), \ \upsilon(\xi) = -\frac{1}{2N_1}\left(\xi^2 - \xi\right),$$

$$\tilde{u}(\xi) = \tilde{C}_1\frac{\xi^2}{2} + \frac{N^2}{2N_1}\left(\frac{\xi^3}{3} - \frac{\xi^2}{2}\right) + \left(\frac{N^2}{12N_1} - \frac{\tilde{C}_1}{2} - 1\right)\xi + 1. \quad (15)$$

Here $\tilde{C}_1 = 6 - \frac{N^2}{N_1}$, and $\tilde{C}_2$ will be further defined from the condition $p(0) = p(2\pi) = \frac{p_a}{p^*}$.

We get:

$$\tilde{C}_2 = -\frac{\tilde{C}_1\tilde{J}_2(\theta)}{\tilde{J}_3(\theta)},$$

where $\tilde{J}_k(\theta) = \int_0^{2\pi}\frac{\mu(\theta)}{h^k(\theta)}d\theta.$

As it was expected, at $N_1 \to \infty, \quad \nu \to \infty$ the results obtained coincide completely with the result for the case of the Newtonian lubricant.

DEFINING OF HYDRODYNAMIC PRESSURE.

In order to define the hydrodynamic pressure we have:

$$e^{\beta T}\frac{dp}{d\theta}=\frac{\tilde{C}_1}{h^2(\theta)}+\frac{\tilde{C}_2}{h^3(\theta)}. \quad (16)$$

In order to solve this equation we should find the function $\mu = e^{-\beta T}$ at first. We will use the expression for the energy dissipation rate under the action of shear forces. We get

$$\frac{dH'}{d\theta}=\frac{2\mu_0\mu\Omega^2 r_0^2 h(\theta)}{\delta}\int_0^1\left(\frac{\tilde{\psi}''(\xi)}{h^2(\theta)}+\frac{\tilde{u}'(\xi)}{h(\theta)}\right)^2 d\xi. \quad (17)$$

The raised temperature will be defined by the expression

$$\frac{dT'}{d\theta}=\frac{dH'}{d\theta}\cdot\frac{1}{c_pQ}=\frac{1}{c_pQ}\cdot\frac{2\mu_0\mu\Omega^2 r_0^2 h(\theta)}{\delta}\int_0^1\left(\frac{\tilde{\psi}''(\xi)}{h^2(\theta)}+\frac{\tilde{u}'(\xi)}{h(\theta)}\right)^2 d\xi. \quad (18)$$

Here Q is lubricant consumption per unit time; c_p is heat capacity at constant pressure.

$$Q=\Omega r_0\delta\int_0^1\psi'(\xi)\,d\xi=\frac{-\delta\Omega r_0\tilde{C}_2}{12}. \quad (19)$$

Let's differentiate the dependence μ on temperature T under θ, we get:

$$\frac{d\mu}{d\theta}=-\mu(\theta)\beta\frac{dT}{d\theta}. \quad (20)$$

Combining (18) — (20), we get:

$$\frac{1}{\mu^2(\theta)}\frac{d\mu}{d\theta}=\frac{24\beta\mu_0\Omega r_0\,h(\theta)}{\tilde{C}_2c_p\delta^2T_0}\int_0^1\left(\frac{\tilde{\psi}''(\xi)}{h^2(\theta)}+\frac{\tilde{u}'(\xi)}{h(\theta)}\right)^2 d\xi. \quad (21)$$

Let's introduce the following designations:

$$K=\frac{24\beta\mu_0\Omega r_0}{h_0^2c_pT_0},$$

$$\Delta_1=\int_0^1\left(\tilde{\psi}''(\xi)\right)^2 d\xi,\quad \Delta_2=\int_0^1 2\tilde{\psi}''(\xi)\tilde{u}'(\xi)\,d\xi,$$

$$\Delta_3=\int_0^1\left(\tilde{u}'\right)^2 d\xi. \quad (22)$$

Here K is the heat parameter.

Taking into account (22) the equation (21) will be modified as follows:

$$\frac{1}{\mu^2(\theta)}\frac{d\mu}{d\theta}=\frac{K}{\tilde{C}_2}\left(\frac{\Delta_1}{h^3(\theta)}+\frac{\Delta_2}{h^2(\theta)}+\frac{\Delta_3}{h(\theta)}\right). \quad (23)$$

Integrating the equation (23), we get:

$$\mu(\theta)=\frac{1}{1-\frac{K}{\tilde{C}_2}\left[J_3(\theta)\Delta_1+J_2(\theta)\Delta_2+J_1(\theta)\Delta_3\right]}, \quad (24)$$

где $J_\kappa(\theta)=\int_0^\theta\frac{d\theta}{h^\kappa(\theta)}.$

Further, we will substitute the function $\mu(\theta)$ by its averaged value:

$$\tilde{\mu}=\frac{\mu(0)+\mu(2\pi)}{2}=\frac{1}{2}+\frac{1}{2}\left(1+\frac{K}{\tilde{C}_2}\left[\Delta_1J_3(2\pi)+\Delta_2J_2(2\pi)+\Delta_3J_1(2\pi)\right]\right). \quad (25)$$

Solving the obtained equations for Δ_1, Δ_2, Δ_3, $\tilde{C}_2$ up to terms of the second order of smallness $O(\eta^2)$, $O(\eta_1^2)$, $O(\eta,\eta_1)$ we get the following expressions:

$$\tilde{C}_2=-\left(6-\frac{N^2}{N_1}\right)\left(1+\frac{\eta_1}{2\pi\omega}(\cos 2\pi\omega-1)\right),$$

$$\Delta_1=\frac{1}{12}\left(6-\frac{N^2}{N_1}\right)^2\left(1+\frac{\eta_1}{\pi\omega}(\cos 2\pi\omega-1)\right),$$

$$\Delta_2=-\frac{1}{6}\left(6-\frac{N^2}{N_1}\right)^2\left(1+\frac{\eta_1}{2\pi\omega}(\cos 2\pi\omega-1)\right),$$

$$\Delta_3=\frac{N^2}{720}+4-\frac{N^2}{N_1}+\frac{N^4}{12N_1^2}.$$

Then for the averaged $\tilde{\mu}$ we get the following expression:

$$\tilde{\mu}=\frac{1}{2}+\frac{1}{2}\Bigg[1+K\Bigg\{-\frac{1}{2}\left(6-\frac{N^2}{N_1}\right)\left(2\pi^2-\frac{3\eta_1}{\omega}\left(\frac{\sin 2\pi\omega}{\omega}-2\pi\right)\right)+\frac{\eta_1\pi}{\omega}(\cos 2\pi\omega-1)+$$
$$+\frac{1}{6}\left(6-\frac{N^2}{N_1}\right)\left(2\pi^2-\frac{2\eta_1}{\omega}\left(\frac{\sin 2\pi\omega}{\omega}-2\pi\right)\right)-\frac{\left(\frac{N^2}{720}+4-\frac{N^2}{N_1}+\frac{N^4}{12N_1^2}\right)}{6-\frac{N^2}{N_1}}\times$$
$$\times\left(2\pi^2-\frac{\eta_1\pi}{\omega}(\cos 2\pi\omega-1)-\frac{\eta_1}{\omega}\left(\frac{\sin 2\pi\omega}{\omega}-2\pi\right)\right)\Bigg\}\Bigg]. \quad (26)$$

Taking into account (16) and (26) the dimensionless hydrodynamic pressure is defined by the expression:

$$p=\tilde{\mu}\left(\tilde{C}_1\tilde{J}_2(\theta)+\tilde{C}_2\tilde{J}_3(\theta)\right)+\frac{p_a}{p^*}=$$

$$=\tilde{\mu}\left(6-\frac{N^2}{N_1}\right)\left(\eta\sin\theta+\frac{\eta_1}{\omega}\left(\cos\theta\omega-1\right)-\frac{\eta_1\theta}{2\pi\omega}\left(\cos 2\pi\omega-1\right)\right)+\frac{p_a}{p^*}. \quad (27)$$

RESULTS OF THE RESEARCH AND THEIR DISCUSSION.

We now turn to the determination of the basic operating characteristics of a radial bearing.

For the component of the supporting force vector and the friction force, taking into account (15) and (27), we get:

$$R_x=\frac{\tilde{\mu}r_0^3\Omega\left(2\mu_0+\kappa_0\right)}{2\delta^2}\left(6-\frac{N^2}{N_1}\right)\left(\eta\pi+\eta_1\left(1-\omega^2\right)\left(\cos 2\pi\omega-1\right)\right),$$

$$R_y=\frac{\tilde{\mu}r_0^3\Omega\left(2\mu_0+\kappa_0\right)}{2\delta^2}\left(6-\frac{N^2}{N_1}\right)\eta_1\sin 2\pi\omega, \quad (28)$$

$$L_{mp}=\frac{\tilde{\mu}\Omega r_0}{2\delta}\int_0^{2\pi}\left[\frac{\psi''(0)}{h^2(\theta)}+\frac{\tilde{u}'(0)}{h(\theta)}\right]d\theta=$$

$$=\frac{\tilde{\mu}\Omega r_0}{2\delta}\left[\left(3-\frac{N^2}{2N_1}\right)\left(2\pi-\frac{2\eta_1}{\omega}\left(\cos 2\pi\omega-1\right)\right)+\left(\frac{7N^2}{12N_1}-4\right)\left(2\pi-\frac{\eta_1}{\omega}\left(\cos 2\pi\omega-1\right)\right)\right].$$

The following values of the parameters included into expressions (28) are used for the numerical analysis, for the lubricant 10w40:

$$\eta=\eta_1=0,3\div 1;\quad \omega=0\div 1;\quad \alpha=0,01\div 3;\quad \beta=0\div 1;$$

$T=30\div 100$ °C; $\mu_0=0,00595\,\frac{N\cdot s}{m^2}$; $P_a=0,08\div 0,101325$ MPa;

$N=0\div 1$; $N_1=1\div 40$; $\Omega=100\div 1800\ s^{-1}$;

$\kappa_0=3,98\cdot 10^6\ \frac{N}{m}$; $\delta=0,00005...0,000071\ m$;

$h_0=10^{-7}\ m$; $l=0,1256\ldots 0,1884\ m$; $u^*=1..3\ m/s$.

Results of the numerical analysis are in the Figures 2-7.

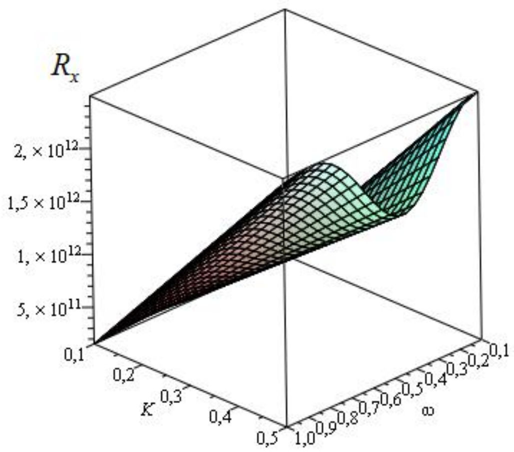

Fig. 2. Dependence of the component of the supporting force vector R_x on the thermal parameter K and on the parameter ω, characterizing the adapted profile of the supporting surface

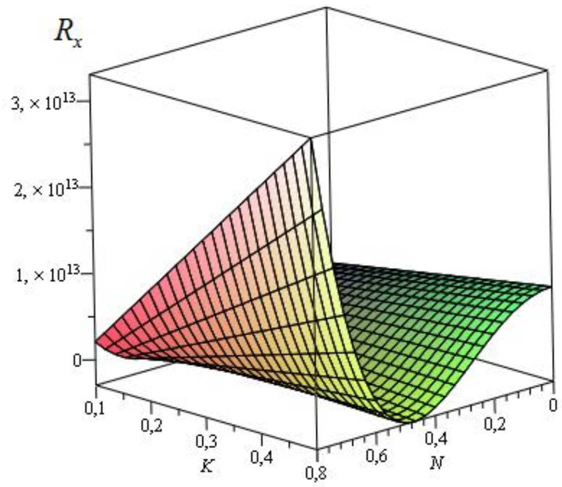

Fig. 3. Dependence of the component of the supporting force vector R_x on the thermal parameter K and on connection parameter N

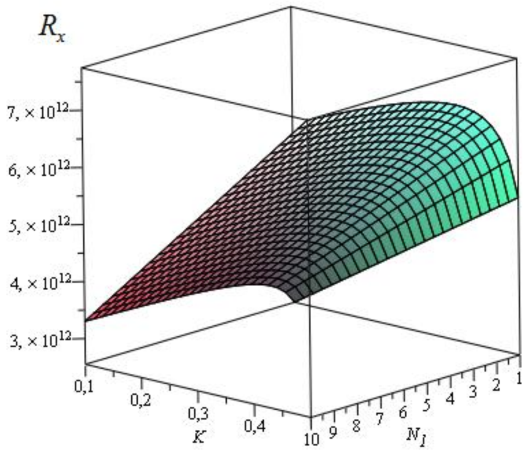

Figure 4. Dependence of the component of the supporting force vector R_x on the thermal parameter K and on parameter N_1, characterizing the size of the molecules of the lubricant

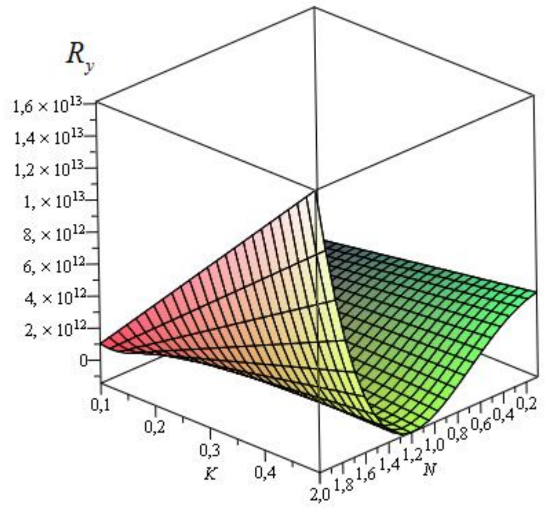

Figure 5. Dependence of the component of the supporting force vector R_y on the thermal parameter K and on connection parameter N

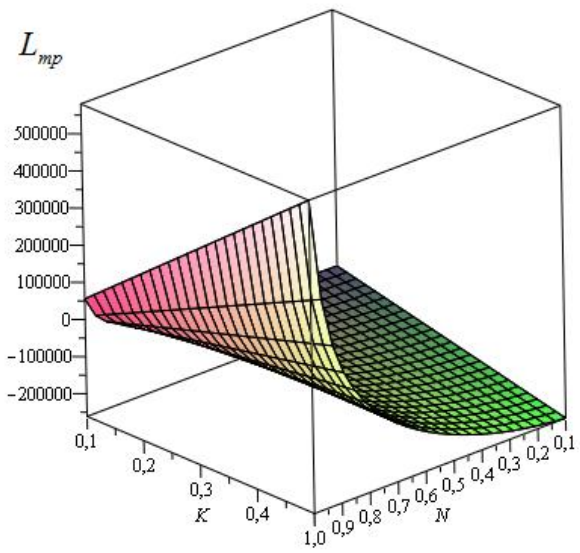

Figure 6. Dependence of friction force L_{mp} on the thermal parameter K and on connection parameter N

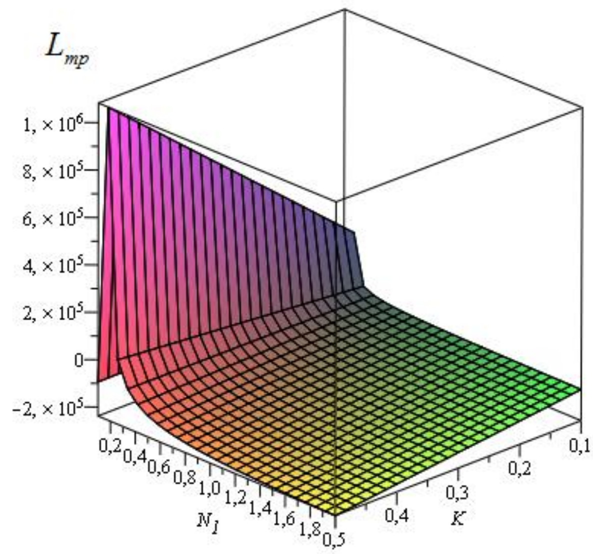

Figure 7. Dependence of friction force L_{mp} от on the thermal parameter K and on parameter N_1, characterizing the size of the molecules of the lubricant

CONCLUSIONS

The analysis of the simulation models and graphs (Figures 2-7) made it possible to draw a number of the following conclusions:

1. A refined simulation model of the infinite radial sliding bearing working under conditions of hydrodynamic lubrication on a micro-polar liquid lubricant with an adaptive profile of the supporting surface is obtained, taking into account the dependence of the viscosity characteristics on the temperature under adiabatic conditions.
2. A significant contribution of the parameters is shown: the parameter N_1 characterizing the size of the molecules of the lubricant, the thermal parameter *K* and the connection parameter *N*, by the value of the main tribotechnical parameters of the bearing in question.

3. It is established that the significant increase in the bearing capacity and decrease in the frictional force occurs with the growth of the thermal parameter *K*, parameter N_1, characterizing the size of the molecules of the lubricant, and also an extremum region appears with the growth of the coupling parameter *N* and the parameter ω, characterizing the adapted profile of the supporting surface.

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