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Existence of a Tunnelling Component of Electrical Drift Current through a Dielectric Film in High Frequency Knots with a Liquid and Boundary Friction

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Abstract. In particular functioning of high-speed rolling bearings with use of lubricant with rather big viscosity can happen without destructions of a high-resistance lubricant film. At the same time the annex of tribovoltage to rolling bearings leads to emergence of electric current caused in particular by tunneling effect of a charge across a film. Control of technical condition of frictional units has to be exercised according to electric parameters of the lubricant film which is implemented in friction zones. Values of these parameters depend on a condition of a lubricant film, and in particular on her temperature which is caused by degree of wear of details of frictional units which function under the influence of mechanical tension. The model can be used for technical diagnostics, and also for decrease of speed of process of wear. In practice the developed model can be used for those productions, vehicles, control systems where failure of frictional pieces can lead to failure of an expensive production inventory, the emergency cessation of production of goods, accidents of means of transportation of goods and people, loss of management of technical systems and also control systems of human activity.

1. Features of electric contact of details of high-speed rolling bearing

Details of high-speed frictional units which are divided by a technological film of a dielectric are, for example, details of rolling bearings with a lubricant layer between them. At high rotation frequencies of bearings, such as $(9...150) \times 10^3 \text{ min}^{-1}$ and also at the maximum deviation $h_m$ of details of bearings from their coaxiality which makes only 1 $\mu$m, in the bearing are implemented the considerable inertial reaction. It is characterized by result $K$ from division of amplitude $w_m$ of a centrifugal acceleration of the bearing and reference value of acceleration $g$ of the free fall:

$$ K = \frac{h_m \omega}{g}, $$

where $\omega$ – the cyclic frequency of rotation of the bearing. As a first approximation a deviation from coaxiality of details of the bearing and consequently, and thickness of a lubricant film should be considered changing in time under periodic laws. At the same time the first harmonica in a range of fluctuations of thickness of a lubricating film is defined by the size of a gap $h_m$ and has an appearance:
\[ h = h_m \sin(\omega t), \] (2)

To deviation (eq. 2) there corresponds acceleration:

\[ \omega = \frac{dh}{dt} = -h_m \omega^2 \sin(\omega t), \] (3)

Amplitude of acceleration is:

\[ \omega_m = h_m \omega^3, \] (4)

With the increased frequency \( \omega \) square dependence of \( \omega_m \) on this frequency causes body height of a factor of acceleration \( K \) (eq. 1). At the same time the dynamic force, operating on the bearing, increases.

The increased dynamic force can cause destruction of the bearing. Therefore for decrease of a gap \( h_m \) high-frequency bearings, as a rule, make with the guaranteed tightness.

As a result of the constructive choice of a gap the technological lubricant film can reach the thickness of values from the several hundredth parts of a micrometer to several tens micrometers. Formation of a lubricant film is promoted by viscous hydrodynamic effect. He accompanies the deformation of rings and bodies of rolling of the bearing necessary for flowing of lubricant in friction zones.

Technical diagnosing of rolling bearings by various electric methods [1] is based on dependence of technical condition of the bearing on a condition of the lubricating film 1 which is formed between rings 2 and 3 and rolling bodies 4 of bearings at its rotation on a shaft 5 as shown in figure 1. Thickness of a lubricating film defines its electrical resistance, active or capacitor. Values of this resistance are measured with use of a circuitry which contains a source of electric energy 6, the slip ring 7 for connection of the rotating details of a bearing to a source 6, the converter 8 of an electric signal and the indicator 9 of results of measurement. Diagnosing of bearings which work in the mode of liquid friction is carried out on the measured values of electrical resistance, on the measured values of resistance carry out diagnosing of bearings which work in the mode of liquid friction.

![Figure 1. Scheme of control of the rolling bearing in the electric way.](image1)

![Figure 2. Typical temporary diagram of fluctuations of electric resistance of the rolling bearing.](image2)
Destruction of a lubricating film changes the nature of friction. A friction stops being liquid and becomes semi-liquid. Violation of continuity of a lubricating film leads to emergence of a direct electrical contact between details 2 and 3 of bearings. In this case the converter 8 has to measure values of the normalized integral time $t_{ni}$ of such electrical contact. Results of this measurement are the cornerstone of monitoring of the bearings working in the mode of semi-liquid friction.

Values of normalized integrated time $t_{ni}$ are equal to the sum of time points $t_i$ of electric contact of details of the rolling bearing divided into the general time $\tau$ of measurements of the moments of $t_i$:

$$t_{ni} = \frac{\sum_{i}^{n} t_i}{\tau}$$  \hspace{1cm} (5)

The figure 2 contains the typical temporary diagram of fluctuations of resistance of the ball-bearing. At the same time electric contacts should be considered intervals of time $t_i$ during which the electric resistance of the bearing is smaller of some experimentally established threshold $R_0$ value of electric resistance of the ball-bearing.

To zero value of time $t_{ni}$ there corresponds the mode of liquid friction. The single value of time $t_{ni}=1$ is implemented, as a rule, in the conditions of dry friction. Values of this time from the range of $0<t_{ni}<1$ correspond to boundary friction.

Thus, the nature of wear of the rubbing surfaces of the bearing is caused, first of all, by a type of friction. At realization of liquid friction, fatigue wear can be the prevailing type of wear. It is caused by the variable nature of force impact on the surfaces of the bearing.

Figure 3. The functional electric scheme of the device for measurement of normalized integrated time $t_{ni}$ of electric contact of details of the ball-bearing.
Such power influence arises because of variability of the forces influencing the bearing and also of rotation of the bearing. In this case about decrease longevity of the bearing it is possible to draw conclusion by fluctuations of electrical conductance of its lubricating film [2]. At semi-liquid friction, destruction of a lubricating film can be caused, in particular, by defects on surfaces of details of the bearing. These defects are caused by abrasive wear of surfaces. At the same time it is possible to draw a conclusion on decrease in durability on growth of the normalized integrated time $t_{n}$ (eq. 5) [3].

In the figure 3 the functional electric scheme of the device for measurement of normalized integrated time $t_{n}$ (eq. 5) of electric contact of details of the ball bearing is represented. The device is developed at the Oryol state university named after I.S. Tourgueniev.

Other The device functions as follows. From a source $GB$ of constant tension via the ball-bearing $BB$ electric current is passed. These current changes in time in the form of function of fluctuations of resistance of a lubricant film of the ball-bearing $BB$. Резистор $R_{BB}$ служит ограничением токачерешенья и делит напряжение $BB$. Ball-bearing $BB$ at the same time serves as the converter of electric current in electric tension. The adjustable $R_{3}$ resistor imitates the ball-bearing $BB$ in a condition of transition to a liquid type of lubricant. On this resistor the threshold value of electric tension which serves for comparison with tension, falling on the rolling bearing $BB$ is formed. The resistor $R_{2}$ serves for restriction of current via the resistor $R_{3}$. Resistors $R_{1}$; $R_{2}$; $R_{3}$ and also the ball-bearing $BB$, thus, form the bridge scheme. Measuring diagonal of the bridge scheme is connected to the comparator $DA$.

The comparator $DA$ has two states at the exit. Conditionally appropriate them values of logical zero and logical unit. If voltage on the ball-bearing $BB$ is less, than tension which falls on the resistor $R_{3}$, then resistance of the ball-bearing is small and corresponds to electric contact of his details. At the same time the comparator $DA$ is installed in a condition of logical unit. If voltage on the ball-bearing $BB$ is more than tension which falls on the resistor $R_{3}$, then resistance of the ball-bearing $BB$ is considerable and corresponds to electric division of details of the ball-bearing $BB$ by means of a lubricant film. At the same time the comparator $DA$ is installed in a condition of logical zero. Because of such features at the exit of the comparator $DA$ is formed the sequence of impulses with an amplitude equal to logical unit, and time lengths $t_{1};...;t_{n}$, which are equal to times of destructions of a lubricant film. Time duration $t_{1};...;t_{n}$, correspond to absissa axis pieces represented in the figure 2.

The generator $GI$ of impulses generates a gate of single amplitude which duration is equal to time $\tau$ of single measurement normalized integrated time of electric contact of details of the ball-bearing.

The generator $GI$ of impulses generates a squitter pulse with single amplitude which period is significantly small in comparison with duration $\tau$ a gate, formed by the generator $GI$.

The impulses formed by the comparator $DA$ and also the squitter pulse formed by the $GI$ generator $GI$ move on a cell of logical multiplication $DD1$. Thanks to it at the exit of a cell of logical multiplication $DD1$ is formed the sequence of impulses with an amplitude equal to logical unit, and time lengths $t_{1};...;t_{n}$, equal to times of destructions of a lubricant film, and these impulses are filled with squitter pulse of the generator $GI$.

Impulses from a cell of logical multiplication $DD1$ and also gates with duration $\tau$, formed by the generator $GI$, move on a cell of logical multiplication $DD2$. Thanks to it at the exit of a cell of logical multiplication $DD2$ is formed the sequence of impulses with an amplitude equal to logical unit, and time lengths $t_{1};...;t_{n}$, equal to times of destructions of a lubricant film, and these impulses are filled with squitter pulse of the generator $GI$, and the total duration of such sequence doesn't exceed duration of time of single measurement of the normalized integrated time $t_{n}$ (eq. 5) of electric contact of details of the ball-bearing.

We will notice that if the lubricant film has been destroyed constantly, then during single measurement $\tau$ the cell of logical multiplication $DD2$ would pass number $N_{t}$ of squitter pulse from the $GI$ generator.
The $RG$ device represents the counter of number of the squitter pulse which are passed by a cell of logical multiplication $DD2$. The $RG$ device also divides number of the filling impulses counted by him into their greatest possible number $\text{N}_{r}$. The result of this division is equal to duration of normalized integrated time $t_{ni}$ (eq. 5) of electric contact of details of the ball-bearing which is measured by the device represented in the figure 3.

The actual values of a factor $K$ (eq. 1) of acceleration can appear significantly more than its values which are calculated (eq. 4) with use of frequency $\omega$ of rotations of one of bearing rings. The matter consists in that the distribution of frequency spectrum of shift $b(t)$ has character of a blow spectrum. It contains frequencies which multiply exceed frequency $\omega$ of rotations of a ring, used in model of amplitude of acceleration $w_{m}$ (eq. 4) as the base spectral frequency. Besides, increase in values of a factor of $K$ (eq. 1) is influenced by such high-frequency process as beating. This process arises at interaction of several defects which are formed on a various surfaces of the ball-bearing [4].

Thus, presence of an electrical contact at details of rolling bearings which is characterized even by rather slight time of the integral duration can demonstrate emergence of the significant dynamic mechanical force. This force in the amplitude significantly surpasses quasistatic force.

However to body height of a rotation frequency of the bearing there is also an increase in a gradient of speed of the relative driving of layers of lubricant along thickness of a lubricating film. It corresponds to body height of force of viscous resistance of lubricant at the movement of a rolling body on a lubricant layer. As a result, there is an increase in a lifting force of a lubricating film. The lifting force prevents destructions of a lubricating film at the relative motion of a rolling bodies and rings of the bearing and also under the influence of mechanical force which is applied to the bearing and also at development of defects on surfaces of rings and rolling bodies of the bearing.

Therefore it is possible to assume that high-frequency rolling bearings work in the conditions of realization of negligible values of the normalized integrated time $t_{ni}$ (eq. 5) in comparison with values similar time for low-frequency bearings. For verification of these assumption direct experiments on measurement of the normalized integrated time $t_{ni}$ (eq. 5) of electric engagement of details of rolling bearings of electric spindle have been executed. Electric spindle are applied in superfinishing metal working of surfaces at the frequency range called above, with high-viscosity plastic lubricant and at the static force which isn't exceeding $10 \, N$. Experiments have revealed the values of the normalized integrated time $t_{ni}$ (eq. 5) reaching $0,0001...0,001$.

The same values of the normalized integrated time were observed, in particular, at rolling bearings of air and gas compressors. They have been oiled by rather low-viscous industrial oil, were functioned at rotation of an internal ring which was provided out by the synchronous electric motor with a frequency $50 \, Hz$, and at motionless external ring. Bearings have been loaded with the radial force which exceeded $1 \, kN$.

At the same time neither at bearings of electric spindles, nor at bearings of compressors during their further exploitation any signs of approach of an emergency weren't observed. Overheating, emergence of foreign sounds, vibration growth, and the most important - the observed further growth of values of the normalized integrated time $t_{ni}$ (5) can belong to such signs. Besides, it is established that decrease of the normalized integrated time $t_{ni}$ (eq. 5) at the mechanical extra earnings electric spindles during increase of frequency of their work is observed only to values of frequencies about $(24...48) \times 10^{5} \, min^{-1}$ then growth of frequency is followed by growth of the normalized integrated time again.

Such experiments allow assuming that increase in electric conductivity of a lubricant film of high-frequency bearings which is theoretically associated with destruction of a lubricant film and electric contact of details of bearings can be caused by the electro physical phenomena which precede in lubricant the film which hasn't lost the continuity.

As such phenomena it is possible to consider tunneling effect. We will consider model of tunneling of electric charge through a lubricant film.
2. Features of electric contact of details of high-speed rolling-bearing

It is known that behavior of a quantum particle with a mass \( m \), with the total remaining energy \( E_e \), near a one-dimensional potential barrier \( U(x) \), with an effective width from the range of values from \( x_1 \) to \( x_2 \) within which \( E_e < U(x) \), and which models thickness of a lubricant film, is described by coefficient of transparency of a barrier[5]:

\[
D = \exp \left\{ \frac{2}{\hbar} \int_{x_1}^{x_2} \left[ 2m(U(x)) - E_e \right]^{1/2} \, dx \right\}, \tag{9}
\]

where \( \hbar \) – normalized on \( 2\pi \) Planck’s constant.

The lubricant film, as a rule, is dielectric. As a result of polarization of this dielectric the potential barrier \( U(x) \) is formed. Owing to film thickness trifle in comparison with radiuses of curvature of rings and of rolling bodies of the bearing, as well as in a case with the ordinary condenser, the potential barrier \( U(x) \) can be modelled on thickness \( x \) a lubricant film of the quasihomogeneous vector field of electric strength \( E \). Size \( E \) acts as a anti-gradient of potential \( \varphi(x) \):

\[
E = - \nabla \varphi(x). \tag{6}
\]

The equation 6 corresponds to linear increase of potential \( \varphi(x) \) on width \( x \) a barrier:

\[
\varphi(h) = |E|h + \varphi_0, \tag{7}
\]

where \( \varphi_0 \) represents the potential formed at rotation of the bearing on the edge of a lubricant film i.e. on a surface of a ring or a rolling body of the bearing. The value \( \varphi \) can be defined by the thermoelectric and triboelectric phenomena in zones of friction of the bearing and also the voltage which is put to the bearing from the electrical measuring instrument.

Potential \( \varphi(x) \) acts as height of \( U(x) \) a barrier normalized on an elementary charge \( q_e \) and consequently, height of \( U(x) \) as well as potential \( \varphi(x) \) (eq. 8), can be considered linearly increasing on length \( x \) a barrier:

\[
D(h) = q_e |E|h + q_e \varphi_0. \tag{8}
\]

The integration constant \( q_e \cdot \varphi_0 \) in expression (eq. 9) can be turned into zero by the corresponding choice of a zero reference datum of potential energy of \( U(x) \) and also zero reference datum of the remaining total energy of \( E_e \) of an electron.

Substitution (eq. 9) in (eq. 6) with the subsequent integration gives the passing coefficient equation through a barrier:

\[
D = \exp \left\{ - \frac{4\sqrt{m}}{3} \sqrt{q_e \hbar} \left[ (q_e |E|x_2 - E_e)^{3/2} - (q_e |E|x_1 - E_e)^{3/2} \right] \right\}. \tag{9}
\]

In the simplest case if to consider the remaining own energy of an electron \( E_e \) small in comparison with height of a barrier of \( q_e |E|x \) within all width \( x \) a barrier, i.e. on all thickness \( h \) of a lubricant film from \( x_1=0 \) from \( x_2=h_m \), expression (eq. 10) becomes simpler to a look:

\[
D = \exp \left\{ - \frac{2}{\hbar} \int_0^{h_m} \left[ 2m(q_e |E|x_2)^{1/2} \right] dh \right\} = \exp \left( - \frac{4\sqrt{m}}{3} \right), \tag{10}
\]

where \( U_m \) – the maximum height of a potential barrier \( U(x) \) (eq. 8) which is implemented at \( x=h_m \).

Entering into (eq. 11) designation:
we receive exponential dependence for $D$ which has an appearance:

$$D = \exp \left( -\lambda h_m^{3/2} \right),$$  

It is necessary to stipulate that in the considered approach the electric resistance of metal elements of the bearing, in particular, of rolling bodies and rings, is considered negligible in comparison with resistance of a lubricant film. And therefore the size $h_m$ is understood as the total maximum thickness of all lubricant films which are formed on surfaces of each of rings. This total maximum thickness models of length of any electrical current tube connecting both rings.

Besides, because of the smallness of thickness of a lubricant film in comparison with rolling body radius, electric current tubes in the offered model are considered as radial. The considered model also neglects electric current tubes of dispelling which pass through air.

Let for unit time on the elementary surface area $ds = dydz$ of any elementary electric current tube, which begins on one of rings in the neighborhood of a point with coordinates $(y; z)$, counted along a rolling ring surface, near a potential barrier $U_m$ there are $dN$ of carriers of a charge $q_e$.

Then through tube $ds$ section, i.e., through an element of a lubricant film in the loaded zone, electric current with current density module is supported:

$$J = D \frac{d(Nq_e)}{ds} \exp \left( -\lambda h_m^{3/2} \right) \frac{d(Nq_e)}{ds}.$$

Through all loaded zones of rolling bearing, i.e. through all cumulative surface $s$ of the lubricant film dividing rings with rolling bodies electric current proceeds:

$$\mathcal{I}(t) = \int_s J(y;z;t) ds = q_e \int_s \exp \left[ -\lambda h_m^{3/2} (y;z;t) \right] dN(y;z;t).$$

where $h_m(y; z; t)$ and $dN(y; z; t)$ – respectively thickness of a lubricant film and number of carriers of a electric charge in a point of a surface of a ring or a rolling body of the bearing with coordinates $(y; z)$ in time $t$.

It is necessary to notice that total, from unit area surface $s$, the number $N$ of carriers of a charge coming to a potential barrier concerning an degree of quantity is estimated by Avogadro's number.

Therefore, measuring by means of the device an average integrated for some time $\tau$ value $I_0$ of current $i(t)$ (eq. 15) in the conditions of rather small height $U_m$ of a potential barrier, it is possible even at small $D$ to find a contribution to results of measurement of a tunneling component of drift electric current. The similar phenomenon is observed, for example, at a research of cold electronic issue with a potential barrier $U_m$ in several electron-volts.

Relying on the received results, we will turn further to a question of how the normalized integrated time $t_n(t)$ bearing which is caused short-term considerable by excesses of instant values of current $i(t)$ of its average integrated value is formed.

3. Temperature dependence of the normalized integrated time of electric contact of details of rolling bearings in model with one-dimensional tunneling

It is necessary to emphasize that the size:

$$J_0 = \frac{d(Nq_e)}{ds}$$
which enters as a multiplicand of the value $J$ (eq. 14) significantly depends on $T$ temperature. According to Dushman-Richardson’s equation the temperature dependence of this value is described by the following formula:

$$J_0 = A \exp \left( - \frac{A_{ex}}{kT} \right).$$

(16)

where $A$ – constant coefficient, $k$ – Boltzmann’s constant; $A_{ex}$ – work of an exit of an electron from bearing material.

It agrees (eq. 16), for example, to triple excess of temperature in the field of any of zones of contact of a rolling body of with rings over average integrated value of this temperature there will correspond almost two hundredfold growth of the size $J_0$ over own average integrated value. It can be caused, in particular, by interaction of defects in a forced zone at rotation of the bearing.

The actual growth of temperature in friction zones at the same time can be such that some microroughnesses will be subjected to local melting or even evaporation. At the same time current of $i(t)$ (eq. 15) can receive a spasmodic increment of the instant values. It can be sufficient for operation of the measuring instrument of the normalized integrated time $t_{ni}$ (eq. 5).

The presented reasoning allow the considered meter readings for measurement of the normalized integrated time of electric engagement in the conditions of realization of tunnel effect as relative total time of temperature flashes with excess by temperature of some threshold value. This feature of the developed model taking into account the stipulated assumptions can form a basis for control of temperature in the loaded zones of the frictional units working with liquid lubricant.

At the same time, changing value of a response level at a gauge meter of the normalized integrated time $t_{ni}$ (eq. 5), and believing that all fluctuation processes which describe functioning of the bearing, are quasistationary, it is possible to receive also function of distribution of estimates of temperature in forced zones of bearings on a degrees scale of temperature size. Such functions of distribution can serve as an additional source of information for assessment of longevity of bearings.

It has been shown above that with growth of frequency of rotation of the bearing growth of forces of viscous resistance to the movement of a lubricant film which accompanying with decrease in his normalized integrated time $t_{ni}$ (eq. 5) has to be observed. However further increase in frequency of rotation has to cause growth of heat release. And consequently it has to cause emergence of temperature flashes in power zones of bearings in case of hit of defects of working surfaces in them. At the same time meter readings for measurement of the normalized integrated time with growth of frequency of rotation of a support have to rise again. It has also been recorded in experiments with electric spindles.
In favor of this conclusion the nonlinear character of the typical volt-ampere characteristic of high-speed bearings indirectly testifies as shown in figure 4. At the same time disproportionately high increase of current of increase of external tension speaks of temperature influence (eqs. 15, 16 and 17).

It is necessary to notice that in zones of friction the charge generators caused thermo- and triboelectric processes operate. Therefore the described tunneling phenomena can be realized in tribo-knots by also natural way, i.e. without application of external tension from a gage meter. Electric equivalent scheme of similar generators contain sources of tension reaching units and even tens of volts. The charges divided by such sources and tunneling through a lubricant film are involved in drift current. It accelerates all types of corrosion.

Allocation of heat from such current which is followed by short-term flashes of temperature in friction zones leads to the expiration and evaporation of micro volumes of material of elements of tribo-knot. Rotation of the bearing with high frequency at each his circulation returns friction zones in force area. It causes systematic, i.e. fatigue wear of the rubbing surfaces. Interacting among themselves, defects develop in dislocation of a crystal lattice of material of tribo-knot. Dislocations form superficial fatigue micro cracks, in which there is a material crumbling eventually. Crumbling accelerates abrasive and thermal wear that finally leads to a bearing exit out of operation.

It is simple to notice that in this case for the purpose of reduction of speed of wear at his earliest stage it is necessary to provide management of thermo- and tribo-currents, directing them bypassing friction zones. In the simplest case it is necessary to connect electrically the rotating details of rolling bearings of the unit that rotated by them, by means of collector knots which contain, for example, copper-graphite brushes. At the same time generators thermo- and tribo-current discharge the charges divided by them through the friction zones which aren't loaded with force.

4. Conclusion

Operation of high-speed rolling bearings can happen to rather viscous lubricant without destructions of a lubricant film. At the same time the annex to the bearing of voltage can be followed by course via the bearing of the electric current caused by tunneling effect of carriers of a charge through a film.

Hit of superficial defect in a forced zone at rotation of the bearing can cause short-term flash of temperature. The high temperature sensitivity of tunnel electric current causes works of a gauge meter of the normalized integrated time $t_{eq}$ (eq. 5) which works for excess by controlled current via the bearing of the value established in a gauge meter. At the same time gage meter indications represent
assessment of integrated time of excess by instant value of temperature in one of forced zones of the
bearing of threshold value of this temperature.

The developed model of a tunneling component of drift electric current through a lubricant film of
the working rolling bearing can serve as theoretical foundation of a management of tunnel currents in
high-frequency frictional units for the purpose of reduction of speed of formation of defects in friction
zones and also for control of technical condition of these zones.

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