Electroresistive method for monitoring the technical condition, quality, reliability and safety the supports of rolling of electrical machines

K V Podmasreryev¹, V V Markov¹, V V Mishin¹, A V Selikhov¹ and N V Uglova¹
¹Oryol State University named after I.S. Turgenev,
95 Komsomolskaya Street, Oryol, Russia

Abstract. The necessity of monitoring the technical condition of the rolling supports of electric machines has been substantiated. It is proposed to use the electrical resistance of the bearing as an indicator of the technical condition of the rolling support. The results of mathematical modeling of electrical resistance in the form of a function of resistance from factors of the internal environment of the bearing and modes of its assembly and operation in a rolling bearing are presented. An electroresistive method for monitoring the technical state the rolling support is proposed, which differs from the known methods by original algorithms for collecting information about the state of bearing parts, experimental studies have been carried out to confirm the efficiency of this method.

1. Introduction
The quality, reliability and safety of electrical machines are determined by their technical condition, which depends on the degree to which the dimensions and parameters of the elements of the electrical machine correspond to their nominal values. Rolling supports play an important role in the formation of the technical condition of an electric machine, since they experience the most intense mechanical loads. The state of the rolling support is determined by the parameters of its main element - the rolling bearing. Thus, to determine the technical condition of the rolling bearing of an electric machine, it is necessary to assess the quality of the bearings that make up this bearing.

Rolling bearings are standard products and are of high quality, reliability and durability as delivered; many modern bearings have an integrated self-lubrication system with artificial intelligence. However, the high quality of the bearing does not provide complete confidence in the performance of the rolling bearing, in which the given bearing is assembled, since its actual state in the bearing is determined by the assembly and operating modes of the bearing. Factors in the assembly and operation of the rolling element can significantly change the condition of the bearing and the electrical machine as a whole.

Among the known methods for monitoring rolling bearings, electrical methods are distinguished. These methods are universal, relatively simple to implement, and inertialess. A variety of electrical methods for monitoring rolling bearings are electroresistive methods. They are based on the physical phenomenon of the dependence of the electrical resistance of the bearing on the factors of its internal environment, assembly modes and operation of the rolling support. Electroresistive methods for monitoring rolling bearings became known in the second half of the 20th century, and information about them was published in many review works, in particular [1, 2].
A well-known group of electroresistive methods for monitoring rolling bearings are methods for monitoring the time of contact of the metal surfaces of rings and rolling elements of bearings. These methods were first developed by scientists S.F. Korndorf and K.V. Podmasreryev in the period from 1979 to 1986, were subsequently developed in the works of their scientific school, and the basic diagnostic parameter received the abbreviation "NIV" - "normalized integral time" [1].

The use of the NIV parameter is limited by two conditions: the mode of mixed lubrication in the bearing and the time of determining the average value of the parameter [1, 3]. A more universal indication of the condition of a rolling bearing is electrical resistance.

The purpose of this work is to describe the results of the development of a method for monitoring the quality of the support by the parameters of its electrical resistance. The parameters of electrical resistance make it possible to carry out a comprehensive assessment of the state of the rolling support, as well as to identify individual defects of its elements in arbitrary lubrication modes.

2. Theoretical basis for electroresistive monitoring of rolling supports

The theoretical basis for the electroresistive method of rolling supports monitoring is a mathematical model of the electrical resistance of the bearing. A rolling bearing is a complex technical system in which mechanical, hydrodynamic and electrical factors are combined. Modelling the electrical resistance of a bearing is based on the use of several fundamental theories, a detailed description of which is presented in [3]. Mechanical factors are modelled in accordance with the theory of contact of real surfaces of the scientific school of N.B. Demkin [4]. The state of the lubricating film is described in accordance with the hydrodynamic theory of lubrication of the scientific school of D.S. Kodnir [5]. The electrical resistance of the friction contact is modelled in accordance with the theory of electrical conductivity of the contact between two rough bodies of the scientific school of A.V. Bely and N.K. Myshkin. The connections between individual frictional contacts within the contact spots of the bodies and bearing rings are modelled by the Nyack distribution [6, 7].

The theoretical basis for the electroresistive method of rolling bearing monitoring is a mathematical model of the electrical resistance of the bearing. A rolling bearing is a complex technical system in which mechanical, hydrodynamic and electrical factors are combined. The basic structural element of a rolling bearing, as a tribological object, is an elementary frictional contact, and the transition from the resistance of a frictional contact to the resistance of the bearing as a whole is carried out in accordance with the equations of M.P. Kovalev and N.Z. Narodetsky [8]. For frictional contact, the retraction resistance \( R_{ST} \) and the lubricating film resistance \( R_{SP} \) are taken into account, determined through the resistivity of the contacting surfaces \( (\rho) \), tunnel surface lubricating films \( (\rho_p) \), boundary film \( (\rho_{GP}) \) and bulk lubricant \( (\rho_{SM}) \). The calculation takes into account the thickness of the lubricating film in contact \( (h) \) within the area \( (S_h) \), the radii of the contact spots for the inner \( (V) \) and outer \( (N) \) bearing rings \( (r_{(V,N)}) \) and the number of contact spots within the friction zones \( (n_p) \):

\[
\begin{cases}
R_{ST} = \frac{\rho}{2 \cdot n_p \cdot r_{(V,N)}}, & h < 3 \, \text{nm}; \\
R_{SP} = \frac{\rho_p}{\pi \cdot n_p \cdot r_{(V,N)}^2}, & 3 \leq h < 10 \, \text{nm}; \\
R_{SP} = \rho_{GP} \cdot \frac{h}{S_h}, & 0.01 \leq h < 1 \, \mu m; \\
R_{SP} = \rho_{SM} \cdot \frac{h}{S_h}, & 1 \leq h \leq 30 \, \mu m.
\end{cases}
\]

The system of equations (1) makes it possible to take into account the possible modes of lubrication in the bearing: dry, boundary and liquid friction. It is the basis of the mathematical model.

The mathematical model of the bearing electrical resistance is represented by the system of equations (1-10). Equations (2) and (3) serve to calculate the contact resistance:

\[
R_{ST} = a_R \cdot \Psi_r(h); \quad R_{SP} = \frac{\rho_{SM} \cdot h_0}{\rho_M \cdot \frac{A_t}{r_x} \cdot \frac{A_y}{A_t - A_y}}; \quad a_R = \frac{\rho_M}{2 \cdot N \cdot \sqrt{\beta \cdot d}}.
\]
\[
\Psi_g(h) = \left[ L \left( \frac{d}{R_q} \right) \left[ 1 - L \left( \frac{d}{R_q} \right) \right] + \frac{R_q}{d\sqrt{2\pi}} \left[ 1 - L \left( \frac{d}{R_q} \right) \right] \exp \left( -\frac{d^2}{2R_q^2} \right) - \frac{1}{4} \right]^{0.5}; \quad \beta = \sqrt{r_p \cdot r_p}. \tag{3}
\]

To calculate the retraction resistance \( R_{ST} \), the following must be specified: auxiliary variables of the electrical resistance function \( a_g \) and \( \Psi_g(h) \); electrical resistivity of lubricant \( (\rho_{oil}) \) and metal surfaces \( (\rho_{M}) \); the smallest thickness of the lubricating film within the contact patch \( (h_0) \); actual \( (A_c) \) and contour \( (A_c) \) contact areas. The following parameters are used in the formulas for the functions \( a_g \) and \( \Psi_g(h) \): integral Laplace function \( L(d/R_q) \); radius of curvature of microroughnesses \( (\beta) \), taking into account the radii of irregularities in the longitudinal \( (r_p) \) and transverse \( (r_{pop}) \) directions; nominal clearance between the rolling element and the bearing ring \( (d) \); the number of irregularities \( (N) \) of the profile within the nominal contact area \( (A_n) \) of the rolling elements and bearing rings; root-mean-square deviation of the height of irregularities from the midline of the profile within the base length \( (R_q) \). The main factor that forms the electrical resistance of a contact is the actual contact area \( (A_c) \), defined as a certain part of the contour contact area \( (A_c) \). Functions for calculating \( A_r \) and \( A_c \) are given by equations \( (4) \) and \( (5) \):

\[
A_r = \pi \cdot N \cdot \beta \cdot d \left[ L \left( \frac{d}{R_q} \right) + \frac{R_q}{d\sqrt{2\pi}} \exp \left( -\frac{d^2}{2R_q^2} \right) - \frac{1}{2} \right]; \quad d = R_p - \delta; \quad N = \frac{A_c}{S_{m1} \cdot S_{m2}}; \tag{4}
\]

\[
A_c = \pi \cdot n_a \cdot n_b \cdot \left[ 3 \frac{F_r}{E \cdot \Sigma \rho} \right]^2 - A_0; \quad \delta = h - d = 3\Sigma \rho \cdot \frac{3}{2} \cdot \frac{2 \cdot K}{\pi \cdot n_a} \cdot \frac{1}{3} \left( 1 - \eta^2 \right) \cdot F_r^2. \quad \tag{5}
\]

To calculate \( A_r \) and \( A_c \), the above parameters must be specified, as well as: the rolling element and ring approaching \( (\delta) \); the height of the surface irregularities \( (h) \) and the dimensionless height of the irregularities \( (h_1) \); the area of the local defect on the surface \( (A_D) \); the step of the irregularities of the profile in the longitudinal \( (S_{m1}) \) and transverse \( (S_{m2}) \) sections; the reduced height of smoothing the irregularities of the profile of surfaces 1 and 2 \( (R_p = R_{p1} + R_{p2}) \); coefficients \( n_a, n_b \) and \( (2 \cdot K/\pi \cdot n_a) \), taking into account the shape of the contacting surfaces; geometric parameter of the sum of principal curvatures of contacting surfaces \( (\Sigma \rho) \); modulus of elasticity \( (E) \); Poisson’s ratio \( (\eta) \); force of normal loading of frictional contact \( (F_r) \).

The equation of the contour contact area \( A_c \) allows one to take into account the effect on the electrical resistance of the contact of two types of surface shape deviations: local defects (holes, shells, risks, etc.) and macrodeviations (eccentricity, ovality, bearing ring cut). The influence of local defects is taken into account by introducing the parameter of the area of the local defect \( A_D \) into equation \( (5) \). The influence of macrodeviations is estimated indirectly through the sum of the principal curvatures of surfaces \( (\Sigma \rho) \):

\[
\Sigma \rho = \Sigma \rho_0 + \sum_{i=1}^{p} Q_i \cdot \sin (k \cdot \varphi + \varphi_k), \tag{6}
\]

where \( \Sigma \rho_0 \) – is the sum of the main curvatures for the contact of surfaces with the nominal profile;

\( Q_i, \varphi_i \) – amplitude and phase angle of the \( k \)-th harmonic of macrodeviations;

\( k \) – harmonic number \( (1 - \text{eccentricity}, 3 - \text{ovality}, 3 - \text{three-vertex cut}) \);

\( p \) – is the limiting number of the considered harmonic.

The random function of the actual contact area \( A_c \) depends on the distribution law of the random variable of the dimensionless height of the irregularities of the contacting surfaces \( h_1 \), which is described by the Nyack distribution and is given by equations \( (7) \) and \( (8) \):
The essence of the electroresistive monitoring method is to assess the technical condition of the rolling support: the roughness of the surfaces of the rolling elements and bearing rings, local defects and macrodeviations of the working surfaces of the bearing parts, operating modes of the rolling support.

The developed electroresistive method makes it possible to monitor the rolling support for the roughness of the surfaces of the bearing cage rotation frequency, bearing cage eccentricity, and bearing cage ovality; the modes of operation of bearings in rolling bearings are assessed: normal load, rotation speed of the rings, type, brand and amount of lubricant; the types of detected defects [2, 3, 4 ... n-order cut];

The compiled mathematical model of the electrical resistance of the bearing makes it possible to model the electrical resistance of the contact of one rolling body with the bearing rings. To calculate the resistance of the bearing as a whole, it is represented as a parallel connection of the contacts of all rolling bodies, and the contact resistance of each rolling body with the rings is determined by solving the problem of the distribution of the normal loading force between the rolling bodies of the bearing [2].

The developed electroresistive method makes it possible to monitor the rolling support by several techniques, differing in the types of detected defects [2].

3.1 Technique for assessing the general condition of a bearing in a rolling support. This technique is based on the use of the $R_s$ diagnostic parameter and includes the following actions:

- select the object of monitoring: select the electric motor, the rolling bearings of which are subject to monitoring, determine the type of rolling bearings in the bearings;

- the modes of operation of bearings in rolling bearings are assessed: normal load, rotation speed of the rings, type, brand and amount of lubricant;

- turn on the object and run in the bearings for 2 hours;

- measure the diagnostic parameter $R_s$ for a time equal to 10 ... 50 periods of rotation of the bearing ring;

The developed electroresistive method makes it possible to monitor the rolling support by several techniques, differing in the types of detected defects [2].

The developed electroresistive method makes it possible to monitor the rolling support by several techniques, differing in the types of detected defects [2].

The developed electroresistive method makes it possible to monitor the rolling support by several techniques, differing in the types of detected defects [2].

The developed electroresistive method makes it possible to monitor the rolling support by several techniques, differing in the types of detected defects [2].

The developed electroresistive method makes it possible to monitor the rolling support by several techniques, differing in the types of detected defects [2].
- based on the value of the $R_s$ parameter, a conclusion is made about the lubrication mode in the bearing and the state of the rolling support (based on the results of comparing the measured value of the $R_s$ parameter with the value acceptable for a given type of bearing and a given lubrication mode).

This technique is easy to implement, is carried out using relatively simple technical means [11] and is efficient in all lubrication conditions.

3.2 Technique for assessing macrodeviations of rolling bearing parts with local loading. This technique allows the quality of the rolling support to be assessed by the condition of the bearing ring under local loading. It is based on the use of the $Kn$ diagnostic parameter and includes the following actions:

- select the object of monitoring: select the electric motor, the rolling supports of which are subject to monitoring, determine the type of rolling bearings in the supports;
- the modes of operation of bearings in rolling supports are assessed: normal load, rotation speed of the rings, type, brand and amount of lubricant;
- turn on the object and run in the bearings for 2 hours;
- connect the rolling support to a monitoring device that allows you to measure the $R_s$ parameter for a time equal to 0.05 ... 0.1 of the rotation period of the bearing ring;
- the test bearing ring is divided into $n$ sections;
- receive $n$ readings of the diagnostic parameter $R_s$;
- build a function of dependence of the diagnostic parameter $R_s$ on the angular coordinate of the normal load vector $Fr$ and carry out its harmonic analysis;
- by the extrema of the harmonic components of the amplitude spectrum, the $R_s$ functions determine the type of the main macrodeviations present on the bearing ring.

The advantage of this technique is the ability to control the durability of the rolling support based on the results of detecting macrodeviations of a locally loaded bearing ring and choosing a rational position of this ring relative to the load.

3.3 Technique for evaluating macrodeviations of rolling support parts with circulating loading. This technique is based on the use of the diagnostic parameter $Kn$ and includes the following actions:

- select the object of monitoring: select the electric motor, the rolling supports of which are subject to monitoring, determine the type of rolling bearings in the support;
- the modes of operation of bearings in rolling support are assessed: normal load, rotation speed of the rings, type, brand and amount of lubricant;
- turn on the object and run in the bearings for 2 hours;
- connect the rolling support to a monitoring device that allows you to measure the parameter $Kn$ at information frequencies calculated by the block of formulas (9);
- based on the results of comparing the value of the parameter $Kn$ with reference data for a given type of bearing, the type, value and orientation of macrodeviations are determined.

The advantage of this technique is the ability to control the durability of the rolling support based on the results of detecting macrodeviations of a circulatingly loaded bearing ring and choosing a rational frequency of rotation of the electric motor shaft.

4. Analysis of experimental data
In order to experimentally test the performance of the proposed electroresistive monitoring method and the declared capabilities of the methods for assessing the state of the rolling support, experimental studies were carried out. Unlike the well-known research results [1, 2], special attention was paid to the operability of the method in the liquid lubrication mode, therefore the bearing was lubricated not with transformer oil, which forms a mixed lubrication mode, but with lubricants that provide a strong and continuous lubricating film, in which the parameter NIV is inoperative: with TAD-17 transmission oil and plastic lubricant "Litol-24".

The object of research was a rolling support with a 1000900 type bearing. An experimental rolling support was installed in a well-known setup, which allows simulating macrodeviations of bearing rings in the range of values from 0 to 50 μm, setting the shaft rotation frequency in the range of 0 to
3000 min⁻¹, normal load in the range of values from 0 to 500 N with local and circulating loading of the bearing rings. A well-known automated system for collecting and analyzing data during tribomonitoring SADT-1 was used as a means of measuring the resistance of the rolling support.

In order to increase the reliability of the experimental data, the research object was thoroughly prepared for the experiment – the test bearing was washed with kerosene, dried for 20 hours, and run-in for 2 hours. During the experiments, stable values of the rolling support operating modes were set: the normal load value was 100 N, the volume of lubricant varied in the range from 8 to 40 mm³, the shaft rotation frequency was 6000 min⁻¹ when examining a locally loaded ring and 4500 min⁻¹ for circulatingly loaded ring.

Experimental data have confirmed the efficiency of the electroresistive monitoring method and the declared capabilities of the methods for assessing the state of the rolling support.

Figure 1 shows the results of assessing the general condition of the bearing in the rolling support using the diagnostic parameter $R_s$.

Figure 1, a show the dependence of the parameter $R_s$ on time during the running-in process of the bearing. Dependencies N1 and N2 correspond to new bearings, and dependence N3 – to a worn bearing in the limiting state. Figure 1, b shows the dependence of the $R_s$ parameter on the type of lubricant and its amount. It can be seen that the values of the parameter $R_s$ significantly depend on the amount of lubricant in the bearing, and the dependences are individual for each type of lubricant.

Figure 2 shows the results of evaluating the macrodeviations of rolling bearing parts with local loading according to the diagnostic parameter $R_s$.

Figure 2, a show the dependence of the $R_s$ parameter on the ovality of the locally loaded outer ring of the bearing lubricated with TAD-17 semi-fluid transmission oil. It can be seen from the graph that with an increase in the ovality value from 5 to 40 μm, the value of the average electrical resistance of the bearing decreases from 0.65 to 0.45 MOhm. A decrease in the electrical resistance of the bearing with an increase in ovality indicates the sensitivity of the $R_s$ parameter to macrodeviations of the bearing rings, and the relatively small dynamic range of the $R_s$ parameter indicates the good lubricating properties of a semi-liquid gear oil.

Figure 2, b shows the dependence of the $R_s$ parameter on the ovality of the locally loaded outer ring of the bearing lubricated with Litol-24 grease. It can be seen from the graph that with an increase in ovality from 5 to 40 μm, the value of the average bearing resistance decreases from 0.7 to 0.2 MOhm. At the same time, the nature of the dependence confirms the sensitivity of the $R_s$ parameter to macrodeviations of the bearing rings, and a wider dynamic range of the $R_s$ parameter indicates a lower efficiency of the grease compared to semi-liquid gear oil. Particularly noteworthy is the section of the graph in Figure 2, b with the ovality of the outer ring $Q = 30$ μm. In this area, there is a significant
scatter in the values of the parameter $R_s$, which indicates a sharp deterioration in the lubrication regime and the degradation of the lubricating properties of the material at high loads.

![Figure 2](image)

**Figure 2.** Dependence of the $R_s$ parameter on the ovality of a locally loaded ring

In order to confirm the possibility of determining the type of macrodeviations of a locally loaded bearing ring (eccentricity, ovality, faceting), a harmonic analysis of the function of the average resistance of the rolling support from the angle of rotation of the shaft – the function $R_s(\phi)$ – was carried out. The results of harmonic analysis are shown in Figure 3.

![Figure 3](image)

**Figure 3.** Harmonic function analysis $R_s(\phi)$ for locally loaded ring

Figure 3, a show the results of the harmonic analysis of the $R_s(\phi)$ function for a locally loaded bearing ring lubricated with TAD-17 gear oil. Figure 3, b shows the results of harmonic analysis of the function $R_s(\phi)$ for a locally loaded bearing ring lubricated with Litol-24 grease. The spectra of the function $R_s(\phi)$ were obtained when simulating the ovality of the outer ring of the bearing, equal to $Q = 10 \, \mu m$. For two types of lubricants, the dependences have a pronounced second harmonic of the function $R_s(\phi)$, corresponding to the ovality of the ring.

Figure 4 shows the results of evaluating the macrodeviations of rolling bearing parts with circulating loading by the diagnostic parameter $K_n$. During the experiment, a 1000900 type bearing
was installed in the rolling support with the number of balls – 7 pcs. For the outer ring of the bearing, ovality was simulated in the range of values from 0 to 40 µm with a step of 10 µm. The inner ring of the bearing was rotated at a frequency of 12.14 Hz (4500 min⁻¹), a circulating load (100 N) created an unbalance device rotating with the shaft.

Figure 4, a show the results of a harmonic analysis of the time function of electrical resistance $R(t)$ of a circulatingly loaded bearing ring lubricated with TAD-17 transmission oil. Figure 4, b shows similar results for a bearing lubricated with Litol-24 grease. Both spectra were obtained with the ovality of the outer ring of the bearing $Q_2 = 10 \, \mu m$.

The spectra of Figures 4, a and b show the presence of harmonic components in the function $R(t)$ at information frequencies calculated by the block of formulas (9) and corresponding to the ovality of the outer ring of the bearing.

Information frequency values:

\[
\begin{align*}
F_s &= 4.5 \, Hz \\
F_0 &= 12.14 \, Hz \\
F_1 &= F_0 \cdot M \cdot L = 12.14 \cdot 2 \cdot 1 = 24.3 \, Hz \\
F_2 &= F_s \cdot z + F_0 \cdot M \cdot L = 4.5 \cdot 7 + 12.14 \cdot 2 \cdot 1 = 55.8 \, Hz \\
F_3 &= F_s \cdot z + F_0 \cdot M \cdot L = 4.5 \cdot 7 + 12.14 \cdot 2 \cdot 2 = 80.1 \, Hz \\
F_4 &= F_s \cdot z + F_0 \cdot M \cdot L = 4.5 \cdot 7 + 12.14 \cdot 2 \cdot 3 = 104.4 \, Hz
\end{align*}
\]

a – transmission oil TAD-17; b – plastic lubricant "Litol-24”;

c – parameter $K_n$ dependence from ovality values $Q_2$ bearing rings

Figure 4. Analysis of the resistance function for a circulatingly loaded ring

Figure 4, c shows the graphs of the dependence of the diagnostic parameter $K_n$ on the ovality of the outer ring of the bearing in the range of values from 0 to 40 µm with a step of 10 µm. The outer ring of the bearing was subjected to a circulating load (100 N) from the unbalance device rotating with the shaft. The inner ring of the bearing rotated at 12.14 Hz (4500 min⁻¹). The dependences were obtained for two types of lubricants: TAD-17 transmission oil and Litol-24 grease.

The experimental dependences shown in Figure 4, c, confirm the sensitivity of the diagnostic parameter $K_n$ to macrodeviations of the bearing ring under circulating loading. The graph also shows that the parameter $K_n$ has a relatively high sensitivity to the values of macrodeviations – at least two
orders of magnitude of the dynamic range of values, the nature of which depends on the value of macrodeviations, and the degree depends on the type of lubricant. These results confirm the theoretical possibility of assessing the macrodeviations of rolling bearing parts with circulating loading by the diagnostic parameter $K_n$.

The experimentally established monotonic character of the investigated dependences shows that deviations of the shape on the raceway of a circulatingly loaded ring lead to an unambiguous deterioration in the state of the lubricant in the bearing. Spectral analysis of a number of realizations of the function $R(t)$ under different operating modes of the bearing and modeling of shape deviations of various types and values showed that the deviations of the raceway of a circulatingly loaded ring, along with a change in the integral characteristics of the function $R(t)$, cause the formation of information harmonic components. In this case, each type of form deviation corresponds to a set of information components characteristic only for it. Changing the value of the deviation of the form only redistributes the weight of the various components, and their information frequencies remain unchanged.

5. Conclusions on work
The results obtained confirm the reliability of the theoretical studies and the efficiency of the rolling bearing monitoring method by the parameters of the electrical resistance of the bearing assembled in this bearing.

Acknowledgments
The authors consider it their pleasant duty to express their gratitude to the faculty and technical specialists of the Department of Instrumentation, Metrology and Certification of Oryol State University named after I.S. Turgenev for useful participation, great technical assistance provided during the experiments, moral support and valuable advice.

References
[1] Podmasteryev K V 2001 *Electroparametric methods of complex diagnostics of rolling bearings* / K.V. Podmasteryev. M.: Mashinostroenie-1. 376 p.
[2] Markov V V 2004 *Control of rolling bearings by parameters of electrical resistance* / V V Markov, V V Mishin // Control. Diagnostics. N. 9. P. 35.
[3] Podmasteryev K V 2005 *Investigation of the influence of macrodeviations of raceways of rings on the state of lubrication in a bearing by the electroresistive method* / K V Podmasteryev, V V Mishin, V V Markov // Friction and Wear. T. 26. N. 5. P. 546-553.
[4] Demkin N B 2005 *Theory of contact of real surfaces and tribology* / N B Demkin // Friction and Wear. T. 16. N. 6. P. 1003-1024.
[5] Kodnir D S 1976 *Contact hydrodynamics of lubrication of machine parts* / D S Kodnir // M.: Mechanical Engineering. 304 p.
[6] Myshkin N K 2002 *Tribology. Principles and applications* / N K Myshkin, M I Petrokovets. - Gomel: IMMS NASB. 310 p.
[7] Kovalev M P 1980 *Calculation of high-precision ball bearings* / M P Kovalev, N Z Narodetsky // 2 ed. M.: Mechanical engineering. 373 p.
[8] Galakhov M A 1988 *Calculation of bearing assemblies* / M A Galakhov, A N Burmistrov. M.: Mashinostroenie. 272 p.