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Author	Family Name	**Zablotskyi**
	Particle	
	Given Name	**Valentyn**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	Lutsk National Technical University
	Address	75, Lvivska St., 43018, Lutsk, Ukraine
	Email	
	ORCID	http://orcid.org/0000-0002-2921-0031
Corresponding Author	Family Name	**Tkachuk**
	Particle	
	Given Name	**Anatolii**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	Lutsk National Technical University
	Address	75, Lvivska St., 43018, Lutsk, Ukraine
	Email	a.tkachuk@lntu.edu.ua
	ORCID	http://orcid.org/0000-0001-9085-7777
Author	Family Name	**Senyshyn**
	Particle	
	Given Name	**Anatoliy**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	Technical University of Munich
	Address	21, Arcisstraße, 80333, Munich, Germany
	Email	
	ORCID	http://orcid.org/0000-0002-1473-8992
Author	Family Name	**Trokhymchuk**
	Particle	

	Given Name	**Ivanna**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	Lutsk National Technical University
	Address	75, Lvivska St., 43018, Lutsk, Ukraine
	Email	
	ORCID	http://orcid.org/0000-0002-0737-6452
Author	Family Name	**Svirzhevskyi**
	Particle	
	Given Name	**Kostiantyn**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	Lutsk National Technical University
	Address	75, Lvivska St., 43018, Lutsk, Ukraine
	Email	
	ORCID	http://orcid.org/0000-0002-8738-8436

Abstract	Under the conditions of operation of high-speed rotor mechanisms, bearing bearings become the primary source of unwanted vibrations, noise, and premature loss of the initial operational properties of the machines. Accordingly, the requirements for the quality of rolling bearings and their performance are constantly growing, and the technological support of the regulated requirements is becoming increasingly problematic. To increase the efficiency of machining operations of bearing parts and ensure the required quality of functional surfaces of rings in automated production, it is necessary to develop new effective methods of design and control of technological processes for the manufacture of individual bearing parts. The article analyzes the principles of technological support of quality parameters of the functional surfaces of the rings to improve and stabilize the performance of roller bearings. The reasons for increasing the vibroactivity of the working surfaces of the rings and the excess of the allowable vibration parameters and bearing noise are investigated. The connections of technological factors of forming operations of turning processing with parameters of microgeometry of the processed surfaces and operational properties of bearings are established. Models of formation of microgeometry of rotation surfaces on turning operations are developed, the reasons and technological features of formation of undulations on the processed surface are revealed.

Keywords (separated by '-')	Adaptive control - Formation - Microgeometry - Roller bearing - Vibroactivity

Author Proof

Impact of Turning Operations on the Formation of Rolling Bearing's Functional Surfaces

Valentyn Zablotskyi[1], Anatolii Tkachuk[1(✉)], Anatoliy Senyshyn[2], Ivanna Trokhymchuk[1], and Kostiantyn Svirzhevskyi[1]

[1] Lutsk National Technical University, 75, Lvivska St., 43018 Lutsk, Ukraine
a.tkachuk@lntu.edu.ua
[2] Technical University of Munich, 21, Arcisstraße, 80333 Munich, Germany

Abstract. Under the conditions of operation of high-speed rotor mechanisms, bearing bearings become the primary source of unwanted vibrations, noise, and premature loss of the initial operational properties of the machines. Accordingly, the requirements for the quality of rolling bearings and their performance are constantly growing, and the technological support of the regulated requirements is becoming increasingly problematic. To increase the efficiency of machining operations of bearing parts and ensure the required quality of functional surfaces of rings in automated production, it is necessary to develop new effective methods of design and control of technological processes for the manufacture of individual bearing parts. The article analyzes the principles of technological support of quality parameters of the functional surfaces of the rings to improve and stabilize the performance of roller bearings. The reasons for increasing the vibroactivity of the working surfaces of the rings and the excess of the allowable vibration parameters and bearing noise are investigated. The connections of technological factors of forming operations of turning processing with parameters of microgeometry of the processed surfaces and operational properties of bearings are established. Models of formation of microgeometry of rotation surfaces on turning operations are developed, the reasons and technological features of formation of undulations on the processed surface are revealed.

AQ1

Keywords: Adaptive control · Formation · Microgeometry · Roller bearing · Vibroactivity

1 Introduction

The quality indicators of an individual unit or machine as a whole are inextricably linked with the quality indicators and performance of each bearing as a separate part of the rotor system, which can potentially be the primary source of undesirable phenomena or characteristics of the whole mechanism, device or machine (Fig. 1a) [1]. Therefore, the requirements for the quality of rolling bearings and their performance are constantly growing, and the technological support of these requirements is becoming more complicated. It is known that the quality of the bearing and its performance

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characteristics, such as vibration, noise, accuracy, reliability, durability, and others, depend on the parameters of microgeometry and physical and mechanical properties of the surface layer of functional surfaces [2]. The leading causes of undulations are the dynamic processes of machining parts on metal-cutting machines, associated with the loss of stability of the machine-tool-part system [3]. Vibrations in the cutting process occur due to self-oscillations, forced oscillations, and deformation of the rings. Self-oscillations are the result of the loss of properties of a given motion during cutting. External perturbations cause forced oscillations. The causes of undulation are forced oscillations of the system caused by various periodic perturbations due to the imbalance of the machine-tool-part system (workpiece, machine spindle, shafts, and gears) [4]. Depending on the oscillations frequency ratio and the speed of relative movement of the tool and the part, the surface shape violation nature is changed. The decisive factor affecting the part's shape is the ratio of the frequency of harmonic oscillations for the tool and the workpiece to the rotation speed of the part [5].

Therefore, the technological support of the regulated requirements for the quality of working surfaces and performance characteristics of roller bearings during their manufacture is an urgent problem.

2 Literature Review

Among the scientific works concerning the problem of technological assurance of the quality of shaping and operational properties of rolling bearings, it is possible to distinguish four directions:

– geometrical, based mainly on the dimensional analysis of technological processes and operations in order to achieve the desired level of accuracy of parts, assemblies, and products [6];
– technological, in which the quality of the surface is considered from the standpoint of the relationship with technological factors [7];
– the rigidity characteristics of the technological system's units, and the own deformations of parts and their influence on the quality parameters of the forming surfaces [8];
– complex, considering the whole set of factors that affect the quality of formation [9].

In the works of these areas, various aspects of the technological formation of parameters of geometric structure of surface, physical and mechanical properties of the surface layer of details of bearings and details with contact interaction are investigated, questions of the influence of technological factors of machining on parameters of quality of surfaces and some operational characteristics of surfaces and details [10, 11]. However, technological influence and control of the parameters of the undulation of the working surfaces of roller bearings in the operations of centerless grinding are not correctly reflected [12].

Based on the analysis of literature sources, it is established that the vibroacoustic characteristics of roller bearings and their accuracy and wear resistance are dominated by shape errors, ripples, and roughness of the contact surfaces [13].

Statistical analysis of product defects that occur in the process of manufacturing parts of roller bearings showed that the leading causes of surface layer defects in accuracy and surface ripple are oscillating processes of the dynamic system of forming the working surfaces of roller bearing rings in turning operations, diamond and abrasive operations and finishing operations [14, 15].

3 Research Methodology

Structural vibrations in bearings are due to two main reasons - deformation of the rings under the action of forces from the rolling elements and fluctuations in the stiffness of the bearing during rotation as a result of the radial component of the load F1 (Fig. 1b). Since the rolling elements move relative to the line of action of the radial load, the stiffness of the bearing changes periodically with frequencies multiples of the frequency of passage of the rolling elements on a fixed ring [16]. In low-precision bearings, structural vibrations are not noticeable, but as the precision of the bearings increases, these vibrations may play a more prominent role. The frequency of structural vibration is equal to or multiple of the value of $f_p = qzf_c$, where z is the number of rolling elements; f_c is the rotational speed of the separator relative to the fixed ring; $q = 1, 2,\ldots$ is the coefficient of proportionality.

Vibrations associated with the structural imperfection of the bearing are because, in the design of the bearing and the rolling contacts, there are sliding contact surfaces due to differences in linear and angular velocities of adjacent parts (Fig. 1b) [17].

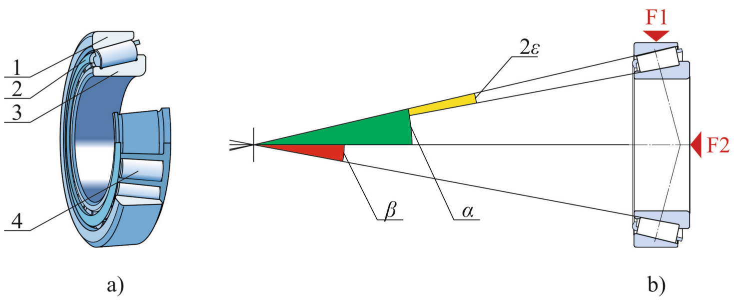


Fig. 1. Construction: 1 – outer ring (fixed); 2 – separator; 3 – inner ring (movable); 4 – rolling elements a) and the scheme of the tapered roller bearing $\beta = \alpha - 2\varepsilon$ b).

The relative speeds between the contacting parts of the tapered roller bearing are determined based on the speed of the inner ring with a fixed outer ring.

$$\text{Separator} \leftrightarrow \text{inner ring}: \; n_{s/ir} = \frac{\sin\alpha}{\sin\alpha + \sin\beta} n_{ir/or} \tag{1}$$

$$\text{Separator} \leftrightarrow \text{outer ring}: \; n_{s/ir} = \frac{\sin\beta}{\sin\alpha + \sin\beta} n_{ir/or} \tag{2}$$

$$\text{Rolling body} \leftrightarrow \text{separator}: \quad n_{rb/s} = \frac{\sin\beta}{\sin\varepsilon} n_{s/ir} \tag{3}$$

Mismatched frequencies occurring in the bearing are determined from expressions (4–6). Relative frequency of the roller:

$$f_{md} = 2 \cdot n_{rb/s} \tag{4}$$

The relative frequency of the inner ring:

$$f_{ir\ md} = Z \cdot n_{s/ir} \tag{5}$$

Relative frequency of the outer ring:

$$f_{or\ md} = Z \cdot n_{s/or} \tag{6}$$

where Z is the number of rollers (rolling elements) in the bearing; n_{ir} – the number of revolutions of the shaft (inner ring).

For the experimental study of the influence of technological factors on the parameters of the microgeometry of the treated surfaces, an automated research unit based on a lathe and an automated research complex Rank Taylor Hobson Talyskan were used.

4 Results

Vibrations, which are associated with structural imperfections of rolling bearings, are manifested at pronounced frequencies and do not significantly affect the formation of the initial accuracy of bearings and bearing assemblies [18]. The vibrations and the operational characteristics of the roller bearings are influenced to a greater extent by the errors in forming the shape of the working surfaces of the rings, the bodies of rotation, and working environment conditions [19].

Shape errors in the manufacture of bearing parts should be divided into 4 groups:

1. deviations of the first order – errors in the placement of working surfaces (different wall thickness of the rings, radial and axial beating, different sizes of rolling elements, etc.);
2. deviations of the second-order – errors in the shape of working surfaces (ovality, number of faces);
3. deviation of the third-order – undulation;
4. deviations of higher orders – roughness, subroughness.

Depending on the rank, all of the above errors cause low-frequency, medium-frequency, or high-frequency vibrations:

– errors in the shape of the raceways, as well as the size and ovality of the rolling elements – low-frequency vibration (in the frequency range up to $10 \cdot f_0$),

- the undulation of rolling tracks – a vibration of the medium frequency (in the frequency range 10…60·f_0),
- the undulation of rolling elements and roughness of rolling tracks – high-frequency vibrations (in the frequency range over 60·f_0).

In the ratio f_0 – the oscillation frequency of the bearing shaft due to the imbalance corresponding to the number of revolutions of the shaft (inner ring) $f_0 = n_в = 1800\ \text{min}^{-1}$.

Given that $f_0 = f_{c/з} + f_{c/в}$, the frequency composition of the spectrum of vibrational oscillations of the bearings due to defects in the rings is determined by the expression:

$$f = \left| k \cdot f_0 - q \cdot Z \cdot f_{c/в} \right| \tag{7}$$

where Z is the number of rolling elements in the bearing; k is the order of harmonics of the undulation of the raceway. Figure 2 (side view) shows the relationship of the geometric structure of the roller bearing with the parameters of the undulation of the working surfaces and the number of rolling elements Z.

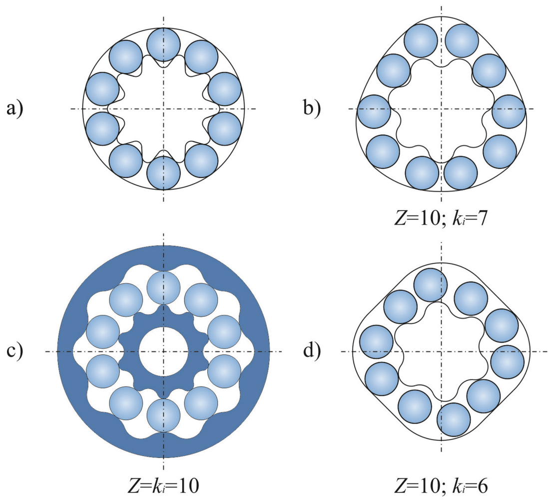


Fig. 2. Influence of the working surfaces' undulation ratio to the number of rotation bodies on the geometric structure of the bearing.

The equation of radial vibration of the outer ring of the roller bearing has the form:

$$\ddot{\chi} + 2h\dot{\chi} + \omega_p^2 \chi = \sum_j F_j \frac{\sin(\omega_j t + \Psi_j)}{M} \tag{8}$$

where χ is the radial vibration displacement of the ring (μm); ω_p – natural frequency; F_j, ω_j, ψ_j, h – amplitude, frequency and phase of the j-th harmonic of vibration disturbances and damping coefficient, respectively.

The solution of Eq. (8) gives the dependencies for vibration displacement χ, vibration velocity $\dot{\chi}$, and vibration acceleration $\ddot{\chi}$.

The modeling of microgeometry parameters is based on surface formation due to the relative movements of a part and a tool [20]. Altitude parameters of the microgeometry such as undulation, surface roughness are determined by the nature and magnitude of the radial movements of the tool relative to the workpiece [21]. The microgeometry step parameters depend on the ratio of the longitudinal feed of the tool and the rotational speed of the workpiece.

For modeling the height parameters of the microgeometry, a mathematical model of the dynamics of forming the working surfaces of the rings on the turning operation are developed. The calculated scheme of the dynamic model of the form's formation process is shown in Fig. 3.

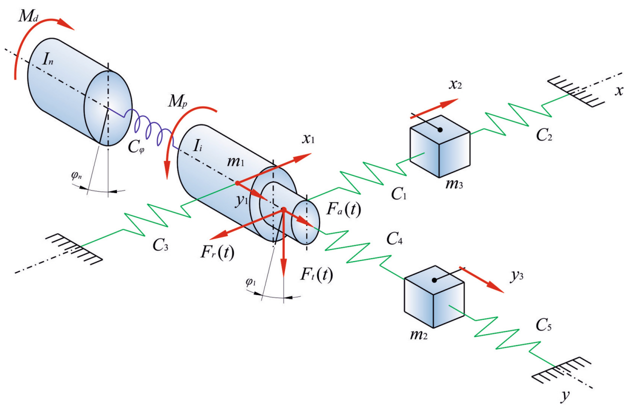


Fig. 3. Calculation scheme of a dynamic system.

The description of the notation of the calculation scheme (Fig. 3) is given in Table 1.

Table 1. Designation of the calculation scheme (Fig. 3).

Denotation	Description
m_1	Spindle weight and part weight
m_2, m_3	Masses of transverse and longitudinal calipers
$C_1 - C_5$	Elastic links
C_φ	Angular stiffness of the drive
M_d, M_p	Moments of cutting
x_1, x_2	Coordinates of displacements of masses m_1 and m_2 along the x-axis
y_1, y_3	Coordinates of displacements of masses m_1 and m_3 along the y-axis
φ_1, φ_n	Coordinates of angular displacements of rotating masses
$F_t(t)$, $F_r(t)$, $F_a(t)$	Cutting force

For a more accurate representation of the process of surface formation, a detailed scheme of the cutting process is given (Fig. 4).

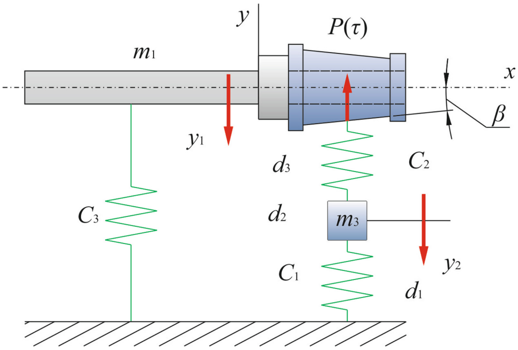


Fig. 4. Scheme of shaping the functional surface of the bearing.

The system of differential equations describing the movement of the tool relative to the workpiece has the form:

$$\begin{cases} m_1\ddot{y}_1 + d_1\dot{y}_1 + c_1y_1 + c_3(y_1 - y_2) = P(\tau) \\ m_2\ddot{y}_2 + d_2\dot{y}_2 + c_2y_2 + c_3(y_1 - y_2) = -P(\tau), \end{cases} \tag{9}$$

where m_1 is the mass of the spindle assembly with the part; m_2 – the weight of the caliper with the tool; c_1 – stiffness of the caliper; c_2 – stiffness of supports and spindle assembly; d_1 and d_2 are the damping coefficients of the bonds; $P(\tau)$ – perturbing force.

Application of the complex amplitudes method allows us to obtain the perturbing force as a variable:

$$P(\tau) = P_0e^{i\omega\tau} \tag{10}$$

where ω is the frequency of the perturbing force; $P_0 = P_y{\cdot}\cos\beta$ is the amplitude of the force, and P_y is the radial component of the cutting force.

The solution of the system of differential equations yields formulas for determining the amplitudes of the relative oscillations of the part and the tool:

$$u_1 = u_0\sqrt{\frac{\left(K_2^2 - \omega^2\right) + 4\mu_2^2K_1^2}{F_1^2(\omega) + 2\left[d\mu_2K_1^2 + f\mu_1K_2^2 - F_2(\omega)\right]\omega^2}} \tag{11}$$

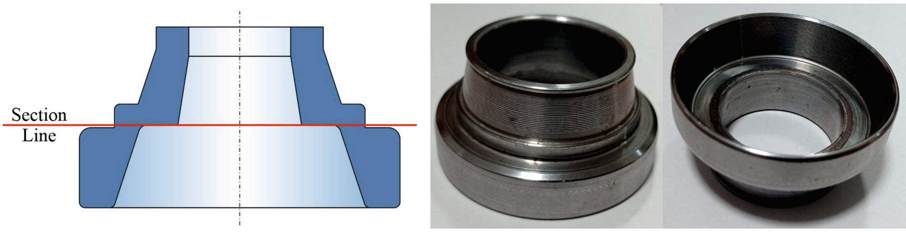
$$u_2 = u_0\sqrt{\frac{\left(K_1^2 - \omega^2\right) + 4\mu_1^2K_2^2}{F_1^2(\omega) + 2\left[d\mu_2K_1^2 + f\mu_1K_2^2 - F_2(\omega)\right]\omega^2}} \tag{12}$$

The frequency of natural oscillations is found from the characteristic equation of the system:

$$f = \sqrt{\frac{1}{2}\left(\frac{c_1 + c_3}{m_1} + \frac{c_2 + c_3}{m_3}\right) \pm \sqrt{\left(\frac{c_1 + c_3}{m_1} + \frac{c_2 + c_3}{m_3}\right)^2 - \frac{4(c_1c_2 + c_2c_3 + c_1c_3)}{m_1m_3}}}\ \mathrm{sec}^{-1} \tag{13}$$

where $x = s\tau/60$ – movement per 1 revolution; $V = \omega\ (D/2) = (\pi D)/\tau$, $\tau = \pi/\omega$.

In order to increase the accuracy of shaping, the design of a continuous workpiece of two rings of the roller bearing is proposed (Fig. 5).



a) b)

Fig. 5. The continuous design of the workpiece of two rings: a) scheme; b) prototype.

As a result of using this type of workpiece, it was possible to increase the accuracy of forming rings on turning operations, halve the complexity of procurement and forming turning operations, avoid the formation of stresses on functional surfaces that occur during installation in the chuck.

Notably, the vibroactivity of the working surfaces of the rings depends on the parameters of the wavy surfaces. By determining the relationship between the parameters of the undulation of the rolling tracks of the rings and the vibroactivity of the bearing revealed an essential pattern that the worst vibroacoustic characteristics of the bearing occur when the number of waves to the k-th harmonic on the inner and outer rings bearing, or when the number of waves of the k-th harmonic is a multiple of the number of rolling elements, ie $f_k = qz$, where f_k is the number of waves of the main k-th harmonic on the raceway.

The best results were observed when $f_k = qz \pm 1$, $fk = qz \pm 2$ and so on, $q = 1, 2, 3\ldots$. The proposed method of spectral analysis of vibroactivity of rolling tracks and vibrations of bearings allows diagnosing the causes of the origin of technological defects.

5 Conclusions

The resistance of the dynamic forming system to resonant perturbations is investigated, and the limits of stability in the coordinates stiffness - feed rate are obtained. Theoretical predictions in the process by modeling a dynamic system of formation are confirmed. It is established that for all variants of finishing turning in the feed range 0.05–0.20 mm/rev step of the irregularities S_z to the average value of the height W_z is less than 40, which indicates the absence of undulation. The maximum deviations of the surface shape ($W_z + R_z$) do not exceed 0.012 mm.

The mechanism of origin of structural and technological defects of roller bearings is investigated. Identification of the relationship between these defects and performance on the example of changes in the bearing's vibroacoustic characteristics formed the basis for developing a strategy for predicting the quality of parts and performance of bearings at the stage of technological design. For diagnosing the causes of vibration, the total spectrum of bearing oscillations should be divided into three bands – low-frequency oscillations (50 Hz–1.5 kHz), medium-frequency (1.5–3.0 kHz), and high-frequency vibrations (1.5–10 kHz). It is established that technological defects cause low-frequency and high-frequency vibrations. The technique on the integrated vibroactivity indicator for rings' working surfaces to define the level of suitability of a ready detail for operation as a part of the bearing and forecasting of vibroacoustic characteristics of rolling bearings are offered.

It is established that the shape errors and waviness of the working surfaces of the rings after the final operations of the superfinishing are transmitted by technological inheritance from the previous shaping operations of turning, roughing, and finishing grinding. In order to prevent such a negative impact of technological heredity, a new method of technological control of the undulation of rolling tracks in turning operations by modeling the dynamics of shaping is being developed. It is established that the reduction of surface waviness in turning operation reduces the oscillations of the components of cutting forces in finishing grinding operations, and hence the geometric ripple, which can account for up to 90% of the error of deviation of shaping accuracy.

In order to increase the accuracy of forming rings on turning operations, as well as to reduce the number of procurement and forming operations, the proposed design of a continuous workpiece set of two roller bearing rings, the introduction of which into production, will reduce the complexity of procurement operations by 35% and reduce cost by 15% of each bearing size.

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