Method of determining the parameters of the texture of the surface of the rolls of rolling bearings by means of quasi-optimal correlation algorithm

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Abstract. The article proposes a new approach to the method for estimating the texture parameters of the surface of the rolling tracks of instrument bearings after profile grinding. The microgeometry of the surface of the bearing raceways was studied on an optical-electronic complex on the basis of calculating the parameters of the autocorrelation function obtained as a result of computer processing of the surface video image. The purpose of this study is improving the technology of profile grinding of bearing raceways through the construction of an optical-electronic information-measuring system for monitoring the parameters of the autocorrelation function.

1. Relevance
Technological parameters of surface formation are taken into account in models of various types [1, 2]. Modern processing methods, characterized by an increasing number of parameters, require new methods for their evaluation [3, 4]. Optical methods of surface evaluation are used more and more widely, for example, to assess tool wear [5, 6]. These methods made it possible to more accurately estimate the tool's wear resistance [7, 8]. Optical methods complement the developed methods for the layout of engineering products in terms of operational control [9, 10]. Tests show the applicability of modern processing methods in the Paradigm of Industry 4.0 [11, 12, 13].

2. Research methods
The considered method for measuring the texture parameters of the roughness of the surfaces of raceways of bearings is associated with the use of optical-electronic means and information technology, surface quality analysis, measurement theory and digital image processing, correlation analysis theory,
probability theory and mathematical statistics. The method used is based on computer processing of the image of the roughness of the surface under study using a quasi-optimal correlation algorithm, which allows estimating the parameters of the correlation function under production conditions.

3. Results and discussion
One of the main indicators of the quality of instrument bearings is their reliability and durability. In this regard, the quality control of the surface of the raceway consists in disclosing the mechanism for forming surface irregularities depending on the properties of the material being processed, the type of processing, equipment parameters, tools, processing modes and other design and technological factors [14, 15, 17]. It is known that the smaller the surface roughness, the higher the fatigue strength of the bearings, as numerous studies have established that the foci of destruction of machine parts from metal fatigue are generated in the cavities of the irregularities on the raceway. At present, optical tools for evaluating surface quality are widely used in mechanical engineering [18–20]. However, these tools, as a rule, can be used only in the laboratory and for sampling.

In [21–22], an optoelectronic method for determining texture parameters based on computer processing of the image of the surface under study was considered. In this case, the multiplicative nature of the additional measurement error arising under the influence of the influence function was established, where \( \Delta \Phi \) and \( \Delta x \) - deviations of the power of the light flux and the angle of its fall on the studied microrelief from the nominal values. The method is based on a comparative correlation processing of the halftone image of the texture of the studied microrelief and a special set of halftone images of the reference textures with known microrelief parameters. Image processing was carried out using the well-known for calculating the two-dimensional correlation function of the expression [23].

The texture parameter of the microrelief is the arithmetic average deviation of the surface asperities from the average surface, defined as the average tone value of the image \( Ra, \mu m \), was determined with a given probability from the experimental dependence \( Ra = f(U_{AV}), \mu m \), where \( U_{AV} \) - random average of the variable component of the autocorrelation function.

To carry out research on the state of the roughness texture of the surfaces under investigation, a complex of equipment considered in [24] was used, namely, a measuring microscope, a video camera and a personal computer. A Computar ZC-F11CH3 camera was used as a video camera, and black and white images of a given format were generated at the output.

For the purpose of conducting studies using the method of profile grinding, samples of standard surfaces of steel ShKh-15 with different roughness were made. The following roughness parameters were determined on the SJ-201P profilograph:
- sample no. 1 - \( Ra = 0.13 \mu m \);
- sample no. 2 - \( Ra = 0.084 \mu m \);
- sample no. 3 - \( Ra = 0.048 \mu m \).

The optoelectronic system of the complex was set up in such a way that the analyzed surface of the reference samples had a size \( 3 \times 2.5 mm \). Luminous flux power \( 600 \cdot 10^3 \) lm fell on the test surface at an angle 45°. The video frame format was \( 320 \times 240 \) pixels.

In [25], it was noted that when using a Computar ZC-F11CH3 black and white video camera, the obtained information is redundant. In this regard, at this stage of the research, the initial halftone image of the surface was converted into a format of 1 pixel - 1 byte. Thus, the range of video signal variation in brightness B in the resulting image was 0–255 relative units.

In this work, we study the roughness of complex surfaces of the raceway (part of the toroidal surface) under production conditions based on optimal algorithms that will significantly improve the speed of the optical-electronic method for estimating roughness parameters.

To solve this problem, quasi-optimal correlation algorithms were considered, which are widely used in the correlation extreme navigation systems of unmanned aerial vehicles [26, 27]. An algorithm with a paired criterial function using binary images was investigated.
\[ r_{x,y}(k_1,k_2) = \frac{1}{N} \sum_{i=0}^{N-1} F_i(\Delta), \]  

(1)

where \( F_i(\Delta) \) – pair criterion function acquires a single value with a match \( i \) – pixel in reference image (RI) and a fragment of the binary current image (CI) roughness,

\( N \) – the number of compared items in RI and CI,

\( r_{x,y}(k_1,k_2) \) – correlation coefficient representing the normalized sum of matched pixels.

The pattern of formation and displacement, selected by RI from the binary image of the texture of the roughness was the same as in [28]. In the image from the first row, a bar is allocated \( N \times N \) pixels and the center of this band is set to the standard size \( N \times N \) pixel. Then the standard, starting from the leftmost position, moves along the selected bar in 1-pixel increments. At each combination of RI and CI is calculated \( r_{x,y}(k_1,k_2) \) according to the formula (4). Calculating \( r_{x,y}(k_1,k_2) \) in the first lane, the next lane of the same format is set, but shifted down one pixel. In this band, a new standard with the same dimensions is set in the center and the same calculations are performed. \( r_{x,y}(k_1,k_2) \) etc. Since the standard is formed in the image of the roughness itself, the coefficients \( r_{x,y}(k_1,k_2) \) are autocorrelation coefficients. After processing the entire image, we obtain a two-dimensional autocorrelation function. This also compensates for the negative impact of the influence function [20] on the roughness texture parameters:

\[ \Delta B = B_T \cdot f_{\text{int}}(\Delta \Phi, \Delta \alpha) - B_E \cdot f_{\text{int}}(\Delta \Phi, \Delta \alpha) = f_{\text{int}}(\Delta \Phi, \Delta \alpha) \cdot 0 \quad \text{when} \quad B_T = B_E \]  

(2)

In addition, it is only at this point that the sum of the pixels of the standard matched by the value of \( B_E \) and fragment CI - \( B_T \), according to (4).

The halftone image was binarized using the adaptive method [25, 27]. The image of the surface was divided into square fragments (windows 8 x 8 pixels) and the average brightness level of the video signal was calculated in each window \( B_T(x,y) \). Because of comparing each pixel of the window \( B_i(x,y) \) with threshold \( B_T(x,y) \) he was given a new meaning by the rule:

\[
B_i(x,y) = \begin{cases} 
0011, & \text{if } B_i(x,y) \geq B_T(x,y) \\
0000, & \text{if } B_i(x,y) < B_T(x,y)
\end{cases}
\]  

(3)

To obtain statistical information on the distribution of periods of change of the correlation coefficients at the level of 0.61 over the entire binary image, a corresponding program was developed. Characteristic changes in normalized correlation signals are shown in figure 1.

Figure 1. Normalized correlation signals of the studied surfaces.

It is also seen from the above dependences that with increasing roughness the frequency of oscillations of the autocorrelation function increases and the proportion of the regular component
increases. At the same time, for the surface with the smallest roughness (ring no. 3), there is a sharp drop in the amplitude of the correlation signal from the method of manufacturing the raceway of the bearing ring, which can also serve as a characteristic sign for identification (recognition) of products with specified high surface quality. To determine the level of the correlation coefficient $r$, on which it is necessary to calculate the amplitude and oscillation period of the autocorrelation functions, according to which the surfaces under study differ quite well from each other, the dependences were constructed $T_{av} = f(r)$, given in figure 2.

As can be seen from the above dependencies, when the correlation coefficient changes within $\approx 0.47-0.53$ the oscillation periods of the autocorrelation functions for surfaces with different roughness differ slightly. With a decrease in the correlation coefficient below 0.47, an increase in the difference in $T_{av}$, and for the surface with the best roughness (curve 1), this indicator reaches its maximum value $T_{av} = 240$ pixels at $r = 0.41$. At the same time, the gap in $T_{av}$ between samples 2 and 3 is $T_{av} = 72$ pixels. This is explained by the whole curve $T_{av} = f(r)$ (figure 2) is above the specified value $r$. Difference $T_{av}$ for rings 1 and 2 at this level, $r$ is only 10 pixels, which is comparable to the standard deviation in the measurement $T_{av}$.

Thus, if the task is to select only rings with a surface roughness given by technical conditions, then you can set a threshold $r = 0.38-0.41$ and discard the rings.

If the task is to identify the surfaces of rings with different roughness and defects, that is, to refer them with a given probability to a particular roughness range, then you can use the value $r = 0.61$, where there is a good difference in amplitude $A_{avg}$ and periods $T_{avg}$ autocorrelation functions.

Conducted research and created a database on the relationship values of the arithmetic mean deviation of the surface profile $R_a$ with an average amplitude of oscillation of the autocorrelation function $A_{avg}$ depending on the level of $r$ ($r = 0.61$) and the size of the base window.

4. Conclusions
Analysis of the data obtained shows that with increasing surface roughness, the average amplitude of oscillation of the autocorrelation function $A_{avg}$ rises. Regression equations (4-6) were obtained depending on the amplitude of the autocorrelation oscillations and the size of the base window. For the base window the size of the standard analytical dependence $R_a = F(A_{avg})$ will take the following form:

\[
R_a = 0.004 \ A_{avg} - 0.16, \ \text{um (base window} \ 4 \times 4) \tag{4}
\]

\[
R_a = 0.039 \ A_{avg} - 0.479, \ \text{um (base window} \ 8 \times 8) \tag{5}
\]

\[
R_a = 0.064 \ A_{avg} - 0.808, \ \text{um (base window} \ 9 \times 9) \tag{6}
\]

The standard deviation of the estimate in determining $A_{avg}$ determined by the formula [27]:

\[
\sigma_r = \frac{\sigma}{\sqrt{n}}, \tag{7}
\]
30 images were examined on the surface of each sample. Specifying the probability of recognizing the texture of the roughness studied $P=0.99$ and $I_{f}=2.576$, we obtain the standard deviations, confidence intervals and amplitudes of the variable component of the autocorrelation function.

Thus, using the optoelectronic complex and the above-considered method for determining the average amplitude of oscillation of the autocorrelation function $A_{avg}$ surface roughness can be calculated using analytical dependencies (4), (5) and (6).

In this case, the following equations should be applied when the surface roughness of the sample:
equation (2) if $Ra = 0.15…0.20$ um, 
equation (3) if $Ra = 0.08…0.15$ um, 
equation (4) if $Ra = 0.02…0.08$ um.

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