Application of quasi-optimal correlation algorithm for surface quality assessment

N V Nosov

1Samara State Technical University, Molodogvardeyskaya str. 224, Samara, Russia, 443100

e-mail: nosov@samgtu.ru

Abstract. The article describes the application of a new approach to assessing the surface roughness of the GTE blade profile after vibration contact polishing. The basis for the calculation of the microgeometry of the surface of the back and the trough of the blades is the average amplitude of the variable component of the autocorrelation function obtained as a result of computer processing of the video image of the surface on the optical-electronic complex. The use of an optoelectronic method for evaluating the microgeometry of the surfaces of compressor and turbine blades allows obtaining the roughness distribution on the surface and the stress concentration coefficient, as well as a more in-depth analysis of the final processing technology.

1. Introduction
Currently, to ensure the necessary operational properties of gas turbine engine parts (GTE), complex technologies based on various physical principles, for manufacturing and for control are used.

A particular attention is given to development of new research areas such as computer-based smart process environments or diagnostic & control systems for figurine-shaped parts. Progress in this area can substantially advance the methodology of GTE surface control.

Development of modern methods and means of surface quality technical control using roughness data (surface microgeometric deviations) obtained with computer-based technologies is one of the greatest challenges of the modern machine building industry.

These guidelines show the best layout for your paper using Microsoft Word. If you don’t wish to use the Word template provided, please use the following page setup measurements.

2. Research objective
One of the most important characteristics of the GTE blade surface quality is a microrelief of its working surface: reliability and durability parameters of many blades depend on a pattern of microgeometric deviations of their working surfaces [1]. It is known that the smoother is the surface, the higher is fatigue resistance of the part; many studies show that fatigue fracture nuclei first appear on the part surface. Surface roughness areas are hotspots of tensions and are one of the reasons for fatigue resistance degradation: tension at the bottom of a groove mark is 2–2.5 times higher than average on the surface layer. Experimental results reveal that roughness decrease from $Ra = 0.74 \, \mu m$ to $Ra = 0.22 \, \mu m$ increases fatigue strength limit of a specimen by 14% on average and prolongs its service life more than three times.
3. Solution method

Creating modern systems of technical quality control and a methodological basis for researching microgeometric deviations of figurine machine part surfaces in production environment via development of an optical electronic information measurement system (IMS) is a challenging issue. This problem includes a number of requirements than modern portable surface microlief measurement devices [2-9] must meet. Such devices must be compact, produce real-time measurement data without physical contact in a production environment, allow digital processing of the produced data and evaluating microlief of figurine surfaces, such as inner cavities of small orifices or working surfaces of molds and dies [10, 11]. Moreover, metrological characteristic of such measurement devices must also be constant regardless of changes in the production environment; finally, the devices must be provided with an energy saving mode.

Existing methods and measurement means of microlief parameters \( \mu_i \) \((i=1, \ldots, r)\) do not allow reducing measurement error below the order of a few tens percent; therefore the objective of this study is development of quality control systems and a methodological basis for research of microlief of figurine surfaces in a production environment using an optical electronic information measurement system (IMS).

4. Theoretical basis

The IMS evaluates the microlief of a studied surface by means of comparing the surface with images of reference surfaces with roughness parameters defined using standard methods [12] and known. As a result, the studied surface is matched with a certain reference surface with a preset recognition probability.

In the original halftone frame of the pixel format \( K_1 \times K_2 \), a strip of width \( N_2 \) in pixels is selected starting from the first line. In the center of this strip is set the standard image size of \( N_1 \times N_2 \) pixels. Then the standard, starting from the extreme left position, moves along the selected strip in increments of 1 pixel. Each time the reference \( u(n_1, n_2) \) and the current fragment \( x(n_1, n_2) \) of the halftone image are combined, the correlation coefficient is calculated.

When the correlation coefficients in the first band are calculated, the next band of the same format but shifted down by one pixel is specified. In this band, a new standard with the same dimensions is set in the center and the same actions are performed, etc. After processing the entire image, a matrix of correlation coefficients \( M_1 \times M_2 \) – a two-dimensional correlation function - will be formed.

The problem in this formulation is solved optimally by means of a two-dimensional spatial filter coordinated with the signal. The output signal will be proportional to the correlation function of the two-dimensional input signal and the maximum signal-to-noise ratio of the filter output will be achieved.

To increase the speed of the calculation program, the analysis of known quasi-optimal correlation algorithms and criterion functions was performed, which showed the prospects of using pair criterion functions and binary images.

5. Experimental results

Profile roughness of turbine 1st stage blade airfoils made without allowance (“ЖС6ФУ” material) after vibratory polishing using a “ЛВП-4” machine was studied. The movement path of a blade during polishing is a result of geometric addition of mutually perpendicular oscillations generated by two crank mechanisms and is shaped as a mesh with controlled parameters, geometrically complex and practically nonreproducible. Such movement path allows creating a uniform microgeometry over the surface of the pressure and suction sides of the blade. Vertical and horizontal oscillation modes directly influence the processing capacity and dynamic loads appearing in the oscillating system. Usually, the oscillation frequency is taken as 20-25 s\(^{-1}\) and the amplitude as 5-10 mm which results in the machining rate of 30–120 m/min.

The machining process simulation has shown the maximum machining capacity is provided by a discrepancy in the proportion of frequencies of figures \( \omega_0 = \omega_h / \omega_v \), where \( \omega_h \) is frequency of horizontal oscillations, \( \omega_v \) is frequency of vertical oscillations. The \( 1/2 \leq \omega_0 \leq 1 \) frequency range was studied. By
setting equal rotation speed of two adjacent figures within ranges: \( B_1 = \frac{1}{2}, B_2 = \frac{3}{5}, B_3 = \frac{2}{3}, B_4 = \frac{3}{4}, B_4 = \frac{4}{5}, B_5 = \frac{5}{6}, B_6 = 1 \), the following dependency is obtained:

\[
\tan \omega_0 = \frac{(\cos B_1 + \cos B_2 + 1)\omega_0 - (B_1 \cos B_1 + B_2 \cos B_2 + 1)}{(B_1 \sin B_1 + B_2 \sin B_2 + 1) - (\sin B_1 + \sin B_2 + 1)\omega_0}.
\]  

(5)

The first part of the equation is a hyperbola, the second one is a tangensoid. By solving this equation for \( \omega_0 \), we obtain the following series of frequency proportions: 0.543, 0.617, 0.704, 0.763, 0.833, 0.917.

In our case, turbine 1st stage blades were machined using \( \omega_0 = 0.833 \) abrasive tapes in two steps: Step 1 П8 63С 16П МА and step 2 П8 63С 6Н МА. Machining modes: polishing rate is 30 m/min, vertical movement range is 4–6 mm, horizontal movement range is 3–5 mm, machining cycle duration is 12–17 s, saddle pressure in the machining zone is 0.4–0.6 МPa.

An optical electronic unit was used to study microgeometry of blade suction and pressure sides. The unit [13] (see figure 1) includes the following components: 1—studied surface, 2—television camera with a CCD sensor, 3—analog to digital converter, 4—memory storage, 5—device for setting window coordinates and sizes for transformation of the input halftone surface image to a binary image as well as for setting reference image size in the binary image, 6—digital computer, 7—device for setting coordinates of the current binary image fragment, 8—correlator and software for processing of video imagery of studied surfaces.

![Diagram of a unit for researching blade surface microgeometry](image)

**Figure 1.** Diagram of a unit (a) for researching blade surface microgeometry (b) of the 1st stage of an aircraft engine turbine.

It is known that surface microgeometric parameters must be uniform over the entire blade surface. Let us agree that uniformity of the surface roughness parameters creates an equiaxial structure and excludes one-directional roughness. For this purpose, an electronic image was rotated by 90°, 180° and 270°, and autocorrelation surface parameters were defined. Matching of their values with a 5% tolerance indicates presence of a certain structure on the blade surface.

Blade surface spots after vibratory polishing were analyzed. Figure 2 shows half-tone and binary images of the selected surface area, a correlation surface and the correlation coefficient change diagram for this area [14, 15].

The surface area format stored in the computer memory was 320×240 pixels in this case. Processing of the experimental results has shown that the average of the variable component of the correlation function calculated for 30 images is \( U_{cp} = 23.1 \) rel. units.

If the studied surface structure (roughness) recognition probability is set to \( P = 0.99 \), the following expression was obtained for the confidence interval:

\[
I_0 = (0.09 \times U_{cp}^3 - 4.2 \times U_{cp}^2 + 68.5 \times U_{cp} - 314.9) \times 10^{-2} \text{ rel. units,}
\]

and for dependency of a structure with roughness of \( Ra = f(U_{cp}) \)—the following expression:

\[
Ra = 0.013 \times U_{cp} - 0.078 \text{ m.}
\]

By inserting the obtained value \( U_{cp} \) into the formula, we find that \( I_0 = 0.77 \) rel. units. Consequently, \( U_{cp_{\text{min}}} = 22.33 \) rel. units, and \( U_{cp_{\text{max}}} = 23.87 \) rel. units. Using the expression for calculation of \( Ra \) of the blade airfoil surface has produced the following results: \( Ra = 0.22 \) m, \( Ra_{\text{min}} = 0.219 \) m, and \( Ra_{\text{max}} = 0.221 \) m. Roughness on the suction side is 15% higher than on the pressure side.
Figure 2. (a) A half-tone image of a blade surface area, (b) a binary image of this area; (c) a correlative surface; (d) correlative coefficient change.

Figure 3 shows roughness fields for roughness of pressure and suction surfaces of a turbine 1st stage blade after vibratory polishing with abrasive tapes in one step П8 63С 16П МА.

6. Conclusion

The study proves that the optical electronic method for evaluation of turbine blade surface quality allows developing surface roughness fields and use them to better analyze the vibratory polishing technology. The research proves that using optimal proportions of vertical and horizontal oscillation frequencies allows creating a uniform surface structure of the blade airfoil profile. The first ever study of surface areas of a turbine 1st stage adjacent to orifices along the entry edge has shown the roughness increases by 1.5–1.7 times around the orifice.

The results obtained are relevant for a number of methods of formation [16-22] and control [23-29] of optical microreliefs in the creation and study of elements of computer optics and diffraction nanophotonics.

Figure 3. Surface roughness fields for a turbine 1st stage blade after the 1st step:
(a) pressure side, (b) suction side.

7. References

[1] Husu A P, Wittenberg U R and Palmov V A 1975 Surface roughness: Probabilistic approach (Moscow: “Nauka” Publisher) (In Russian)

[2] Abramov A D, Nosov N V, Podsekin I A and Voronin V N 2005 Evaluation of surface roughness of optical-electronic method Vestnik of Samara State Technical University. Technical Sciences Series 33 89-94
[3] Ivliev N A, Kolpakov V A, Krichevskii S V and Kazanskiy N L 2017 Determination of Concentration of Organic Contaminants on a Silicon Dioxide Surface by Tribometry Measurement Techniques 60(9) 869-873 DOI: 10.1007/s11018-017-1285-1

[4] Borodin S A, Volkov A V and Kazanskiy N L 2009 Device for analyzing nanoroughness and contamination on a substrate from the dynamic state of a liquid drop deposited on its surface Journal of Optical Technology 76(7) 408-412 DOI: 10.1364/JOT.76.000408

[5] Kazanskiy N L and Popov S B 2010 Machine vision system for singularity detection in monitoring the long process Optical Memory and Neural Networks 19(1) 23-30 DOI: 10.3103/S1060992X10010042

[6] Abul'khanov S R and Kazanskiy N L 2018 Information pattern in imaging of a rough surface IOP Conference Series: Materials Science and Engineering 302 012068 DOI:10.1088/1757-899X/302/1/012068

[7] Whitehouse D J 1994 Metrology of surfaces. Principles of industrial methods and devices (Institute of Physics Pub.)

[8] Kazanskiy N L 2012 Research & education center of diffractive optics Proc. SPIE 8410 84100R DOI: 10.1117/12.923233

[9] Ulker O 2018 Surface roughness of composite panels as a quality control tool Materials 11(407) DOI: 10.3390/ma11030407

[10] Nosov N V, Abramov A D and Khaustov V I 2009 Study of surface roughness bobinowanie rollers on the basis of their autocorrelation functions Vestnik of Samara University. Aerospace and Mechanical Engineering 3-2(19) 45-53

[11] Abramov A D, Zinkovsky A I, Nosov N V, Nikonov A I and Rodionov V A 2011 Determination of surface roughness of the raceways of the bearings of the instrument using quasi-optimal correlation algorithm Izvestia of Samara Scientific Center of the Russian Academy of Sciences 13(4-3) 645-651

[12] Abramov A D and Nosov N V 2016 Estimation of parameters of a microrelief of surfaces of details of machines based on correlation of quasi-optimal algorithms Vestnik komp'iuternykh i informatsionnykh tehnologii 9 19-25

[13] Abramov A D, Nikonov A I and Nosov N V 2006 Method of monitoring article surface roughness The patent RF of Invention N2413179, G01B 11/30 (2006/01), G01N 21/93 (2006/01). Russian Bull of Inventions 6 (27.02.2011)

[14] Abramov A D 2007 Evaluation of the microgeometry of the surface of the GTE blades based on the analysis of their autocorrelation functions Vestnik of Samara State Technical University. Technical Sciences Series 2(20) 117-123

[15] Abul’hanov S R, Skuratov D L and Khaimovich A I 2017 Correlation image analysis of surface roughness Key Engineering Materials 746 296-304

[16] Kazanskiy N L 2018 Modeling diffractive optics elements and devices Proc. SPIE 10774 1077400 DOI: 10.1117/12.2319264

[17] Kazanskiy N L, Uspleniev G V and Volkov A V 2000 Fabricating and testing diffractive optical elements focusing into a ring and into a twin-spot Proc. SPIE 4316 193-199 DOI: 10.1117/12.407678

[18] Kazanskiy N L, Kolpakov V A and Kolpakov A I 2004 Anisotropic etching of SiO2 in high-voltage gas-discharge plasmas Russian Microelectronics 33(3) 169-182 DOI: 10.1023/B:RUMI.0000026175.29416.eb

[19] Abul'khanov S R, Kazanskiy N L, Doskolovich L L and Kazakova O Y 2011 Manufacture of diffractive optical elements by cutting on numerically controlled machine tools Russian Engineering Research 31(12) 1268-1272 DOI: 10.3103/S1068798X11120033

[20] Bezus E A, Doskolovich L L and Kazanskiy N L 2011 Interference pattern formation in evanescent electromagnetic waves using waveguide diffraction gratings Quantum Electronics 41(8) 759-764 DOI: 10.1070/QE2011v041n08ABEH014500

[21] Kazanskiy N L, Stepanenko I S, Khaimovich A I, Kravchenko S V, Byzov E V and Moiseev M A 2016 Injectional multilens molding parameters optimization Computer Optics 40(2) 203-214 DOI: 10.18287/2412-6179-2016-40-2-203-214
[22] Kazanskiy N L, Moiseev O Yu and Poletayev S D 2016 Microprofile formation by thermal oxidation of molybdenum films *Technical Physics Letters* **42**(2) 164-166 DOI: 10.1134/S1063785016020085

[23] Doskolovich L L, Golub M A, Kazanskiy N L, Khramov A G, Pavelyev V S, Seraphimovich P G, Soifer V A and Volotovskiy S G 1995 Software on diffractive optics and computer generated holograms *Proceedings of SPIE* **2363** 278-284 DOI: 10.1117/12.199645

[24] Karpeev S V, Pavelyev V S, Khonina S N, Kazanskiy N L, Gavrilov A V and Eropolov V A 2007 Fiber sensors based on transverse mode selection *Journal of Modern Optics* **54**(6) 833-844 DOI: 10.1080/09500340601066125

[25] Golovashkin D L and Kasanskiy N L 2011 Solving diffractive optics problem using graphics processing units *Optical Memory and Neural Networks* **20**(2) 85-89 DOI: 10.3103/S1060992X11020019

[26] Bezus E A, Doskolovich L L and Kazanskiy N L 2014 Low-scattering surface plasmon refraction with isotropic materials *Optics Express* **22**(11) 13547-13554 DOI: 10.1364/OE.22.013547

[27] Egorov A V, Kazanskiy N L, Serafimovich P G 2015 Using coupled photonic crystal cavities for increasing of sensor sensitivity *Computer Optics* **39**(2) 158-162 DOI: 10.18287/0134-2452-2015-39-2-158-162

[28] Kazanskiy N L and Kolpakov V A 2017 *Optical materials: Microstructuring surfaces with off-electrode plasma* (CRC Press)

[29] Poleschchuk A G, Korolkov V P, Nasyrlov R K, Khomutov V N and Konchenko A S 2016 Methods for on-line testing of characteristics of diffractive and conformal optical elements during the manufacturing process *Computer Optics* **40**(6) 818-829 DOI: 10.18287/2412-6179-2016-40-6-818-829