Electrooptic estimation of texture parameters of precision surfaces

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Abstract: We have developed a method of high-precision texture analysis of machined surfaces. We used the methods of autocorrelative processing of images of rough surfaces and the methods of computer-based optics for the analysis. We carry out the analyzed surface microrelief recognition by comparing the analyzed texture with the reference texture. In this study we determined the variation in the parameters of reflected light flux with respect to its luminous power and the angle of incidence on a rough surface. We detected considerable change in parameters of light flux using video signal. In accordance with the Russian standards, these changes are characterized with the influence function. We determined the following: the influence function has a multiplicative character. To minimize the influence function, we suggest to use a hardware tool that implements the proposed method of texture analysis. The hardware calculates the functional of the analyzed surface and the functional of the reference surface. We suggest to determine the resemblance of the analyzed surface and the reference surface based on the ratio of the said functionals. We believe that this approach allows to simplify the control and measurement instrumentation for texture recognition.

The authors of works [1-14] used the texture analysis for computer processing of images of surfaces of various nature. The problem of analyzing the surface textures is known in the study of roughness, contaminants and deviation of optical surfaces [1-3], in forensics [4-5], in medicine [6-7], in materials science [8-14] and in other areas of human activity. Various heuristic and mathematical criteria and methods are introduced to classify and evaluate various surfaces and their deviations [1-18].

The increase in the accuracy of manufacturing of machinery components brings new requirements of surface roughness control. In our opinion, contactless control methods should be used for analyzing the roughness of small or large components. In mass production, the most acceptable method of roughness control is the analysis of a microroughness image. We analyzed a raster image of the surface or a video stream of changes on the rough surface as an image of the rough surface.

We believe that a 3d model of texture shall be reproduced to analyze textures of machined surfaces. The authors of certain works used a time-series model [16], a cellular model [15], syntactic models [17], two-dimensional models of random Markov field [18], etc. to reproduce the three-dimensional model of surfaces.

We did not find the sources of information, where the texture of machined surfaces of high accuracy was analyzed. This fact indicates that the surface textures formed by technological impact are not studied sufficiently. We suggest to carry out the recognition of a rough surface texture based on the correlation analysis using the image of the surface.

The purpose of the article: to develop a method for controlling the texture of machined surfaces of high accuracy. The application of the method developed allows to increase the reliability of control of.
rough surfaces of mass production components and create hardware for contactless recognition of the texture of surfaces of various nature.

2. Research Objective
The methods for controlling the surface roughness are divided into contact and contactless. Many national standards state that roughness control should be based on a profilogram (cross-section) of a rough surface. We believe that such control leads to losing the information on the nature of microroughnesses (texture). By its nature, roughness is a three-dimensional object, and a profilogram is a two-dimensional object.

In the works [19-21], the authors suggest to control the surface texture by means of entropy, fractal, and spectral analysis. We believe that these methods are complicated in terms of hardware implementation. For this reason, the use of such equipment for mass production is difficult or impossible.

Based on the analysis of production practices, we determined the following:
- it is relevant to use a contactless method to control the surface texture under the mass production conditions;
- it is advisable to use the raster image of a surface formed by technological impact to control such surface;
- statistical analysis of a halftone image of surface texture is the most informative for the technological application.

For the above reasons, we have developed an optical contactless method to control the surface texture. We believe that it is necessary to compare the analyzed texture and the reference texture of surfaces to control the texture of machined precision surfaces. We use correlation filtration to compare the two textures. This approach allows to analyze the surface texture in the places where other methods of roughness control measurement cannot be applied.

The texture control method developed by us has an algorithm that can be implemented on a microcomputer and built into an automated control system.

We believe that the hardware implementation of the suggested method is particularly in demand when controlling the surfaces of diffraction elements [11, 15, 22-32].

3. Procedure
We used a Smart Vision measuring microscope to carry out the surface texture analysis [33]. The microscope is equipped with a computer. In our research we used a black and white video camera DIGITAL CAMERA Computar ZC-F11CH3.

The luminous flux was formed by an incandescent lamp with the power \( P = 60 \text{ W} \). We adjusted the luminous power by changing the voltage \( U_{\text{max}} = 36 \text{ V} \) supplied by a stabilized constant-voltage source. We measured the illumination of the surface analyzed with a Yu-117 luxmeter (LLC "Zapadpribor", Russia). When measuring, we set the luxmeter perpendicular to the incident light. The area of the luminous spot on the surface of the luximeter was \( S = 0.00126 \text{ m}^2 \). The luminous flux had a power of \( 600 \times 10^{-3} \text{ lm} \).

For our research we used samples of reference surfaces with different texture made of a heat-resistant alloy. The roughness parameter \( R_a \) was determined for the said samples using a SJ-201P profilograph (produced by Mitutoyo): sample No. 1: \( R_a = 0.13 \mu m \), sample No. 2: \( R_a = 0.084 \mu m \), sample No. 3: \( R_a = 0.048 \mu m \), and sample No. 4: \( R_a = 0.025 \mu m \).

The image of the analyzed and the reference surfaces had the size 320 × 240 pixels. The luminous flux fell onto the analyzed surface at an angle of 45°.

4. Insights
Black-and-white images of the analyzed surfaces are shown in Fig. 1. In this case the Sample 1 with the highest roughness after surface grinding shows a vertically-oriented texture in the form of black and white stripes.
Figure 1. Video images of the analyzes samples.

The orientation of black and white components is less evident in the surface structure of the Sample 2 with lower roughness as compared to the Sample 1. The presence of relatively distinct stripes on the image can indicate the dominating impact of a regular (periodic) component. The Samples 3 and 4 had lower roughness, they do not have scratches oriented in any direction. This indicates the influence of the stochastic component on the formation of texture of these surfaces.

We should point out that 3 bytes were allocated for each pixel in the video images of the surfaces. Therefore, when using a black and white video camera Computar ZC-F11CH3, the information is redundant. Therefore, at this stage of the research, the original halftone image of the surface was transformed into the 1 pixel - 1 byte format.

In our case, the video signal range in terms of brightness B in the resulting image was 0 - 255 relative units. At the same time, we calculated the following characteristics of the surface image: the average value of video signal over the whole frame of the halftone image of the surface - $V_{av}$, the average amplitude of variable component of video signal - $U_{av}$, and the average period of video signal variation - $T_{av}$ at the $V_{av}$ level. The results of the research are shown in Fig. 2.

Figure 2. Variation in the average amplitude of variable component of video signal with respect to the reference luminous power $F_r$ for the surfaces with various roughness: 1 – $R_a = 0.13 \ \mu m$, 2 – $R_a = 0.084 \ \mu m$, 3 – $R_a = 0.048 \ \mu m$, 4 – $R_a = 0.025 \ \mu m$.

The analysis of video signals showed that the most significant effect on the surface texture is produced by the variable component of signal $U_{av}$, which decreases significantly as the surface becomes less rough. Therefore, it can be used for the most accurate identification of different textures.

The analysis shows that when a luminous flux $F_r$ increases from $100 \times 10^{-3}$ to $300 \times 10^{-3} \ \text{lm}$, $U_{av}$ changes more rapidly, especially for the surface with $R_a = 0.13 \ \mu m$ (chart 1 of Fig. 2). As the surface becomes less rough this parameter changes less considerably. As the luminous flux $F_r$ increases further from $300 \times 10^{-3} \ \text{lm}$ to $1100 \times 10^{-3} \ \text{lm}$ the value $U_{av}$ changes slightly. We shall note that in this case the function of luminous flux $F_r$ transformation into the output value $U_{av}$ depends both on the luminous power and the surface roughness parameters, that is, $U_{av} = f(F_r, R_a)$.

Let us take the value $F_{r \ n} = 600 \times 10^{-3} \ \text{lm}$ as the nominal value of a luminous flux, $F_{r \ min} = 200 \times 10^{-3} \ \text{lm}$ as a minimum value, $F_{r \ max} = 1000 \times 10^{-3} \ \text{lm}$ as a maximum value. The chosen range of values corresponds well to the working values of a luminous flux which can be observed in practice under production conditions. Changes in the luminous flux can occur for various reasons:
In this paper we suggest a method of error correction, which involves using the ratio of two leads to errors of up to 150% in determining the texture height parameters. When the luminous power varies, a change in the angle of incidence of the light flux from 10° to 80° can lead to errors in determining the height parameters of the analyzed texture that can reach 54%.

The realization of the equation (1) does not lead to an increase in the size of the hardware system. The task of identifying a two-dimensional video signal is solved using a two-dimensional spatial filter matched to the signal. The filter response follows the equation:

$$\frac{G_1(U_{\delta i}(X_{\mu i}))}{G_2(U_{\delta i}(X_{\mu i}))}, \quad i = 1, \ldots, r. \quad (1)$$

In this ratio the same multiplicative components of the numerator and denominator $f_{infl}(\Delta F, \Delta \alpha)$ are cancelled.

The realization of the equation (1) does not lead to an increase in the size of the hardware implementation of the method, since the same set of values $U_{\delta i}$ will be used in the functionals.

We assumed that the input image of the analyzed surface $x(n_1, n_2)$ is processed by a linear discrete system. The task of identifying a two-dimensional video signal is solved using a two-dimensional spatial filter matched to the signal. The filter response follows the equation:

$$y(n_1, n_2) = \sum_{k_1=-\infty}^{\infty} \sum_{k_2=-\infty}^{\infty} u(k_1, k_2) \cdot x[k_1 - (n_1 - n_{01}), k_2 - (n_2 - n_{02})]. \quad (2)$$

The equation (2) is a two-dimensional convolution of the signal $u(k_1, k_2)$ and the impulse response of filter $x[k_1 - (n_1 - n_{01}), k_2 - (n_2 - n_{02})]$. The impulse response of filter is derived from the expected two-dimensional signal by its direct reflection with respect to coordinate axes $n_1$ and $n_2$ and the reflected signal bias in the direction of the original signal to $n_{01}, n_{02}$ readings. The output signal $y(n_1, n_2)$ shall be proportionate to the autocorrelation function of a two-dimensional input signal. The maximum signal-to-interference ratio will be reached at the output of the filter.

A strip with the width of $N_2$ pixels is allocated in the original halftone picture with the size of $K_1 \times K_2$ pixels. In the center of this strip, a reference is defined with a size of $N_1 \times N_2$ pixels. Then the reference moves from left to right along the dedicated strip in steps of 1 pixel. Upon each alignment of the reference $u(n_1, n_2)$ and the current fragment of the halftone image $x(n_1, n_2)$, the correlation coefficient is calculated according to the formula (3).

$$r_{xy}(k_1, k_2) = \frac{\sum_{n_1=0}^{N_1-k_1} \sum_{n_2=0}^{N_2-k_2} (u(n_1, n_2) - m_u)(x(n_1-k_1, n_2-k_2) - m_x)}{\sigma_1 \sigma_2}, \quad (3)$$

where $(n_1, n_2)$ are the indexes of the elements in the reference window, $(k_1, k_2)$ are the coordinates of the reference inside the search area $K_1 \times K_2$, and $\sigma_1$ and $\sigma_2$ are the mean-square deviations of the values $u(n_1, n_2)$ and $x(n_1, n_2)$ from the mathematical expectations $m_u$ and $m_x$ correspondingly.

After calculating the correlation coefficients in the first strip, the next strip is defined with the same format as the previous one, but lowered by one pixel. In the centre of this strip, a new reference with the same dimensions as the previous one is defined, and the same actions are performed, etc. After the processing of the entire image, a matrix $M_1 \times M_2$ of the correlation coefficients or a two-dimensional autocorrelation function will be generated in the memory. If we analyze the equation (6), we can note that its numerator and denominator are the sums of the products of the signals $x(n_1, n_2)$ and...
\( u(n_1, n_2) \). Consequently, these signals will be subject to the multiplicative impact of the influence function \( F_{infr}(\Delta F, \Delta \alpha) \).

As we can see from the above equation, its structure corresponds to the structure of the equation (1) and the influence functions are cancelled. Consequently, the function (4) can be considered as a special case of the ratio (1) and assert that it has the required compensation property for eliminating the additional error that arises when estimating the microrelief parameters based directly on the video signal, and does not require any additional equipment.

As can be seen from the above equation, its structure corresponds to the structure of the equation (1) and the influence functions are cancelled. Consequently, we can consider that the function (4) is a particular case of the equation (1) and assert that it has the required compensation property for eliminating the additional error that arises when estimating the microrelief parameters based directly on the video signal, and does not require any additional equipment. For the empirical support of the theoretical assumptions on the compensation of the influence function by mathematical methods, the influence of the luminous power on the texture parameters of the analyzed samples was studied. The results of the studies are shown in Figures 3, 4.

**Figure 3.** Variation in the average amplitude of autocorrelative function with respect to the reference luminous power \( F_r \) for the surfaces with various texture: 1 – \( Ra = 0.13 \mu m \), 2 – \( Ra = 0.084 \mu m \), 3 – \( Ra = 0.048 \mu m \), 4 – \( Ra = 0.025 \mu m \).

**Figure 4.** Variation in the average amplitude of autocorrelative function with respect to the angle of incidence of the reference luminous power \( F_r \) for the surfaces with various texture: 1 – \( Ra = 0.13 \mu m \), 2 – \( Ra = 0.084 \mu m \), 3 – \( Ra = 0.048 \mu m \), 4 – \( Ra = 0.025 \mu m \).

The analysis of the results obtained shows that the application of the optoelectronic method together with the correlative processing of images and the analyzed precision surfaces eliminates the multiplicative error that arises as a result of the change in the parameters of the luminous flux by a purely mathematical method without using any additional measuring equipment.

5. Conclusion
Our research has shown the following:

1. The developed method for controlling the surface texture of machinery components showed high sensitivity to surfaces with different roughness.
2. The developed method for controlling the surface texture showed high stability in relation to the multiplicative error. This fact increases the reliability of the control.
3. Hardware implementation of the developed algorithm of the control method is characterized by small computational costs. This fact allows to use the developed method in mass production of mechanical engineering.
4. The proposed method controls the texture on the basis of a black and white image of the surface. This fact reduces its capabilities in controlling structural changes on the surface (burn mark) or in controlling biological surfaces.
5. The proposed method can be recommended for controlling the grooves of bearing rings, as well as for controlling the optical diffraction elements.
6. References

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