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Method for studying shape of cutting tool by light field recorder

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***Abstract*—A technique for controlling the shape of the surface and the defects of the cutting tool by an optoelectronic system of the light field is proposed. The physical and information models of the optical-electronic light field recorder, the mathematical model of the edge of the cutting surface of the tap, which allow one to construct the optimal optical scheme for image registration and create algorithms for determining the deviation of the tool shape from the reference profile by wavelet analysis and frequency-coordinate transformation are considered. It is shown that the use of frequency-coordinate transformation algorithms allows determining deviations of geometric shapes of working surfaces, detecting local defects less than 1% of the height of the profile of the cutting part of the tool.**

Keywords—cutting tool; threading tap; shape of the surface; light field recorder; wavelet analysis; continuous wavelet transformж; CWT; frequency-coordinate analysis.

I. INTRODUCTION

Development of new cutting tool technologies, study of their performance characteristics are a very urgent task. Traditional methods of cutting tool geometry do not provide sufficient information. Control of deformation of the shape and defects of the tool is the main part of the development of new production technologies and the introduction of cutting tools.

Optical methods allow controlling all constructive characteristics of the shape of the cutting tool. However, they do not provide high accuracy of surface deformation control against the background of the three-dimensional geometry of the tool. At the same time, optical methods can provide high performance control.

New optoelectronic systems, based on the registration of the total number of beams (light field), coming from the object of control in different distributions, make it possible to realize the control of the shape and surface defects of three-dimensional objects, to eliminate the influence of the basic distortions of the introduced optical system.

Currently, a number of companies developed registrars with light field: «Raytrix», «Lytro Inc.», «Sony Corporation», «Samsung», and others. It is known that the properties of light field recorders can be effectively used to determine the geometric properties, surface geometry and its quality (Patent of the firm "Apple.Inc." No. US 2016 / 0063691A1 «Plenoptic cameras in manufacturing systems»). The use of such recorders to study the quality and deformations of the cutting tool has not been previously carried out. Applying this approach to controlling the deformations of the cutting tool will improve the efficiency of industrial monitoring of tool exploitation and provide the necessary base for the development and research of new cutting tool technologies.

II. PURPOSE OF RESEARCH

The purpose of this paper is to investigate the possibility of applying the method of recording the light field for the accurate determination of the characteristic deviations of the working profile and the presence of surface defects.

III. RESEARCH

Taps were used as an object of research. Improvements in the quality and accuracy of thread tapping after their magnetic abrasion, the appearance of deformation of the surface of the cutting edges and the appearance of defects on them have been investigated [1].

To investigate the shape and defects of the tap, an optical light field recorder from Lytro Inc. was used. [2]. Figure 1 shows the physical and information model of the optic-electronic system for monitoring the tap surface by the method of recording the light field, which reflects the geometric parameters of the shape and topography of its surface. The initial information field (I_0) of the light field is formed by the interaction of the beam beams of the lighting system *1* (L_0) with the surface *2* ($S(x, y, z)$) of the monitored object:

$$I_0(\overrightarrow{L_1}) = \vec{L}_0 \otimes S(x,y,z)\,, \tag{1}$$

where $\vec{\boldsymbol{L}}_1 = \sum L_i(x,y,\vartheta,\varphi)$ is the collection of all light rays reflected from the surface of the object.

The method for describing the rays of light field $\vec{\boldsymbol{L}}_1$, which is used in the registrars of the firm "Lytro Inc." [3], consists in indicating the coordinates of rays' intersections of two planes: The plane of the rear wall of the main lens (***H***) and the plane of the photodiode array (***M***). The coordinates of any ray $L_i(x, y)$ and the direction of its motion (ϑ,φ) are determined by the coordinates of the ray intersection of these planes $\boldsymbol{H}(u,v)$ and $\boldsymbol{M}(s,t)$: $\vec{L}(x,y,\vartheta,\varphi) \equiv \vec{L}(u,v;s,t)$. The light field in the plane of the matrix photo detector (M) describes the integral energy brightness of points in space, related to the intensity and directions of the rays from these points.

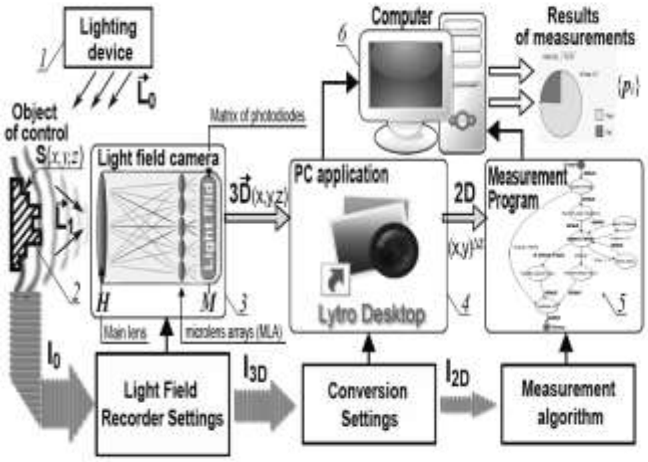

Fig.1. Information model of the optoelectronic system for recording the light field: *1* – lighting system; *2* – object of control; *3* – the recorder of a light field; *4* – conversion program; *5*– measurement program; *6* – computer

The optical system of the light field recorder forms a file with the information structure of the 3D image Im_{3D} (x, y, z) ($I_{3D} \subset I_0$). The information field of the given 2D image (I_{2D} (x, y)) is generated by the algorithms of the application "LytroDesktop" from the information field of the 3D light fixture file (I_1=I_{3D}) based on the 4-dimensional Fourier transform [3]. On the other hand, the information field determines I_{2D} layer remote distance z, displayed at a predetermined depth space Δz:

$$I_{2D(z)}^{\Delta z}(x,y) = \Re(I_1)\,, \qquad (2)$$

where $\Re$ is the light field transformation functions.

The complete algorithm for the formation of two-dimensional images ($\Re$) is determined by a number of functions that determine the formation of a given histogram in the illuminance channels, taking into account the redundancy of ADCs of photodetectors in the represented image format.

The optical system of the light field recorder *3* forms a file with the information structure of the *3D* image ($I_{3D} \subset I_0$). The information field I_{2D}(x, y) of the selected layer is set by the parameters of the light field conversion algorithm according to the LytroDesktop application *4* in a *2D* image (I_{2D}=I_{3D}) based on the four-dimensional Fourier transform.

A plane image of the light field is obtained by means of integrating the signals from the photodiodes under the microlenses. Digital refocusing is determined by the choice of the method of summable signals from the photodiode sections under each microlens.

Thus, the method of recording the light field has invariance with respect to the change in the uncontrolled conditions for recording images, on the one hand, and, on the other hand, it provides the advantageous aspects of the methods of morphological analysis of images, including the coordinate of the height of the surface profile (OZ) [2].

To control the shape and quality of the tapped surface, an optoelectronic system, based on the Lytro Illum light-field digital camera (B5-0036) [2, 3], was used. Figure 2a shows a model of the experimental setting for recording the light field of taps, Figure 2b shows the algorithm for obtaining the information component of the monitored parameters.

Dominant information components of control of local defects and features of the geometry of the working surface $\{p_i\}$ are obtained by the following application of measuring algorithms (Fig. 2, b). In each layer of space, at a given distance and depth (z, Δz), one can display the geometric parameters of the shape of the control object.

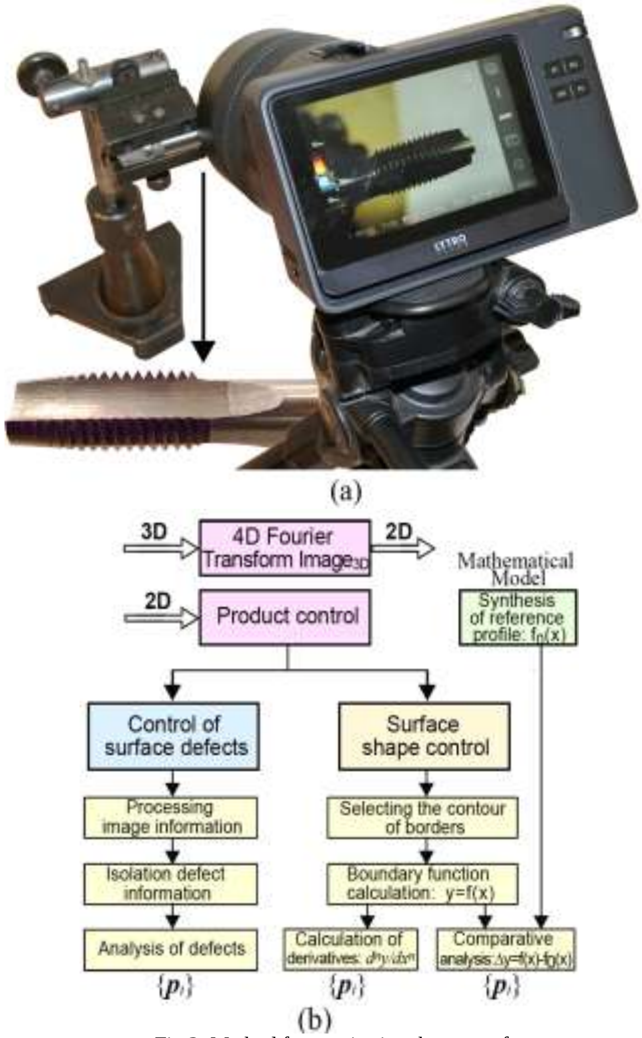

Fig.2. Method for monitoring the tap surface: (a) image registration; (b) algorithm for measuring surface deformation

Evaluation of the accuracy of production and the appearance of operational deformations and defects requires the creation of a mathematical model of the tool, taking into account possible defects. A computer model describes the algorithm for creating a three-dimensional surface of a tool (Fig. 3, a). Comparison of the computer model and the physical model with the obtained light field recorder (Fig. 3, b) defines the basic information signs of measured deformation of the tool.

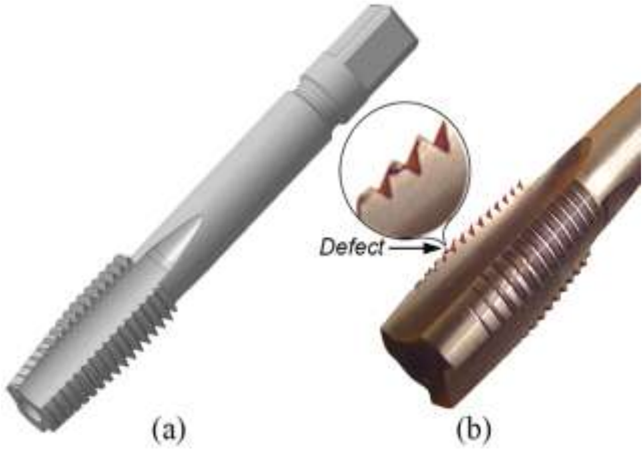

Fig.3. Optical tap model:
(a) Computer three-dimensional model of the tap surface; (b) The physical surface from the light field recorder

To obtain the accuracy of measuring linear dimensions, the optical system was calibrated [4]. The theoretical features of the calibration of light field chambers are considered in [5]. Practical questions of calibration are considered in [2].

The profile function of the cutting edge of the tap was obtained from the converted 2D image by isolating the image of its contour curve. To convert the contrast of the image $\mathrm{Im}_0(x,y)$ to the curved path of the maximum contrast path ($\mathrm{Im}_P(x,y)$), two different algorithms are used. In the first case, the difference between the two scaled images:

$$\mathrm{Im}_P = \beta_1\{\mathrm{Im}_0\} - \beta_2\{\mathrm{Im}_0\}. \quad (3)$$

The scale transformation ratio was set by changing the resolution of the original image $\mathrm{Im}_0(N\mathrm{x}M) \rightarrow \mathrm{Im}_1(N_1\mathrm{x}M_1)$, where $\beta_1=N_1/N$. In the second case, the image filtering function is used.

The most well-known methods of isolating the line of image contours by filtration methods [6] are Laplacian, Prewitt, Sobel, Roberts, Canny:

$$\mathrm{Im}_P = Filter\{\mathrm{Im}_0\}. \quad (4)$$

Studies have shown that scale transformations of a sharp image with a volumetric texture give a significant error in determining the structure of the boundaries, while filters (Laplacian, Prewitt, Sobel) can reflect the boundaries of the edge zone.

The contour image was digitized by a special program [7, 8]:

$$\mathrm{Im}_P(x,y) \rightarrow \{y_i=f(x_i)\}_{i=1,\mathrm{N}}. \quad (5)$$

In the digitization algorithm, the authors used the method of determining the coordinates of the profile function $y=f(x)$ along the maxima of the continuous wavelet transform (CWT) [9] curves in the obtained discrete sample (5) in the image profile lines:

$$y_i = \max(CWT^w\{g_j(y_i)_{\mathrm{j=1,M}}\}), \quad (6)$$

where $g_j(y)= \mathrm{Im}_P(x_i,y)$, CWT^w is a continuous wavelet transform for a given type of wavelet w, which ensures better allocation of the information component.

Experimental studies have shown that good digitization of the curves in the image is achieved, using the following types of wavelets: «bior 3_1», «Hear». «Mexican Hat», and some others. Justification of the method for choosing the type of the wavelet is described in [10].

The filtering functions extract not only the image of the boundary curve, but also the surface relief (Fig. 4 c). Taking into account the filtering properties of different types of wavelets, one must experimentally select the types of wavelets in the process of digitizing the image. Studies have shown that the accuracy of determining the y coordinate by the method of determining the CWT^w maxima for weakly localized contour curves can reach 0.3 pixels.

Algorithms for image processing, surface design (Figure 3) were developed in the application of National Instruments (NI) - Vision Assistant (Fig. 4, a-d), followed by the creation of a virtual instrument (VI) in the NI LabVIEW development environment.

Methods of estimating the accuracy of manufacturing and operational deformations and emerging local defects presuppose a mathematical model (Fig. 3, b) of the tap body, taking into account the specification of possible characteristic defects (Fig. 4, a-d).

The mathematical model of the tap must be represented by functions that describe simple geometric shapes that take into account the technological operations of manufacturing and operating the tool. Additive representation in the mathematical model of the shape of the tap and perturbing factors simplifies the subsequent analysis of deformations and surface defects. The profile function of the tapping part can be described as follows:

$$y = f(x) = f_1(x) \otimes f_2(x) + f_3(x) + f_4(x), \quad (7)$$

where $f_1(x) = \Pr(x,s,A)$ is the main function of the tapping profile, $f_2(x)$ is the profile change function along the tool length, $f_3(x)$ is the distributed distortion function of the tap profile, $f_4(x)$ is the local profile defect function.

The profile function is defined by a trapezoidal periodic function that provides the specified pitch, height and profile angle:

$$f_{10} = \sum_{k=1}^{K} tri\left(\frac{x}{b} - k \cdot S\right); \quad tri(x) = \begin{cases} 1-|x|, & |x|<1 \\ 0, & |x|\geq 1 \end{cases}. \quad (8)$$

The function of the tapping profile is determined by the specified trapezoid parameters (p_{up}, p_{down}):

$$f_1(x)=\begin{cases} f_{10}(x), & f_{10}(x)<p_{up}, \quad f_{10}(x)>p_{doun} \\ p_{up}, & f_{10}(x)\geq p_{up} \\ p_{doun}, & f_{10}(x)\leq p_{doun} \end{cases}. \quad (9)$$

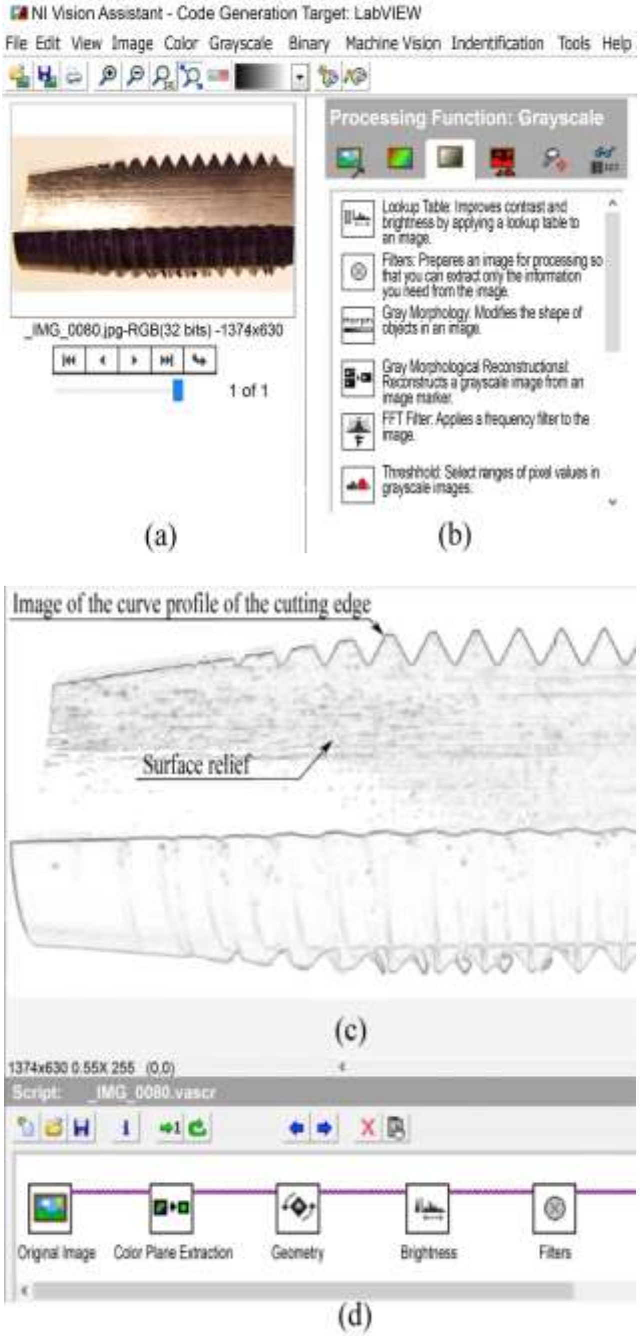

Fig.4. Isolation surface shape contour:
(a) The original image; (b) Function Palette;
(c) Dedicated contour curves; (d) Script (algorithm) for extracting the contour curve

The function of the profile shape is determined on the basis of the initial function $f_1(x)$ and the specified function for changing the profile along the length $f_2(x)$:

$$f_S(x)=f_1(x)\otimes f_2(x)=\begin{cases} f_1(x), & f_1(x)<f_2(x) \\ f_2(x), & f_1(x)\geq f_2(x) \end{cases}. \quad (10)$$

The definition of the distributed distortion of the profile $f_3(x)$ and the definition of local defects $f_4(x)$ are of interest. The distributed distortion profile is an asymmetric periodic function having such properties as convexity, pits or inflection.

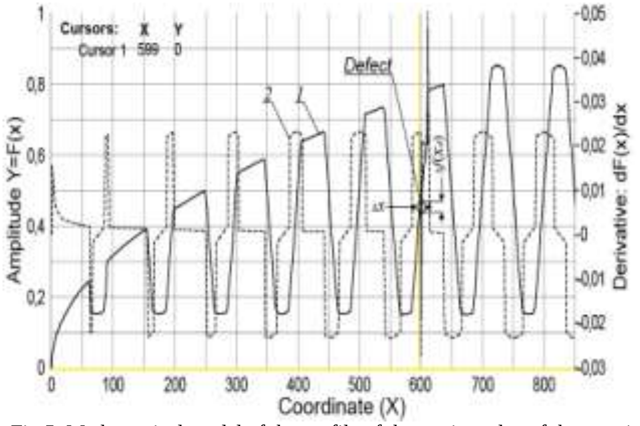

Fig.5. Mathematical model of the profile of the cutting edge of the tap: *1* - Profile boundary function; *2* - The first derivative of the profile boundary function

The profile of the cutting edge of the tap according to the presented mathematical model is shown in Figure 5 (Plot 1). On the lateral side of the tap profile, a given local defect with a relative amplitude of $\Delta f(x_d)/f(x_d)=0.02$, $\Delta x=2$ pixels in length, was created at the point (Cursor 1). The criterion for the deviation of the shape of the surface from the given and the presence of defects is the behavior of the first and second derivatives of the profile function (Plot 2).

The main criterion for the deviation of the shape of a surface from a given surface and the presence of its local defects is the behavior of the first and second derivative functions of the profile. However, for digitized images, this approach has a high error and low reliability. It is obvious that simple mathematical methods of its analysis, including spectral analysis methods, do not have the necessary sensitivity to small perturbations.

However, for digitized functions having small short distortions, this approach has a high error. At present, a more accurate method of differentiation based on wavelet transforms is known [11]. Earlier it was shown that this approach makes it possible to determine more accurately not only the first derivative of the function, but also the second derivative (the form of the inflection of the function) [10].

There are mathematical methods that allow one to distinguish the dominant information component of such functions: wavelet analysis methods (WA) [12], the methods of joint time- frequency analysis (JTFA) [13], integral transformations, for example Hilbert and Hilbert Huang. The JTFA method includes the following main spectrograms: STFT Spectrogram, Gabor Spectrogram, Adaptive Spectrogram, Wigner-Villi Distribution, Choi-Villiams Distribution, Cone Shaped Distribution.

A study of the Gabor transformation (Fig. 6) is performed to analyze the distributed and local features of the surface profile. The Gabor transform allows choosing the frequency and spatial resolution, the spectral window.

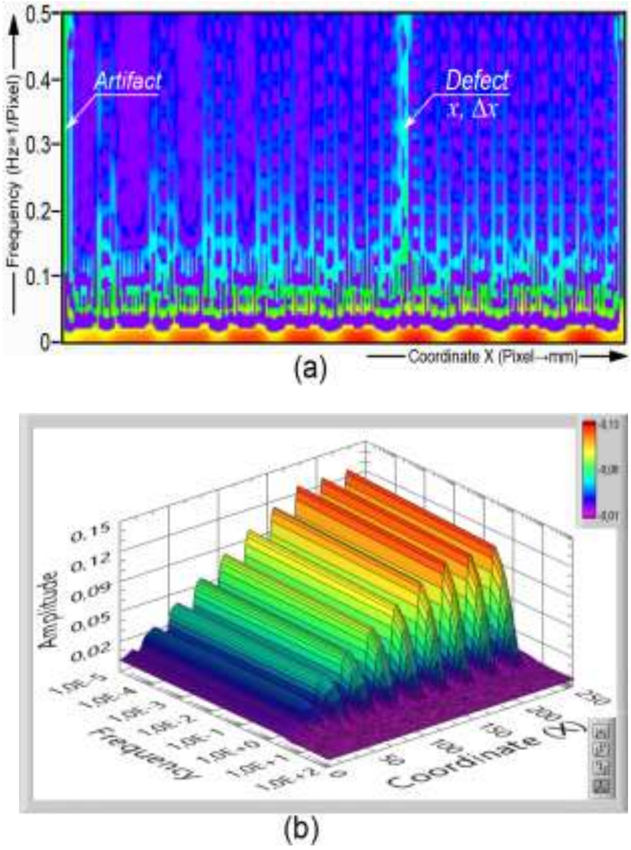

Fig.6. Gabor spectrogram profile tap function:
(a) graph of intensity; (b) 3D graph of the spectrogram

Figure 6 shows that the Gabor spectrogram of the profile of the product reflects the position and character of the given local defects of the profile (Fig. 6, a). The spectrograms of the product profile function show all the characteristic features of the profile change along the length (Fig. 6, b).

A comparative analysis of layers of images of the light field provides more opportunities for highlighting the information component of the controlled volumetric parameters of the product surface. The process of converting the source file of the light field makes it possible to select arbitrarily layers of different thicknesses Δz at different distances z from the optical system $\mathrm{Im}(z,\Delta z)$. This makes it possible to isolate and analyze various information components of the bulk structure of the surface. To determine the volume parameters is the various correlation functions of different layers, of different thickness (by analogy to the methods of interference of wave fronts) located at different distances along the depth of space (Z axis). Correlation functions can be implemented by binary functions of morphological analysis (M) of specified image layers

$$\mathrm{Im}(z_1 \because z_2) = \mathrm{Im}(z_1,\Delta z_1) \overset{\mathrm{M}}{\bigotimes} \mathrm{Im}(z_2,\Delta z_2) \qquad (11)$$

In addition to the analysis of the shape and topography, you can use the surface layer transformation function

$$\mathrm{Im}_{\aleph}(z_1 \because z_2) = \aleph_1\{\mathrm{Im}(z_1,\Delta z_1)\} \overset{\mathrm{M}}{\bigotimes} \aleph_2\{\mathrm{Im}(z_2,\Delta z_2)\}, \qquad (12)$$

where $\aleph_1$ and $\aleph_2$ are the rotation and scaling of surfaces

The morphological functions of the NI Vision Assistant (Color Operation) application allow performing the following binary operations on image layers: «ADD», «Subtract», «Multiply», «Divide», «Multiply Divide», «Modulo», «Absolute Difference», «AND», «Not AND», «OR», «Not OR», «Exclusive OR», «Not Exclusive OR», «OR Logical Difference». The morphological operation "Modulo" to two selected layers of the light field image distinguishes micro features of the surface shape, and the "Not AND" operation of the macro features of the surface shape. Thus, the processing of layers of a three-dimensional image, allows you to get the information structure of the shape of the surface of the product. The choice of layers of the three-dimensional image Im(z, Δz) and morphological operations is based on experimental studies. Further, with the chosen parameters of the layers, the deformation of the tool surface during operation was carried ou.

Studies have shown that the shape of the surface is determined not only by the resolution of the layers of focused images, but by the set of recorded reflected rays in the direction of their propagation. The latter fact provides a much higher sensitivity to surface defects having different ability to scatter beams.

Comparison of the studies carried out with the data on the study of the creation and operation of the cutting tool [14-16] showed that the proposed procedure has great accuracy and reliability in determining the deformation of the tool surface, the appearance of defects in the cutting profile. Therefore, this technique can be used to determine the modes of operation of the instrument.

IV. CONCLUSION

The method of recording the light field makes it possible to obtain more complete information about the form and defects of a controlled product of complex shape that does not depend on changes in image registration conditions and distortions, introduced by the optical system.

Studies have shown that the image of the light field allows one to measure the geometric dimensions of the shape of the product with an accuracy of 2 times greater than that of optical systems with a matrix of photodiodes of the same size.

It is shown that the structure of the image of the light field makes it possible to use the method of high-precision comparison of the product profile with a mathematical model by methods of mathematical analysis, based on integral transforms, for example, time-frequency analysis.

It is shown that to obtain informational characteristics of the surface of the cutting tool, one can use the methods of morphological analysis of layers of a three-dimensional image, obtained from a light field recorder. Studies have shown that the use of the principle of registration of the light field allows for precise control of the surface topology of the products, including relief, micro defects and roughness. The possibility of determining the technological features and defects in the technological processing of the surface of the cutting tool is shown.

REFERENCES

[1] Yu.M. Baron. «Magnetic Abrasive Processing». Moscow. Mashinostroitel, No. 2, pp.32-34, 1968.

[2] V.E. Makhov, A.I. Potapov and S.E. Shaldaev, «Control of the Image Function Optoelectronic System Conversion Method in Image Contrast». Kontrol. Diagnostika, №7, pp. 12-24, 2017.

[3] Ren Ng. «Digital light field photography». A dissertation submitted to the department of computer science and the committee on graduate studies of Stanford University in partial fulfillment of the requirements for the degree of doctor of philosophy, 2006.

[4] V.E. Makhov, O.S. Repin and A.I. Potapov, «Research of algorithms automated calibration optoelectronic measuring systems with matrix photo detectors». Kontrol. Diagnostika, №8, pp. 67-74, 2014.

[5] Yunsu Bok, Hae-Gon Jeon, In So Kweon, «Geometric Calibration of Micro-Lens-Based Light-Field Cameras Using Line Features». Sep 2014. Springer International Publishing, pp. 47-61. [European Conference on Computer Vision (ECCV), 520 p., 2014].

[6] Rafael C. Gonzalez, and Richard E.Woods, «Digital Image Processing (3rd Edition)». Prentice-Hall, Inc. Upper Saddle River, NJ, USA, 2006.

[7] V. Makhov, V. Liferenko and E. Borisov, «A general approach to the digitization of plots in LabVIEW environment». Components & Technologies, №9, pp. 141-146, 2016.

[8] V. Makhov and S.E. Shaldaev. «Precision optical measuring systems for the shape of products and tools». Vestnik DonNTU. Special issue «Metallurgicheskie protsessy i oborudovanie», №4, pp. 50-57, 2016.

[9] I. Daubechies. Ten Lectures on Wavelets. SIAM Press, Philadelphia , 1992.

[10] V.E. Makhov and A.I. Potapov. «The Measuring optical system in a mechanical instability of control object». Kontrol. Diagnostika, №1, pp. 12-21, 2013.

[11] Jianzhong Wang. «Wavelet approach to numerical differentiation of noise functions». Communications on Pure and Applied Analysis (CPAA), Vol. 6, Num. 3, pp. 873–897, Sept. 2007.

[12] V. Liferenko, A. Zakutaev and V. Makhov. «Computer implementation of wavelet analysis methods in the development environment of virtual instrument NI LabVIEW». Components & Technologies, №9, pp. 132-139, 2015.

[13] V. Makhov, V. Liferenko and A. Zakutaev. «Methods of the time-frequency signal analysis and computer implementation in LabVIEW». Components & Technologies, №7, pp. 137-142, 2016.

[14] V. Maksarov, A. Keksin, «Methods of increasing the quality of the thread pitches». Estonian University of Sciences, 09-13 May 2013. Tartu, Estonia, p. 133-138. [International Conference «Biosystems Engineering. Production Engineering», 320 p., 2013].

[15] V. Maksarov, Yu.M. Baron, V.G. Vasiliev and V.I. «Skripchenko. Improvement of Thread Cutting Processes in Power Plant Engineering Products». Energomashinostroenie, №1, pp. 24-27, 1987.

[16] A. Keksin and V. Maksarov. «Methods of increasing the quality of the thread pitches». Agronomy Research, Vol. 11 (1), pp. 139-146, 2013.