Reduction of defects in the process of formation of precision surfaces of titanium alloy products

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Abstract. The article proposes a new method of reducing defects in the process of formation of precision surfaces of titanium alloy products, which are significantly influenced by self-oscillation in the process of processing. The technique of controlling the amplitude of self-oscillations in the optical image of blanks with a digital camera of the light field and vibration parameters from the Doppler radar is presented. Studies have shown that the vibration signal from the surface of the product obtained by Doppler locator gives more complete information about the defects of the treated surface, information related to the process of formation of precision surfaces and the causes of self-oscillations. Optical method of control of self-oscillations on the basis of registration of a light field expands a range and accuracy of control of self-oscillations in 10 times. The configuration of the measuring scheme with parametric illuminator allows reducing defects in the process of formation of precision surfaces of products from titanium alloys. Studies have shown the possibilities of using vibration control to control the technological process to reduce defects in the process of forming the precision surfaces of titanium alloy products.

1. Introduction
Increasing the temperature in the cutting zone leads to an increase in cutting forces and accelerated nodular growth, creating a passivation oxide film on the surface of the workpiece. These phenomena increase the level of vibration activity of the products in the process of their processing, which leads to the formation of surface defects and reduces the quality and accuracy of precision surfaces. Forced vibrations and self-oscillations have the greatest impact on the cutting process. The main reason for the emergence of self-oscillations is the cutting process itself. Since under cutting conditions the temperature in the chip-forming zone becomes critical, the tool and the surface to be machined are subject to temperature "impact", dyeing of carbide particles, which leads to the clockwork and increase of self-oscillations [1].

In this regard, it is necessary to take a comprehensive approach to ensuring the dynamic stability of the technological system of machining based on the application of new methods to reduce the self-oscillating process of machining due to the removal of nodules from the cutting edge of the tool and provide technological control of the emergence and vibration level of the workpiece. All this indicates the necessity to determine the parameters of vibration in the technological process, providing the technological possibility of their elimination.
Taking into account the specifics of this problem, the optical method of vibration parameters control can be considered the most applicable. There are different methods of vibration determination based on coherent [2] and incoherent optical schemes of focused and unfocused image. The use of coherent methods in technological processes is difficult. The easiest way to use is to obtain a focused image, where the vibration amplitude is determined by the analysis of the blurring area of the image boundaries [3]. The optical method has a high locality to the controlled product, noise immunity to vibrations of surrounding objects (cutter, machine parts). However, this method has a narrow range and low accuracy of measurement, requires precise focusing of the optical design system. The optical method of blurring the borders of the image does not allow you to determine the form of vibration of vibrating objects.

Recently, new digital cameras of the light field have appeared which record the coordinates and direction of the rays [4, 5]. This does not require focusing the system in the control zone, there is an additional opportunity to improve the accuracy and range of measurement due to the algorithmic accounting of the change in the ray stroke during vibration.

Of the non-contact methods of vibration control [6] the most interesting are radar methods of control [7], which allows you to analyze the vibration signal by various methods, including methods of spectral, frequency-temporal [8], wavelet analysis [9]. Radar methods make an integral assessment of vibration parameters of the entire reflective surface in the radar zone. The disadvantage of the method is the difficulty to provide the control of the part in the conditions of the surrounding parts of the equipment, subject to their own vibrations.

In the present work, the vibration stability of mechanical processing of titanium alloys by the wavelet method is studied by the analysis of the blurring zone of the image obtained from the digital camera of the light field and the frequency-temporal analysis of the vibration signal from the Doppler radar.

2. Materials and Methods
The Raytrix R42 light field recorder [10] with CMOS sensor was used - it records 42 mega-rays (100-200 spatial layers), has an effective resolution of up to 10 megapixels per 7 frames per second. (pixel size 1.12 microns).

The work uses Doppler radar (13 mm), acoustic input device NI platform cRIO-9072 with input module (signals) voltage NI 9223: 4-channel 16-bit. module C-series, ± 10 V, 1 MB / s. Parallel input provides asymmetrical analog input.

To build a measurement application in the image, we used the application development environment based on virtual device technologies - NI LabVIEW [11]. The functions of the driver of the technical vision module NI IMAQ Vision [12] were used. An additional module NI Advanced Signal Proceedings Toolset was used, which includes the functions of signal processing based on the combined frequency of time and wavelet analysis of non-stationary signals. The image processing algorithm is built using the NI Vision Assistant application, data analysis and reporting. To receive and process the signals from the Doppler radar we used our own application (based on the LabVIEW programming area).

3. Proposed Methodology
A measuring system (fig. 1) was used to monitor the self-oscillations of the workpiece 1 with tool 2. The recording system included a Doppler locator 3 which recorded the reflected signal from the cylindrical surface of the workpiece and an optical light field recorder of the 4 edge zone of the workpiece. Parametric illuminator 5 was used to illuminate the part. Both recorders record normal to the surface vibration of the part.

The direction of sighting of the optical recorder 4 was set along the edge of the cylindrical surface of the workpiece 1 outside the chip formation and removal zone 6. The same direction of Doppler locator registration should be outside the chip formation zone 6, the surface of the cutter 2 and other vibrating surfaces of the process equipment.
A Doppler locator signal removes a vibration signal from a large part of the part surface. At the same time, it is more informative because it contains the shape of the signal in time. However, it should not capture other machine, tool and chip surfaces, which may distort the signal. The signal from the locator 3 through the data acquisition board 7 (NI 9223) is transmitted to the computer platform 8 (NI cRIO-9072). To receive the signal and analyze it from the Doppler locator, a virtual device was developed in the LabVIEW programming environment [11, 15]. The algorithm of the device operation is presented in fig. 2a, the fragment of the front panel of the device - in fig. 2b.

Virtual device is built on the principle of object-oriented programming. It contains buttons to control the algorithm 2-16 (fig. 1b), which perform in a given sequence of actions associated with fragments of the algorithm (fig. 2a). Only those buttons that are related to possible operations at each stage of the virtual device operation are active.

Analysis of signals was carried out by selecting a characteristic fragment of the signal duration, determining its amplitude A and the main frequency f0. Filtering of the signal allows to eliminate the signal noise and to isolate the part's own vibration.
Frequency-temporal analysis of vibration signals has shown that for each cutting mode there are specific features of signals (fig. 3) related to the cutting process and chip separation process. Low-frequency area of the spectrogram has the greatest informativeness, high-frequency area of the spectrogram displays the influence of the workpiece's surface texture. It is possible to see in real time the process of vibration development (fig. 3c) and its attenuation associated with chip separation moments.

Figure 3. Spectrograms of the Gabor 5-th order of a fragment of a vibration signal from a surface of a detail: a) strong natural fluctuations; b) small natural fluctuations; c) the allocated frequency of natural oscillations

RF monitoring is very informative, however, it is time consuming to process and requires constant monitoring of the measurement circuitry configuration and calibration of measurements.

In some cases, it is sufficient to determine the vibration amplitude. To extend the range of vibration amplitude measurements by optical method [3], to increase the accuracy of vibration amplitude measurements, to eliminate the need for precise focusing in the work, the optical scheme of registration on the basis of digital camera of the light field [4, 13, 14-16] is proposed.

The program of processing of a light field file forms the image with the set focusing plane, depth of sharply displayed space and angle of view of the camera. Lightness distribution in each line of the image profile determines the brightness gradient in the border zone in the image of the detail. If the pattern oscillations occur, the border area of the image is blurred $A_{xT}$ during the exposure of the image frame $T$ (fig. 4).

Illumination histograms $I(x)$ in selected image profile lines $L(z)$ of the detail profile show the characteristic bends of the light function $I(x)$, caused by vibration are visible, but it affects the saturation of the receiver. Low-vibration blurring zone is small and does not provide sufficient sensitivity and accuracy in determining the vibration amplitude. The recorder based on a digital lightfield camera provides an opportunity to algorithmically change the angle of view, i.e. to obtain a series of images with shifted field of view from the lightfield file $\text{Im}^{3D} \rightarrow \{\text{Im}^{3D}(x + \Delta x_j, z)\}_{j=1}^K$. 
Figure 4. Distribution of light in the profile line of the part image:
a) static state of the part b) rotation and vibration of the part

The total image, which implements scanning of the field of view in one frame of a single exposure, expands the border blur zone caused by vibration, increases the size of the function sample in the vibration zone.

\[ \text{Im}^{2D}(x, z) = \sum_{i=1}^{K} \text{Im}(x + \Delta x_i, z) \, . \]

To determine the accuracy of the vibration parameters determination by the method of scanning the angle of sighting the computational experiments of comparing one image and a series of images - two images - were carried out (fig. 5). The zone of light distribution function (Plot 1) is widened, and its first derivative (Plot 0) becomes smoother and more informative.

Figure 5. Light distribution and the first derivative in one image profile line with changing the angle of view

The increase in the vibration zone can be achieved by a linear number of pixels under the microlenses or the number of registered layers in the light field file (specified by the manufacturer), i.e. by about 10 samples. Parameters of vibration are defined by the analysis of curves of coefficients of continuous wavelet transformation (CWT) \( g(x) \) of total illumination in profile lines [3] on the given length of a detail \( z \subset (z_1, z_2) \):

\[ g(x) = \sum_{m} \text{CWT}(\sum_{z=z_1}^{z_2} \text{Im}^{2D}(x, z)) \]

By configuring the optical system (linear magnification and distance to the control zone), you can improve the accuracy of vibration parameter determination for a given range of vibration amplitude.

Experiments have shown that measurements obtained in the image provide more than 5 times more accuracy in reducing defects in the process of formation of precision surfaces of titanium materials.
4. Conclusion
The carried out researches have shown that the method of measurement in the system of images allows to receive a vibration signal from a precision surface of a product, carrying the information of all parameters of technological process. Vibration control is carried out in real time, which allows you to control the rapid reduction of the defective layer in the process of formation of the technological process. At the same time, the integral value of the radar signal for the assessment of defects in the surface of the product is sensitive to the external environment, which requires each time to calibrate the measuring scheme.

The optical light field recorder method is used to assess the defective layer of precision surfaces without affecting the environment. The joint use of the optical recorder with the radio locating recorder allows to estimate the defective layer of precision surfaces of titanium alloy products with high sensitivity within 1-2 microns.

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