The sapphire tips of the active control devices of detail's dimensions of produced with hollows and ridges, with the possibility of determining the lateral approximation of ridges

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Abstract. The high speed rotation of ≥10 turn/s details with intermittent surfaces when machining on grinding machines and small time tabs detail past the tip with a duration of less than 1-5 ms necessitates synchronization of the measurements in the active control devices (ACD) depending on the current position of the ridge and it lateral approach. The implementation of optical methods to control the shape of details and high-precision measurement of movements are also in demand in the ACD. The use of sapphire tips allows to solve three problems simultaneously: to create an asymmetric lateral optical flow to determine the lateral approach of the ridge of the detail, to use the tip as a reflector to measure the movements of the lx, and to form a cut-off border to control the shape of the product.

The article presents two optical ACD schemes implementing these capabilities with amplitude conversion of the optical signal and phase synchronization of the output signal frequency with the rotation of the detail. The conditions for ensuring a small roughness of the surface of the sapphire tip Rz under active control of the detail dimensions and the peculiarities of the formation of refractive and reflected optical flows with the help of it are considered. It is shown that the small roughness of the surface of the sapphire tip Rz ≤ 0,1 μm, ensuring the coherence of the reflected optical flux, is achievable under the condition of a small effort of its clamping to the product ≤ 3H, which is similar to the processing of sapphire in quasi-plasticity to obtain a faultless surface. The article discusses the optical-mechanical, dynamic and metrological characteristics of the ACD using a laser interferometer movements.

1. Introduction

The tasks of increasing labor productivity, set by the leadership of Russia, and successfully solved by the active control devices (ACD) of the sizes of the details present new requirements for them in the current state of the art and technology. Since the 60s of the XX century, leading in the field of active control of the dimensions of details in the process of machining on metal cutting machines are the scientific teams of MGTU "STANKIN", OmSTU, MSTU name N.E. Bauman, JSC "NIizmereniya" [1-6]. Recently, a sufficient number of publications have appeared in Russia concerning various aspects of the development and application of methods and means of active detail control and developing this direction [7-11].

Judging by the publications, the issues of the development and effective use of the ACD are relevant for representatives of scientific teams from different countries [12-16], but the Italian firm Marposs [17] is the recognized leader in this field.
It should be noted in common, which unites all the existing designs ACD is the application for the contact measurement of the dimensions of the measuring tips (in next text - tip) of the high strength, but non-transparent materials. This is the simplest and most reliable, but does not allow the fullest use of optical methods and controls, limiting the prospects for the implementation of high accuracy and extensive functionality. However, attempts of active use optical directly ACD with contactless measurement methods also face significant technological constraints due to the presence of flow, vapour, mist from the cutting fluid (coolant), complex conditions, etc.

In this regard, the most promising are fundamentally new hybrid ACD with the use of tips made of high-strength, wear-resistant, but optical transparent materials, such as diamonds and especially widely available artificial corundums, such as sapphire, ruby, which allow to implement contact and non-contact measurement methods. Such opportunities are most demanded for active control of the most difficult products in the form of products of tool production having intermittent surfaces with hollows and ledges. So in Russia since 2013 in this area appeared and began to be created laser ACD with sapphire tips [18-22]. Also, new contactless [19, 22, 23] and hydraulic jet [24-26] ACD were created, which expand the possibilities of detail size control. However, the reserve of improvement in the direction of enhancing the functionality of such ACD is far from exhausted and this article is devoted to the consideration of one of these possibilities.

2. Formulation of the problem
Now the process of measuring the dimensions of details with an intermittent surface made with hollows and ridges, implemented in ACD with high – strength and optically transparent sapphire tip, based on mechanical contact, being essentially tactile, and does not allow to determine the lateral approximation (next-the approximation) of moving ridges of products. Since for different conditions of control contact time can be no more than 1-5 ms, for quick measurements need to advance information about the approach of the ridge. At the same time, fixing the moment of touching between the ridge of the detail and the tip can be quite late, potentially leading at best to a dynamic component of the error for cyclic measuring instruments, and at worst – to the defective operation of the entire ACD.

In addition, the control of the frictional drive, to ensure the ceasing of the tip in the troughs between the ridges and are practically binding site of the modern ACD also implies the availability of information about the current position and the approximation of the ridge of the detail.

This task is complicated by the possible changes in the speed of rotation of the machine and the presence of a large number of details, such as tool production with short and/or asymmetric ridges (Figure 1), the movement of ridges which are difficult to accurately determine in advance by calculation.

![Figure 1. Cross section with short and asymmetrical ridges of the drills (a-d): spiral, four-belt with straight fluted, for gun, for rifle and for core drill (d,e): for light alloy and combined.](image)

The solution of the problem of determining the lateral approximation of moving ridges of details in laser ACD, simultaneously intersects with the problem of optical control of the detail shape [22], solved by ACD, and the desire to improve the accuracy of measurements of the movements of the sapphire tip when using it as a reflector for the laser interferometer movements [18, 19]. The latter is
possible, first of all, while maintaining the coherence of the optical flow passing through the sapphire tip.
In this regard, the research task is to develop and study a sapphire tip ACD with the ability to determine the lateral approximation of the ridges of the detail implemented in conjunction with the optical control of the detail shape and the use of a sapphire tip as a reflector for the laser interferometer movements.

3. Theory
In order to solve this problem, two designs of ACD with asymmetric optical flow were developed: with amplitude registration of the reflected signal (Figure 2) and phase synchronization of rotation of the detail (Figure 3). Their composition, principle of operation and calculation of the main parameters are considered further on the example of one-contact measurements at unidirectional motion (rotation) on a cylindrical grinding machine with the implementation of a black and white method for controlling the shape of the detail and high-precision measurement of the movement of the sapphire tip laser interferometer.

3.1. The composition and principle of operation of amplitude ACD
The developed optical scheme ACD (Figure 2) includes a tip 1 consisting of a sapphire fiber 2 and a protective coating 3, optical elements 4 and 5, a laser interferometer of movements 6, working with the input 7 and reflected 8 optical streams, an illuminator 9, a lens 10, a camera 11, a comparator 12 and a recorder 13, which can be created on the basis of a video camera and a thermal imager operating in different spectral wavelength ranges, as described in [21]. Processing of the detail is carried out 14 grinding wheel 15.

The operation of the device in the processing of the detail and the active control of its size can be divided into 3 stages depending on the position of the ridge relative to the tip:
1) is substantially remote;
2) approaching;
3) passing by.

Figure 2. ACD’ optical scheme with a sapphire tip and a single-ended output of the optical flux by using the amplitude method of forming a Gating signal.

During the first stage, the ridge of the detail is essentially removed from the sapphire fiber 2 of the tip 1. Laser interferometer 6 generates an input optical flux illuminating optical element 4, made in the form of a connection of an optical wedge and a scattering lens based on the elements of integral and/or Fresnel optics. Its output is formed a divergent optical flow, the next through the sapphire fiber 2 and illuminating the inside surface in the range of angles: $\alpha_{\text{inc}1} < \alpha_{\text{lim inc}} < \alpha_{\text{inc}2}$, where $\alpha_{\text{lim inc}}$ – limit (critical) angle of incidence, which defines the condition of total internal
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reflection. The area of the illuminated spot is smaller than the area of the sapphire fiber 2 and this creates a cut-off line used to control the shape of the detail 14.

Part the next through the sapphire fiber 2 divergent optical flow and then exits out outside the tip 1, forming asymmetric side stream 16 composed of refracted rays within a specified range of angles: from $\alpha_{1}=60^{\circ}$ to $\alpha_{2}=90^{\circ}$. This flux of refracted rays follows in the direction of the expected appearance of the ridge of the detail 14.

The other part of the optical flow following the sapphire fiber 2 is mirrored from the contact surface of the tip 1 to the optical element 5, passes through the diaphragm, the mirror and returns as a reflected stream 8 to the laser interferometer of movements 6. Thus, a tip 1 with a similar triangular stroke of light for the laser interferometer 6 acts as a prism, the movements of 1x which are associated with the size of the detail are measured with high accuracy.

In the second stage, when approaching the ridge of the detail 14 illuminated by an asymmetric optical flow 16 formed from refractive rays, a multidirectional diffusely scattered radiation is formed. Part of it should be in the opposite direction, passes through a sapphire fiber 2, the beam splitter 9 and then to the entrance of the photodetector 11, the output signal $U_{id}$ which follows to the input of the comparator 12 forming the signal $U_{strob}$. The output of the comparator 12 is connected to the input of the recorder 13.

As the ridge of the detail approaches 14, the level of the reflected optical signal and $U_{id}$ signal increases and after reaching a certain threshold level corresponding to the specified position of the protrusion of the detail before the mechanical touch with the tip 1 comparator 12 forms a positive pulse Delta of the $U_{strob}$ signal corresponding to the beginning of the third stage and allowing the operation of the recorder 13 for video fixation of the image of the end surface of the protrusion passing through the cut-off border, , thermal imaging pattern for the correction of measurement results with the formation of a digital signal $N_{reg}$.

After passing the ridge past the tip, the level of the reflected signal, the signals of the $U_{id}$ sharply decreases forcing the comparator 12 to form a negative pulse drop, which eventually blocks the operation of the recorder 13 until the next protrusion approaches, after which the cycle repeats.

In accordance with the algorithm of operation, as well as, judging from the diagram of the refractive flow direction and the route of the reflected flow from the detail, it is possible to form an equivalent optical scheme that is close to the flow path in the fiber-optic reflectometric displacement sensors with the corresponding conversion function (Figure 3b) previously well studied in [27].

![Figure 3](image)

**Figure 3.** The equivalent optical scheme of the widely used fiber optic time domain reflection displacement sensors (a) and the transformation function (b)

The formation of the threshold level $U_{1}$ allows in the end to create the gate signal $U_{strob}$ for a specific current position of the projection of the detail to control operations in the ACD. Despite its simplicity, this technical solution has the following disadvantages:
• The amplitude of the $U_{ld}(l)$ from a variety of external flashes, different "wildness" in turbulent or dispersions the coolant flow, the reflection properties of the moving ridges, which ultimately leads to errors in the formation of the gating signal $U_{strob}$: $\Delta l = l_{vb} - l_{va}$ (Figure 3a);
• It is impossible to realize the synchronized rotation of the detail for its full turn with frequency signal and to implement the coordinate–temporal reference of the external surface of the object to check its surface at the given coordinates.

3.2. The composition and principle of action ACD with phase synchronization of the rotation of details
Further expansion of the functionality associated with the introduction of phase synchronization of the rotation of the ridges of the detail with a frequency signal by using the phase automatic frequency control (PAFC), shown in Figure 4. This device consist of a phase detector 18, a low-pass filter 19, a generator controlled by a voltage of 20 and a divider 21.

![ACD's optical scheme with phase synchronization of the output signal frequency and rotation of the detail](image)

Figure 4. ACD's optical scheme with phase synchronization of the output signal frequency and rotation of the detail

The use of the PAFC system is quite common, and its mode of operation is well studied. A feature of this PAFC system is the formation of the output signal with frequency $f_{pafc}$, which after divider 21 corresponds to the frequency of rotation of the ridges of the detail. For the balanced mode of the PAFC, the frequency of its output signal is equal to the frequency of pulses generated by the photodetector from the running ridges of the detail $f_{pdc}$, from which the equation is derived

$$f_{\text{pafc}} = \frac{N_{nrid}}{k_{\text{div}}},$$

(1)

where $k_{\text{div}}$ - the division coefficient, $N$ - the rotational speed in turn/s, $n_{rid}$ - the number of ridges of the detail.

Using the formula (1) to determine the value of $f_{\text{pafc}}$ frequency of the signal used for gridding, for example, with a step $l_{\text{step}}=1$ μm on the outer surface of the cutter

$$f_{\text{pafc}} = \frac{N_{nrid}}{k_{\text{div}}} = \frac{2\pi RN}{l_{\text{step}}},$$

(2)

For a five-cogs cutter ($n_{rid}=5$) with a diameter of 20 mm and a rotational speed of 10 turn/c, the frequency of $f_{\text{pafc}}=600$ kHz, and the division coefficient determined from formula (1) as will be 12000.

3.3. Optical and mechanical characteristics
Earlier in the works [19, 28] the results of theoretical and experimental studies of the loading capacity of sapphire tips under shock loads in the process of active control of the sizes of details with an intermittent surface and in particular with a five-tooth cutter rotating at an angular velocity of 600 turns/min =10 turns/c were presented. It was shown that the surface roughness $R_z$ was 0.15 μm. This
was the first experimental test of high strength parameters of sapphire, which confirmed the possibility of its use as a material for ACD tips. However, the obtained Rz value corresponds to a significant, up to 30-70 times the permissible load, which, as shown in [6], should not exceed 3 N. And this gives reason to assume that such a mode of interaction of sapphire tip with the processed detail is close to microgrinding in the quasi-plasticity mode to obtain a faultless surface, well studied in [29, 30] and the possibility of reducing the Rz, at least 2-3 times, to values of 0.05-0.08 μm.

These calculated values of Rz make it possible to ignore the parasitic diffuse scattering of light in the wavelength range of 0.6-0.76 μm, characteristic of most of the measuring laser and read the reflected light from the surface of the sapphire tip of the mirror, and the image captured by the recorder allowing to reach the highest possible resolution.

To calculate the parameters of the refracted stream 16 can be used a known expression

\[ \frac{\sin \alpha_{inc}}{\sin \alpha_{ref}} = \frac{n_{cool}}{n_{spf}}, \]

where \( \alpha_{inc} \) and \( \alpha_{ref} \) – the angles of incidence and refraction of light to the surface of the sapphire fiber, \( n_{cool} \) and \( n_{spf} \) - the refractive indices of sapphire and the coolant.

The boundaries of the optical flow formed by the optical element 4 can be calculated using the parameters of the deflected flow. The limiting angle of incidence of \( \alpha_{lim inc} \), at which a refractive stream is formed, directed along the surface of the tip 1, vertically upwards according to Figure 2. The refractive index of sapphire \( n_{spf}=1.76 \), and for coolant, for example, based on glycerol, \( n_{cool}=1.47 \) and in accordance with this \( \alpha_{lim inc} = \arcsin \frac{n_{cool}}{n_{spf}} = \arcsin \frac{1.47}{1.76} \approx 56.6^\circ. \)

Due to the fact that part of the optical flow covering the inside surface of the sapphire tip must mirror effect, it is taking its width is equal to \( \approx 9.4^\circ \), we obtain the value of the upper boundary of the illuminating optical flow \( \alpha_{inc1} \) equal to 66°.

The lower value of the angle of incidence of light \( \alpha_{inc2} \) falling from the inside to the surface of the sapphire tip is associated with the maximum value of the refraction angle for the exiting refractive rays. Taking the width of the formed asymmetric flow equal to 30° with the corresponding refractive angle \( \alpha_{ref}=60^\circ \), it is possible to calculate the value of the angle of incidence \( \alpha_{inc2} = \alpha_{ref} = \alpha_{inc2} \approx 46^\circ. \)

Thus, for the designed optical circuit ACD with the development of emerging optical flow with a width of 30°, consisting of refracted rays, and creating mirrored beams for use sapphire tip as a reflector in cooperation with a laser interferometer it is necessary to form the optical element of the optical flow with a width of 20°. This thread should cover the surface of the sapphire tip from the inside and within the angular sector from \( \alpha_{inc2}=46^\circ \) to \( \alpha_{inc2}=66^\circ. \)

According to the geometric rules and the flow of optical rays in the contact area of the detail 14 and sapphire tip 1 for isosceles triangle ABC (Figure 5) the ratio of the triangle side to the sine of the opposite angle is equal to two radii of the circumference described near this triangle

\[ \frac{|AC|}{\sin \alpha_{inc}} = 2R \]

\[ (3) \]

\[ \text{Figure 5. Formation of an asymmetric optical flow in the form of a flux of refracted rays within the angle of ABC from incident rays at an angle of } \alpha_{inc2} \text{ in the contact zone of the detail 14 and} \]
Based on this formula, the rotation time \( t \) of the surface of the detail from point C to point A can be approximately determined as follows:

\[
\begin{align*}
    t \approx & \frac{|AC|}{v} = \frac{2R \sin \alpha_{ref}}{2\pi R N_n ridi} = \frac{\sin \alpha_{ref}}{\pi N_n ridi n_cool} \\
\end{align*}
\]

As you can see, formula (3) demonstrates the one of the main relationship for these ACD between the size of the detail, its rotational speed and the optical parameters of the tip and the environment. And so allows to calculate their values for optimal scheme ACD.

3.4. Dynamic characteristic
In this section will be the estimation of the dynamic characteristics for two modes of operation ACD:
1) determining a lateral proximity of the ridges of the detail;
2) high-precision measurement of sapphire tip movements by laser interferometer.

3.4.1. Dynamic characteristics in determining the lateral approximation of the ridges of the detail. Modern photodetectors working in the fiber-optic communication lines allow recording frequencies of the optical signals until 1 GHz, having a delay time of <1 ns. Taking the comparator 12 delay time of with the reserve equal to \( \approx 1 \mu s = 10^{-6} \) c and assuming that during this time the ridge moves at a distance of 3 mm, the displacement speed will be \( 0.003/10^{-6} = 3 \times 10^3 \) m/s. The obtained value is comparable to the first cosmic velocity and has never been realized on metal-cutting machines, which confirms a significant margin of speed and the overall feasibility of this possibility.

3.4.2. Dynamic characteristics of high-precision measurement of sapphire tip movements by laser interferometer. In the process of active control of detail dimensions, the tip carries out various movements. Thus, during movement to (or from) detail the speed usually does not exceed 50 mm/s, and at different stages of processing the detail [23] is the following values:

- For black grinding 200-500 \( \mu m/s \),
- For fine grinding 10-50 \( \mu m/s \),
- For fine grinding 10-50 \( \mu m/s \).

The rate of exit of the tip of the \( v_n \) to the ledge from the cavity of the detail during the so-called return movements in the process of active control can be determined for the worst conditions, when the fall between the ledges is \( \approx 50 \mu m \), and the exit from it to the ledge occurs during 1 ms. In these data, the value \( v_n \) is equal to 50 \( \mu m/s \).

As you can see, the maximum speed of the tip movements at different stages of the active control does not exceed 50 mm/s and when the laser interferometer with a wavelength \( \lambda = 0.63 \mu m \) receives the maximum value of the Doppler frequency range taking into account the double stroke of the beam \( f_{dop} = 2v_n/\lambda = 170 \) kHz. For acousto-optic (AO) laser interferometers with a modulation frequency of AO \( f_{mod} = 8 \) MHz, this is only \( \approx 2\% \) and is not a critical value, confirming the possibility of their use.

3.5. Metrological characteristics
As follows from the author's studies [31] the resolution of AO laser interferometers of movements with phase-digital transformation can be reduced to \( \lambda/3000 \), making \( \approx 0.2 \) nm. It follows from this that the total measurement error will largely consist of substantially larger components, such as temperature error and error of the mechanical system ACD: tip shape, straight guides, etc.

The possibility of thermal imaging measurements carried out using the recorder 13, allows you to enter the correction of the measurement results depending on the temperature of the detail and the tip, significantly reducing its share. More detailed metrological analysis is beyond the scope of this article and will be considered in the following publications.

4. Experimental result
Currently Omsk state technical University conducted testing of a prototype of the ACD laser with a sapphire tip. The mechanical scheme providing repeatability of movements of a tip at the level of 1 μm is created.

Experimentally confirmed the presence of a defect-free surface (Figure 6a) as a result of sapphire surface treatment with micro-tool quasi-plasticity's mode [29, 30]. This mode allowed to obtain the surface roughness from $R_a = 1.95$ nm, as follows from the profilogram in Figure 6b, according to the established ratio of $R_z = 5R_a$ allows us to estimate $R_z = 10$ nm = 0.01 μm. The value comparable in order with the obtained value can be obtained by reducing the clamping force of the protrusion to the tip to 3N, i.e. up to 30-70 times relative to the force specified in [28]. This is confirmed by numerous experimental studies of doctor of technical Sciences, prof. Leun VI for almost during about 20-year period in the 70-90 years of the XX century to obtain the surface of the opaque tip almost polished mirror surface.

![Figure 6a](image1.png)  ![Figure 6b](image2.png)

**Figure 6.** The treated surface of the sapphire cylinder (diameter 31 mm) and profilogram the surface of the sapphire element $R_a = 1.946$ nm after mirogrinding by quasi-plasticity's mode

The possibility of measuring the shape of the surface of the detail is clearly visible when registering the image (Figure 7) obtained by processing the cutting tool [32].

![Figure 7](image3.png)

**Figure 7.** The image of cutting tools using a cut-off line

5. Discussion of results

1. The article analyzes two designs of the ACD with the possibility of determining the lateral approximation of the protrusion of the detail: with the amplitude transformation of the optical flow and phase synchronization of the output frequency signal and the rotation of the detail. It is shown that the first variant is simpler, and the second one is more accurate and allows to carry out coordinate – time binding of the external surface of the detail with an accuracy comparable to $\approx 1$ μm to register its surface at the given coordinates.
2. The equations linking time and optical parameters of the considered ACD structures are obtained, which allow to optimize them for different processing conditions, sizes and parameters of details, characteristics of measuring devices.
3. Discusses the issues of ensuring minimum roughness of the surfaces of sapphire tips in the measurement process based on the execution conditions of quasi-plasticity's mode. The results of experimental work confirming the achievement of such.
4. Discusses the issue of implementation of the cut-off method to control the shape of the detail with the help of sapphire tips with the application of the Gating pulse emerging from the lateral approximation of the projection of the detail.

6. Conclusion
1. Determining a lateral proximity of the projection of the detail allows you to synchronize the measurement process of the laser ACD and to provide control of the sizes of details having a discontinuous surface with short ridges or asymmetrical arrangement. Implementation of this functionality can be carried by amplitude signals with the formation of a Gating pulse delta or phase synchronization of the frequency output signal with the rotation of the detail using the PAFC system. The first option is simpler, but the error of forming a Gating pulse delta depends significantly on the optical conditions of the ACD. The second option is more noise-resistant with the additional possibility of coordinate–temporal reference of the external surface of the detail with a resolution $\approx 1 \mu m$ for the registration of the surface at the given coordinates.
2. As a result of experiments it was shown that the sapphire can be successfully used as a bits ACD. The clamping force of the lugs ACD details having a discontinuous surface, for example, five-cogs cutters that are significantly greater than 3 N for 30-50 and up to 70 times, i.e. equal to $\approx 90210$ premiere. this N leads to wear of the sapphire tip with the formation of surface roughness $Rz=0.15 \mu m$. The resulting surface roughness for such large loads does not allow it to be used without parasitic scattering for visible wavelengths. At the same time, it can be confidently assumed that the reduction of 30-70 times to the level of $\approx 90-210$ H efforts of pressing the ACD tips to details with an intermittent surface will allow to obtain the surface roughness of $R_s$, at least 2-3 times and bringing the value of $R_s$ to the values of 0.05-0.07 $\mu m$, i.e. to the level of the so – called "mirror" surface for red wavelengths of 0.6-0.76 $\mu m$. This has the result successfully achieved in terms of mirogrinding sapphire details in the quasi-plasticity's mode obtaining a defect-free surface have been well studied in numerous works.
3. Improving the surface quality of sapphire tips, allowing the use of a visible part of the wavelength spectrum, simplifies the optical control of the surface shape of the details, effectively separating it from thermal measurements of temperature using thermal radiation in the near infrared range. The developed design of ACD extends the functionality of laser ACD with sapphire tips increasing the Arsenal of promising methods and tools for controlling the size of details.

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