The active control devices of the size of products based on sapphire measuring tips with three degrees of freedom

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Abstract. The article presents the results of the calculation of the load capacity of the active control devices (ACD) sapphire tip, which showed nearly 30-fold margin of safety to shock loads and experimental researches in mechanical contact with 5 cogs cutter 15 mm in diameter rotating with a frequency of 1000 rpm, which confirmed the calculations, determined the surface roughness $R_z$ of the contact area of no more than 0.15 µm. Conditions have been created for recording without distortion of the image through a sapphire tip in contact with the processed article.

A ACD design with new functionality is proposed: with one, two and three degrees of freedom of the sapphire tip and allows measuring the taper of the article and measurements on the chord. It is shown that with the implementation of their fixed head like the frame of the gyroscope with the rotations around the axes OY and OZ. It is shown that the rotation of the tip around the axis OX can be replaced more convenient for the implementation of the angular offset of the transferred image due to rotation of the output end of the flexible optical waveguide relative to the input. This makes it possible to reduce the "blurring of the image" during registration of the fast moving product profile when the slope of the recorder lines coincides with the slope of the edges of the image elements of the selected moving elements of the article.

1. Introduction

It is known that the use of active control devices (ACD) of products sizes allows to increase productivity up to 100% or more in the manufacture of products on a variety of machine tool applications in the aerospace industry, instrument, machine and machine tool.

ACD has been actively developed in the 60-ies of XX century [1,2] and until today actively developing in Omsk State Technical University [2,3]. Now one of the leading manufacturers of ACD for quality machine tool is an Italian firm, Marposs [4]. However, these ACD, with high resolution, up to $\approx 0.4$ µm for smooth cylindrical products, significantly reducing their metrological characteristics when measuring the dimensions of products with intermittent surfaces. And use metal measuring tips (the tips) do not allow the use of optical methods of measuring and registration of images of the surface. Russia is probably the only manufacturer ACD is AS "Niiizmereniya". So, they produced the instrument BV-4304 for control of parts of a continuous surface (with hinged bracket) readability of digital reading is 1 µm [5].
Since 2013, a direction has appeared in Russia [6] associated with laser ACDs using sapphire (ruby) contact tips (Fig. 1), and later also contactless [7] and hydrojet [8] ACDs were developed. However, despite this rapid development, the ACD still has large reserves of improvement. Such promising directions associated with the measurement of taper products or dimensions along the chord, causing the possibility of angular rotations of the tips with one, two and/or three degrees of freedom. Discussion one of the options ACD with these features and this article.

![Figure 1. A model of a laser ACD with a ruby tip in contact with a product having a discontinuous surface.](image)

2. Formulation of the problem

The tasks of this research are to analyze the results of theoretical and experimental studies of their load capacity when mechanically contacting sapphire tips with a product having a discontinuous surface. Analysis of transmission conditions without distortion through a sapphire tip in contact with the workpiece, images of its surface. Also, the research task is to consider the developed ACD with the realization of one two and three degrees of freedom of the tip due to their rotations around the axes OX, OY and OZ.

3. Theory

To confirm the possibility of using sapphire as a high-strength and optically transparent material for arrowheads in the ACD was the calculations of the load capacity to blow loads when contact measurements [6] and experimental studies [9], the results of which are presented next.

3.1. Calculation of load capacity of sapphire tips

The loading capacity of the sapphire tip were determined through calculation of margin of safety $k_{ms}$, determined by the ratio of impact loading $F''_{bl}$ sapphire rod does not lead to its mechanical failure (cracking, chipping or other defects), to the specific pressure generated in the process of leaving the tip $F'_{bl}$ with depression on a ledge in the control of dimensions of products with intermittent surface:

$$k_{ms} = \frac{F''_{bl}}{F'_{bl}}$$  \hspace{1cm} (1)

The calculation carried out in [6] showed that when using a tip of sapphire will be provided with almost 30-fold safety margin and confirmed the high blow strength of this material to mechanical contact with the goods having a discontinuous surface. measurements [6] and experimental studies [9], the results of which are presented next.

3.2. Experimental study of mechanical characteristics of the contact sapphire tip with a workpiece having a discontinuous surface

In addition, the experiments verified the correctness of the calculations and confirmed by the actual highly shock-resistant sapphire crystal rod of rectangular cross-section 5x6 mm and a length of ~20 mm at its mechanical contacting flat end with 5 cogs cutter 15 mm in diameter rotating with a frequency of -1000 rpm exceeds the empirical value up to 50 times the standard pressure of ~3 H and no return movements of the tip, mandatory for high accuracy contact measurement.
After conducting this experiment for two sections of flat end face in contact with the mill were removed profilogram (Fig.2), the results of the analysis are defined roughness $R_z$ of no more than $0.15 \mu m$. with these features and this article.

![Image of profilograms for two segments](image1)

**Figure 2.** The profilograms of the two segments (a) end of sapphire rod after mechanical contact (b,c – with zoom, the value 1 cell: height $\approx 0.38 \mu m$, length $\approx 33 \mu m$).

### 3.3. Conditions of registration of the image without distortion of the product surface through contact with her sapphire tip

It is known that the influence of surface roughness $R_z$ on the changes of passing (or reflected) optical flows or violation of the coherence of laser radiation from spurious diffuse scattering can be neglected under the condition of $\lambda/6 \geq R_z$. And taking into account the obtained experimental results can be generated for this condition:

$$\lambda \geq 0.9 \mu m,$$

where $\lambda$ is the wavelength. The resulting condition means the transition from a visible range to an infrared radiation (IR), invisible to human eyes.

Enhancing the functionality of the ACD with the sapphire tips can be carried out by measuring the temperature of the product pyrometric method. For different modes of operation, cooling conditions and material of the product surface temperature usually ranges up 20° to 450° C, forming IR radiation in the range $\Delta \lambda_t \approx 1.0$ to 1.6 $\mu m$. This range included in the wavelength range defined by condition (2), and the possibility of spurious cross-effects of “dimensional” and pyrometric measurements on each other. This disadvantage can be eliminated in the following ways:

#### 3.3.1 The use two different recorders for separate pyrometric and "dimensional" measurements. Use for pyrometric and "dimensional" measurements on individual recorders with different spectra of sensitivity spaced relative to each other is not less than 1 $\mu m$, described by the system of inequalities:

$$\{2,0 \ \text{мкм} \leq \Delta \lambda_t \leq 2,6 \ \text{мкм};$$

$$1,0 \ \text{мкм} \leq \Delta \lambda_t \leq 1,6 \ \text{мкм}.\}

#### 3.3.2 The use general recorder for pyrometric and "dimensional" measurements. Use one common recorder for the single wavelength range of infrared radiation $1.0 \mu m \leq \Delta \lambda_t = \Delta \lambda_t \leq 1.6 \mu m$, but with amplitude modulation of optical flow for "dimension" and pyrometric measurements at different
frequencies. Subsequent frequency separation of the optical signals is possible through the use of digital signal processing.
The rotation of the products with discontinuous surface, such as a drill or milling cutter, leads to a natural amplitude modulation of the optical flow is defined by a discontinuous surface and the number of teeth \( n \) and the rotational speed \( N \) to write the expression:
\[
f_t = \frac{n}{N},
\]
while, as a rule, in the low frequency range: 50 to 200 Hz. For example, for a rotation frequency of 1000 rpm 5-cogs cutter, the frequency of passage of the teeth past the tip amounted to \( f \sim 85 \) Hz [9]. So the frequency of the backlight \( f_{\text{lig}} \) used when registering image should be significantly higher for subsequent efficient frequency separation of the signals of low-frequency modulation \( f_t \), the generated heat flux, in writing it in the form of empirical equations: \( f_{\text{lig}} = k f_t \), where \( k > 5 \).

3.4. ACD based sapphire tip with three degrees of freedom.
In 2016 we developed a family ACD with sapphire tips with one, two and three degrees of freedom. In all these technical solutions for fixing the video image surface with the possibility of subsequent processing and the so-called telemetry is used recorder (CCD-camera). It can be installed from the back side of the movable tip or to be fixed optically coupled with the tip through a light guide. Scheme ACD with three degrees of freedom and a general view of the tip shown in Fig.3 and 4, respectively.

![Figure 3. Scheme of the developed ACD with three degrees of freedom.](image)

The developed ACD consists of a transparent tip 1 with an optical guide 2 and a protective coating 3, a frame 4 with two degrees of freedom, a first 5, a second 6 and a third 7 axial drives for rotations around the axes \( OY \), \( OZ \) and \( OX \), respectively, a measuring rod 8, a flexible fiber 9, the guides 10, the linear actuator 11, the collimator 12, the two-axis meter 13, the radiator 14, the fiber set 15, the recorder 16. It is assumed in the article that the drives can also perform the brake functions.
The main components developed by ACD dimensions 17 have the following features. The protective coating 3 is opaque and installed on the front and (fully or partially) the side surfaces of the transparent light guide pads 2. It forms on the surface of the hole and the size of the zone of contact with the workpiece 17 tip 1 window for input/output of optical radiation and protects the light guide pads 2 mechanical shock impacts.
Frame 4 is a so-called gyroscope frame, inside which due to the axial actuators 5 and 6 managed signals and \( U_{\text{rot1}} \) \( U_{\text{rot2}} \) can be rotated around the axes \( OY \) and \( OZ \) tip 1 together with an associated mechanical and optical front end of a flexible optical waveguide 9.
The rod 5, being a hollow tube with a cross section mainly of a polygon with a through inner hole is inserted the front part of the guides 10, and the rear linear actuator 11 that is controlled by the signal \( U_{\text{mov}} \). Front of the measuring rod 8 is designed forked end with a movable connection of the handpiece 1.

Flexible light guide 9 is a fiber-optic cable, the minimum diameter of which can reach only about 0.37 mm [10], consisting of a set of fibers with a regular stacking and preservation of the structure of the transmitted image, is bendable, at least for the connection phase with transparent cap 1 with the stock length, providing the possibility of angular displacements up to 180° rear end. Its front end is attached via the optical elements to the rear side of the light guide pads 2, with possibility of turning with him, lighting the surface of the product 17 and transceiver reflected optical and thermal flows to the recorder 16. The rear end of the flexible light guide 9 accommodated within the third axial actuator 7 for rotations around the x-axis (equivalent to the third degree of freedom) of the images transmitted through the collimator 12 to the recorder 16.

![Figure 4. Tip with two degrees of freedom, fixed in the measuring rod (flexible fiber and guides are not shown).](image)

Along a flexible optical fiber 9 is laid a set of fibers 15 used for switching from the emitter 14 illumination modulated with a frequency \( f_{\text{ill}} \) illuminating optical radiation angle of the surface 17 so that the emerging from it, the cut-off was in the field of view of the flexible optical waveguide 9 and, accordingly, the recorder 16.

Dual-axis meter 13 is used to measure the position \( l_x \) and angles \( \alpha_{oy} \) and \( \alpha_{oz} \), tip 1 with the formation of the output signal \( N_{\text{out}}(l_x, \alpha_{oy}, \alpha_{oz}) \). The most convenient two-axis measuring 13 implemented on the basis of three laser triangulation linear encoders that measure the spatial parameters of the tip 1 by the coordinates of its three points. For each such point, the sensor illuminates a laser beam tip 1 with the formation on it of the light spot in the form of so-called "Bunny" and records the position of this Bunny coordinate-sensitive receiver.

Recorder 16 is a CCD-matrix [11], the registered image of the surface of the product 17 and its thermal radiation in a single IR range \( \Delta\lambda_{\ell} \approx \Delta\lambda_t \approx 1.0 \ldots 1.6 \, \mu m \) with an output digital signal \( N_{\text{out}} \). For the recorder 16 introduces the concept of axes of the recorder, the appropriate one of the lines of the rows of its cells. It is used to achieve matching it with the tangent to the element 16 (the cutting edge of the tool, thread, etc.) to enhance the resolution of the image by eliminating smudging of the recorded image according to the technology of the time delay accumulation [12].

The principle of the developed ACD is the implementation of contact and contactless measurements. Contact measurements are realized when approaching the tip 1 to the surface of the product 17 to a mechanical contact with it. Current position \( l_x \) of the tip 1 forced turns \( \alpha_{oy} \) and \( \alpha_{oz} \) due to the size and
taper of the 17 items measured in our two axis filament meter 13, for example, through the use of the three triangulation sensors with the formation of the output signal $N_{\text{out}}(l_x, \alpha_{oy}, \alpha_{oz})$.

In the process of contacting one of the methods of optical inspection of surface profile is also implemented – shadow method. To this end, the emitter 14 is formed of a modulated optical signal of the backlight, the illuminating angle of the surface 17 so that the emerging at the same cut-off is field of view optical input of the flexible light guide 9. Any surface irregularities, for example, the thread pitch for screw surface (Fig.5), forming near the cut-off individual pattern of shadows, passed down a flexible optical fiber 9 to the input of the recorder 16.

With them is also transmitted thermal radiation generated by the product 17, is proportional to its temperature. The subsequent digital signal processing $N_{\text{rec}}$ with a different frequency separation of the optical signal is information about the surface roughness of the product and the temperature of the product of $T_{\text{det}}$.

Figure 5. An example of the implementation of the shadow method developed by the ACD when controlling the thread parameters (the image of the shade of the "cut-off" border transmitted to the input of the recorder).

4. The discussion of the results

4.1. The calculation of the load capacity of the sapphire tip to the ACD

The results of the calculation of the load capacity of the sapphire tip to the ACD, ensuring a nearly 30-fold safety factor for shock loads and experimental researches in mechanical contact with 5 cogs cutter 15 mm in diameter rotating with a frequency of 1000 rpm, which confirmed the calculations, determined the surface roughness $R_z$ of the contact area of no more than 0.15 µm. This value determines the transmission of optical flow in the infrared range with wavelengths of more than 0.9 µm to eliminate the effect of spurious diffuse scattering.

4.2. The calculation of the load capacity of the sapphire tip to the ACD

The design of the ACD allows to implement new functionalities: one, two and three degrees of freedom of the sapphire tip in the form of its angular movements. In one embodiment, this tip is similar to the frame of the gyroscope, in which the tip can be rotated around axis OY and OZ with the possibilities of the measurements of the taper of the product and measurement "chord". To reduce "motion blur" during the registration profile’s fast movement products technology time delay of accumulation of rotation of the tip around the OX axis in the present device it is necessary to substitute the angular displacements of the transmitted image using the by turning the end of the flexible optical waveguide.

4.3. The visualization and registration image the surface of the product by using shadow method
Designed ACD allows also to visualize the surface of the product with the registration image, shadow method, by measuring the temperature of the product pyrometric method.

5. Conclusion

5.1. The use of sapphire for high-strength and optically transparent ACD tips

Studies have confirmed the possibility of using sapphire as a material for high strength and optically transparent ferrules ACD for contact measurement of dimensions of products with intermittent surfaces.

5.2. Sapphire tips with one, two and three degrees of freedom for ACD

The developed design ACD demonstrates the possibility of creating sapphire handpieces with one, two and three degrees of freedom in the form of angular offsets. One degree of freedom associated with the rotation of the tip around the axis OY, is primarily applicable to measurements of size and taper of the workpiece. The second degree of freedom defined by angular displacements of the tip around the axis OZ and can be used for measuring the "chord". The need for the third degree of freedom of the tip due to the desire to improve the image resolution fast-moving processes to reduce "motion blur" according to the technology of the time delay of the accumulation by selection of the angle of inclination of the recorder, namely, rows of photocells of the CCD coincident with the angle of the picture elements of the end product.

5.3 The sapphire tips for wide functionality possibility ACD

The conducted research provide the basis for the establishment of the contact and contactless ACD with sapphire tips with greater functionality.

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