Questions of construction of the telescopic devices of the active control of the sizes of products with corundum tips

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Abstract. The article considers the issues of improvement of active control devices (ACD) of the sizes of products with intermittent surface in the direction of increase of accuracy of measurements, expansion of functionality and simplification of their design. The composition and principle of action ACD with telescopic guides on the basis of console pinned corundum rod, increasing the rigidity of the design, transmitting optical signals and changes's pressure from the compressor for control movement of the measuring tip. It is proposed to use magnetic fluid to fill the gaps of these telescopic guides.

It is shown that the value of the specific energy of the contacting $W_{cont}$ corundum tip with product ledges, defined by the calculation path, corresponds to the quasi plasticity mode of the material and does not lead to fragile destruction, providing ≈ 40 times the stock strength.

The first results of experimental working out of the pilot model of this ACD by use telescopic guides on the basis of console pinned steel rod are presented.

1. Introduction

Modern tasks of development of production of rocket and space technology, machine-tool industry, machine-building, instrument-making connected, first of all, with import substitution and increase of productivity of work, can be successfully solved with use of the big scientific and technical reserve in many directions and, in particular, in the field of active control devices (ACD) of the sizes of products. The development of active control of the size of products on cutting machines began in the second half of the XX century and by the end of the 1980s in the USSR reached the maximum. Leaders in this direction were researchers of scientific groups MSTU "Stankin", OmSTU, MSTU of the name of N.E.Bauman, JSC "Niizmerenija" [1-3]. In last time new works in this direction have appeared in Russia [4-8]. The ACD is also engaged in the development of foreign scientists work to improve ACD too [9-13], and the Italian firm Marposs [14] is the leading in this field.

Now there has been an understanding that some of the most promising are hybrid contact and/or contactless ACD with high-strength wear-resistant and optically transparent tips, realizing maximum of functionality, accuracy of measurements by optical methods of control. The priority in this belongs to Russia, since in 2013 began to create and investigate laser ACD with sapphire tips [15-19] and now these devices have the big possibilities of improvement else.
2. Formulation of the problem

Active control of the size of products with intermittent surface, such as drills, cutters, sweeps, gears, etc. is probably one of the most difficult tasks. And the mechanical part of the ACD developed for this purpose are sufficiently stringent requirements related to the need to reduce the dynamic effort to 3 N when contacting with the part, and provide a wide range of movement speeds tip.

Small dynamic forces are the key to minimizing the error and eliminating the brittle destruction of the corundum tips, while preserving the wide possibilities of optical control methods.

The speed of displacement of the tip in the measurement process may vary: during reconfigured from one size to another \( v_{disp} \), usually should be not less than 5 mm/s, for rough grinding - \( v_{rou} = 200...500 \) μm/s, for clean grinding- \( v_{clean} = 10...50 \) μm/s, for nursing \( v_{nurs} = 0.5...2.0 \) μm/s. As you can see, the ratio of the maximum speed of displacement \( v_{rou} \) to the minimum \( v_{nurs} \) reaches a very high value ~ 10000, forcing the use of complex microgeaboxes. And as shown by some experiments the using of stepper motors, in, is undesirable due to the heating of some mechanical part of the ACD and the appearance of temperature error.

The division optical and mechanical parts in the hybrid ACD increase of mass-dimensional parameters of movable elements, dynamic efforts and frequencies of return movements of the measuring tip at the moment of its exit from a hollow on a ledge, which can reach \( \approx 100...200 \) Hz. The desire to reduce such dynamic forces by using of rolling guides with these movements during long time leads to the inevitable loosening of mechanical parts, denoting the next contradiction.

In addition, the questions of increasing the accuracy of measurements and the need to ensure synchronization of measurements with the current position of product ledges are traditionally relevant.

So the improvement of ACD is conducted in the direction of successful solution of the maximum number of the above limitations and problems taking into account the increase of accuracy of measurements, expansion of functionality and simplification of their design. Such issues are not sufficiently reflected in modern studies and this article is aimed at filling this gap.

3. Theory

To date, a method of active control of the size of products and ACD was developed by using the compressor, telescopic guide with a central console sapphire rod and external, internal tubes with filling the gap between them is a magnetic fluid with controlled viscosity. Composition this ACD, the principle of operation, the features of its functioning and main technical parameters are presented further.

3.1. Composition and principle of action ACD with optically transparent telescopic guides

Developed ACD dimensions and geometric parameters of the surface of the product is shown in figure 1, which includes indicator 1, control system 2, tip 3, optical element 4 with coating, tube 5, corundum rod 6 with eccentrically displaced through longitudinal capillary 7, measuring rod 8 with installed inside it optically transparent partition 9, compressor 10, brake 11 with the use of magnetic fluid in the gaps between tube 5 and corundum rod 6; displacement sensor 12, working with illuminating flow 13 and the reflected 14 optical flows, the recorder 15, fixing the optical flow 16, following from the tip 3.

Next part of the article consist of a description of the ACD’s operation on the example of work on the grinding machine. During processing rotating product 17, made with hollows and ledges, is brought to the desired size by removal of excess metal (allowance) grinding wheel 18 when watering coolant.

The feature of the ACD is to use of cantilevered corundum rod 6 (sapphire or ruby) placed inside the measuring rod 8, forming sliding guides. Similarly, the measuring rod 8 is installed inside the tube 5, fixed by its external surface, also with the formation of sliding guides. Such a mechanical connection allows the measuring rod 8 to freely carry out longitudinal movements with high stability due to the rigidity of the structure to the transverse shifts, allowing to significantly increase the repeatability of measurements.

Inside the measuring rod 8 is hermetically installed transparent partition 9, forming an air cavity with the
end of the corundum rod 6, eccentrically shifted relative to its axis through the longitudinal capillary 7 which is connected to the compressor 10. Control system 2 formed on its third output the signal $U_{disp}(t)$, which goes to the compressor 10. And through the capillary 7 into the air cavity pressure or dilution form compressor 10 leads to an increase or decrease in volume and accordingly movements partition 9 and measuring rod 8 to the product or vice versa.

![Figure 1. Scheme of telescopic ACD.](image1)

![Figure 2. Scheme formation of asymmetrical optical flux for determination of lateral coming of a product ledge.](image2)

The ACD consist of the transparency of the corundum rod 6, partition 9 and tip 3, which is used for transmission of optical flows. Optical flow, following from tip 3 passes through them through to the recorder 15, participating in determination of deviations of a form of its surface black and white method. In addition, the transparency of the above elements is also used to measure the displacement of the tip by means of a motion sensor, implemented on the basis of the triangulation sensor, as shown in figure 1, or more precise laser interferometer.

### 3.2. Possibilities of determination of lateral coming of product ledges and control of shape of its surface

Determination of lateral coming of product ledges 19 and control of the shape of its surface is one of the most perspective possibility of modern ACD with optically transparent tips. Their realization allows to make the measuring process more predictable, and connections between blocks more synchronized and to carry out additional automatic measuring operation. Their peculiarities have already been discussed in detail in [18] and the links between optical and dynamic parameters for realization of this are defined. The main expression linking the optical and dynamic parameters of the scheme, by means of which the time of turning $t_1$ of the surface of the product from point C to point A in the figure 2 can be approximated as follows:

$$t_1 = \frac{|AC|}{v} = \frac{2\text{Rsin} \alpha_{ref}}{2\pi \text{RN}_t} = \frac{\text{sin} \alpha_{ref}}{\pi \text{N}_t} = \frac{n_{sapp}\text{sin} \alpha_{in}}{\pi \text{N}_t n_{cool}}$$

where $n_{sapp}$ and $n_{cool}$ – refractive indices of sapphire and coolant, $\alpha_{ref}$ and $\alpha_{in}$ – angle of refraction for outgoing light's beams and angle of incidence for outer surface of the sapphire tip.

### 3.3. Determination of the loading mode of the corundum tips during mechanical contacting with product ledges
Calculation and analysis of the effects of percussion mechanical contacting corundum tips with product ledges is most convenient to do in the admission of similarity and proximity of the nature of the process to the grinding of fragile products, worked in practice [19]. Thus it is accepted, that ledges of a product are similar to grains of a grinding wheel, peculiarities of processing of which are close enough. And so three states of the surface layer of the corundum are possible depending on the specific energy of contacting $W_{cont}$:

- for elastic deformation of the material
  \[ W_{cont} < W_{el} = \frac{\tau_p^2}{2 \cdot E}, \]  
  where $\tau_p$ – the limit of Peierls, which corresponds to the beginning of movement of material dislocations and determines the mode's boundary of the transition from the elastic deformation of the material to quasi plasticity mode, calculated as $\tau_p = 3.6 \cdot 10^{-6} E$. So, fraction $\frac{\tau_p^2}{2 \cdot E}$ converted to a view $(3.6 \cdot 10^{-6} \cdot E)^2 / 2E \approx 6.5 \cdot 10^{-12} E$, and inequality (2) changes its appearance
  \[ W_{cont} < 6.5 \cdot 10^{-12} E \]  

- for the quasi plasticity mode
  \[ 6.5 \cdot 10^{-12} E < W_{cont} < \frac{\sigma_p^2}{2 \cdot E}, \]  

- for fragile destruction
  \[ W_{cont} > W_h = \frac{\sigma_p^2}{2 \cdot E}, \]  

Some time ago were calculated some values for sapphire, according to [19]: limit Peierls $\tau_p = 126$ kPa, $W_{el} = 0.223$ J/m$^3$ and $W_{fr} = 1.625 \cdot 10^8$ J/m$^3$. Accordingly for calculation specific energy of contacting $W_{cont}$ everybody can use the formula deduced for a mode of grinding of sapphire billet:

\[ W_{cont} = \frac{\alpha \cdot k_f \cdot F_z \cdot v \cdot t_z}{S_{ave} \cdot \delta}, \]  

where $\alpha$ – an empirical coefficient of energy distribution of friction between the product and the grinding tool, it is accepted equal to 0.5, $k_f$ – coefficient of dynamic friction, $F_z$ – force of clamping for the cycle of processing, $v$ – speed of movement of grinding tool relative to the surface of the workpiece, $t_z$ – time of contact of the workpiece and grinding tool for the processing cycle, $S_{ave}$ – the average contact area of the workpiece and grinding tool for the processing cycle, $\delta$ – depth of cutting for the processing cycle.

Allowing proximity character of influence by a grinding tool and the cutter used in experimental researches [16] and with select $\approx 50$-fold overload it is possible to estimate the value of loads $W_{cont}$ and their consequences on corundum tip. So, we have $\alpha = 0.5$; the average contact area of the tip with cutter depends on the width of the cutter's ribbon with value $\approx 1$ mm and the width of the end of the sapphire rod with value $\approx 5$ mm and is equal to $5 \cdot 10^{-6}$ m. Friction coefficient between sapphire and stainless steel – 0.15, linear speed of moving cutter cutting with the diameter of 15 mm and the number of turnovers of 1000 turn/min is $\approx 0.8$ m/s and accordingly the time of passing cutter on the contact line of the tip length of 660 $\mu$m corresponds to $\approx 0.82 \cdot 10^{-3}$ C. The depth of defects in the structure of the crystal lattice can be estimated as at least 3–4 times more than in [19] because of the significantly higher load, so we can admit $\delta \approx 4 \cdot 10^{-4}$ m.

And after using all these data in the formula (6), we get next:

\[ W_{cont} = \frac{0.5 \cdot 0.15 \cdot 150 \cdot 0.8 \cdot 0.82 \cdot 10^{-3}}{5 \cdot 10^{-6} \cdot 4 \cdot 10^{-3}} = 3.7 \cdot 10^6 \text{ Pa}. \]  

The obtained value is less than the maximum permissible value of the $W_{fr} = 1.625 \cdot 10^8$ J/m$^3$ and so the character of the shock mechanical contacting corundum the tips with product ledges corresponds to the quasi plasticity mode without fragile destruction. It is important, that the ratio $W_{fr}/W_{cont} \approx 44$, obtaining more than 40-fold safety margin during using corundum tips in contact measurements. This value is very close to the calculated 29-fold safety margin previously defined in the work [15] by using an
alternative independent method. It demonstrate the high reliability of accepted assumptions and correctness of mathematical calculations.

3.4. Results of metrological analysis ACD with laser interferometer

The initial practicing of the telescopic ACD was carried out using a console solid stainless steel rod inserted inside the measuring rod and an incremental photoelectric converter of linear movements LIR-3 [23], Production of SKB IS (St. Petersburg). This ACD had the resolution ≈0.1 μm with measuring range ≤ 100 mm.

The more perfect version of ACD, presented in Figure 1a, contains a laser triangulation displacement sensor RF603-15/2 with a measuring range of 5 mm, resolution of 0.2 μm and accuracy of ≈ 1 μm [21]. However, the achieving a higher level of accuracy parameters is possible, probably only by the use laser interferometer in the ACD. Thus the resolution can be reduced to values ≈ \(\frac{\lambda}{1000} \approx 0.6 \text{ nm} \) [22,23], and even to ≈ \(\frac{\lambda}{3000} \approx 0.2 \text{ nm} \) [24], where \(\lambda\) is the wavelength of the laser, for He-Ne laser \(\lambda=0.6328 \mu\text{m}\).

One of the essential for such constructions ACD becomes the temperature error arising from heating of a corundum tip during the measurements. Metrological analysis for similar ACD has previously been carried out in [25] and it was shown that for the ACD with corundum tip, the main components of the error \(\Delta l_{\text{acd}}\) can be considered the error of the laser interferometer \(\Delta l_{\text{li}}\) and the error caused by thermal the extension of the tip \(\Delta l_{\text{tip}}\), given that they are independent of each other and have a normal distribution. According to this, the expression for the total error is takes the next form:

\[
\Delta l_{\text{acd}} = \sqrt{\Delta l_{\text{li}}^2 + \Delta l_{\text{tip}}^2} .
\]  

(7)

However, since in most cases the tip is the predominant source of error and \(\Delta l_{\text{tip}} > \Delta l_{\text{li}}\), therefore, the expression (7) should be converted to type \(\Delta l_{\text{acd}} \approx \Delta l_{\text{tip}}\). At the same time two optical circuits of ACD are possible: without a reference channel and at its introduction. In the first case, the expression for temperature error from the heating of the \(\Delta l_{\text{tip}}\) is determined by the expression

\[
\Delta l_{\text{tip}} = 2\Delta l_{\text{r}} \cdot \text{tg} \alpha_{\text{ref}} = 2\Delta l_{\text{r}} \cdot \text{tg} \left(\arcsin \frac{n_{\text{cool}}}{n_{\text{sap}}} \right) = 2\Delta l_{\text{r}} \cdot \frac{n_{\text{cool}}}{n_{\text{sap}}} \sqrt{1 - \left(\frac{n_{\text{cool}}}{n_{\text{sap}}}\right)^2} .
\]  

(8)

where \(\Delta l_{\text{r}}\) – the measurement error insertion the thermal expansion of the tip, \(\alpha_{\text{ref}}\) – the angle of full internal reflection, \(n_{\text{sap}}\) и \(n_{\text{cool}}\) – refractive indices of sapphire and coolant.

At substitution of values for sapphire \(n_{\text{sap}}=1.76\) and coolant on the basis of glycerin \(n_{\text{cool}}=1.47\) the expression is received formula \(\Delta l_{\text{tip}} \approx 3\Delta l_{\text{r}}\), by which some time ago was calculated the values \(\Delta l_{\text{r}}\) for three values of thickness of sapphire tips at heating at 20º C, respectively: 0.9 μm, 1.8 μm and 2.7 μm. Figure 2 show dependences of temperature measurement errors \(\Delta l_{\text{r}}\) from tip heating \(\Delta T\) for some values of the tip's depth: 1 mm, 2 mm and 3 mm.
Figure 3. Dependences of measurement errors $\Delta T'$ from tip heating $AT$ for some values of the tip's depth: 1 mm, 2 mm and 3 mm.

Calculations performed for the second variant using the reference channel showed that the measurement error can be reduced to nanometer units [25].

4. Results of experiments
During some last year Dr. Leun V (OmSTU) was created and experimentally investigated prototype of the wide-range telescopic ACD. Initially, for ease of implementation, the console-mounted solid stainless steel rod with a diameter of 10 mm, entered inside the measuring rod, was applied. This did not lead to a significant increase in the effort of moving the measuring rod, but improved the repeatability of measurements, reaching $\approx 1 \, \mu m$ (figure 4). During this experimental work of telescopic ACD is used an incremental photoelectric transducer of linear displacement LIR-3 [20], produced by the SKB IS (St. Petersburg) with the achievement of the following characteristics: discrete measurements - 0.1 $\mu m$, measuring range- $\leq 100 \, mm$, the maximum speed of the tip to/from the workpiece before the measurements $\geq 10 \, \mu m/s$, the minimum speed of bidirectional movements in the measurement process $\approx 2 \, \mu m/s$, resolution of displacement $\approx 1 \, \mu m$. Now being worked out experimental-design aspects of use in laser measuring meters (figure 5) by using the triangulation and interferometric technique for creation of hybrid ACD.

Figure 4. Research pilot sample ACD with the console fixed steel rod of telescopic guides

Figure 5. Research pilot sample ACD with a laser sensor of displacement
Possibilities of creation of telescopic guides with a sapphire rod are based on the experimentally developed technology of manufacturing of high-precision sapphire plunger pairs, the results of which are presented in [26-28]. Its feature lies in the sawing of the whole sapphire monolith "Bul" (growth by the method of Kyropoulos) or "boats" (growth by method Bagdasarova) diamond circles with the receipt of square blocks. Further, these blocks are processed on the universal grinding machine model CG 2535-AL or CG 2550-AL, universal grinding machine semiautomatic model 3U12AAF11 with UBD and other diamond circles with large grains of diamond, to obtain rough processed sapphire cylindrical billets.

At rough grinding of the received billets the diamond circles, drills and hons are applied, with sizes of diamond grains 0.8... 0.1 mm and coolant: 5W-ADDINOL Super light 5W-40, OW-CASTROL Formula SLXOW-30 and others.

At average grinding of billets mechanically process diamond tools with size of diamond grains 0.3...0.09 mm, reaching minimum tolerance with surface roughness $R_a$: 1.25...1.6 $\mu$m.

Fine grinding of billets is carried out by diamond abrasive circles on a bundle M1 with the size of grains 125/100 $\mu$m, 100/80 $\mu$m. The concentration of 100%, the diamond brand AC 15, AC 20, AC 32, the speed of the instrument is 5 m/s, reducing the surface roughness to the values of $R_a$: 0.63 … 0.80 $\mu$m. The rate of removal of the product reaches 1000 $\mu$m/min.

Finish non-abrasive processing of the workpiece surface realize by means of plastic deformation of the roughness surface due to ultrasonic oscillations with frequency 21…23 kHz magnetostrictive transducer with concentrator on distance of 0.3…1 mm from the surface of the sapphire element, reducing the surface roughness to the values of $R_a$: 0.020...0.025 $\mu$m.

5. The discussion of the results

The developed design of ACD demonstrates high accuracy of measurements, wide functionality and relative simplicity of design. The implementation of the central cantilevered stem from the optically transparent high-strength corundum (sapphire, ruby) allows to reduce the dimensions of the mechanical and optical parts of the ACD and to apply the compressor to control the movement of the measuring rods and tip. The use of telescopic sliding guides already at the stage of working out of the pilot sample ACD showed high efficiency, demonstrating high frequency of measurements ≤ 1 $\mu$m.

It is shown that the value of the specific energy of the contacting $W_{cont}$ corundum tip with product ledges, defined by the calculation path, corresponds to the quasi plasticity mode of the material and does not lead to fragile destruction, providing ≈ 40 times the stock strength. The obtained value is close to the results of calculations, carried out earlier on the alternative method, demonstrating high reliability of accepted assumptions and correctness of mathematical calculations.

Error of measurements ACD with corundum tips by use of laser interferometers can make the following values: 0.3 $\mu$m, 0.6 $\mu$m and 0.9 $\mu$m for tips of thickness 1 mm, 2 mm and 3 mm respectively at heating them on 20 ºC (without a reference channel laser interferometer) and no more than some nanometers (with the introduction of the reference channel of the laser interferometer).

6. Conclusion

- The use of telescopic sliding guides with a cantilevered rod of high-strength and optically transparent corundum leads to an increase in the rigidity of the mechanical design of the ACD, increasing the repeatability of measurements and can become basis for the construction of prospective high-precision ACD.

- The use of optically transparent tips expands the functionality of ACD, allowing to realize the possibilities of contact and/or contactless measurements, lateral coming with synchronization of the ACD and control the shape of it surface. Application as such materials corundum (sapphire, synthetic, ruby) at impulse shock loads at the level of ≤ 3N, arising at contacting with a detail, correspond to a mode quasi plasticity corundum, without causing to their cracking and allowing you to actively use them in ACD.
Increase of accuracy of measurements ACD is possible by use of laser interferometers movements. The main component of the error is caused by the temperature extension of the tip, which is significantly reduced by the introduction of the reference channel.

The modern technological level allows to realize telescopic sliding guides ACD by use sapphire plunger pairs.

The combined use of telescopic guides, high-strength and optically transparent measuring tip and laser interferometer moves allows one of the most promising combinations of technical solutions for multifunctional full high-precision ACD.

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