Methods for improving accuracy in measuring deviations from roundness and cylindricity

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Abstract. The problem of improving the technical level and quality of industrial products is now one of the most important tasks. The performance of machining workstation, machines and instruments depends on the quality of production of parts and assemblies and the accuracy of their connections. Precision parameters play a special role in machine tool construction and instrumental production of parts for the aerospace industry. In machines, the value of the torque transmitted by the spindle of the metal cutting machine to the tool, the durability of roller conical bearings, as well as the tightness of connections, the strength of press fits, the correctness of centering on conical surfaces, the accuracy of kinematic pairs and circuits, especially in the spindles of precision CNC machines, which significantly affects the quality of the manufactured products.

At present, to achieve the necessary accuracy of manufacturing parts, numerous criteria for the performance of lathes have been developed, which are regulated by GOST Standards and other technical documentation.

The main criteria for the machine's performance are its geometric and kinematic accuracy, static rigidity, positioning accuracy, heat, vibration, and wear resistance, as well as other parameters.

However, even if all the requirements of the standards are met, it is not possible to guarantee the production of a part that fully meets the requirements of the working drawing.

This is because in the machining process on the lathe, there is a whole set of operational loads, has a random nature, resulting in a trajectory forming elements of the machine are distorted, resulting in distorted shapes and its accuracy rate.

Particular attention is paid to precision parameters in the aerospace industry, since it is there that the highest requirements are imposed on the processed products.

In accordance with the GOST standard deviation from roundness is defined as the greatest distance \(\Delta\) from the points of the real profile to the adjacent circle:
Similarly, the deviation from cylindricity is determined — this is the greatest distance $\Delta$ from the points of the real surface to the adjacent cylinder within the normalized section $L$.

The deviation from the cylindricity is controlled by measuring the deviations of a limited number of control points or profiles (lines) lying on the controlled surface.

For such tasks, round meters are most often used that provide precise rotational and translational movement [1-2].
Before measuring, the part is centered and leveled along two sections located on the boundaries of the normalized section. Then the controlled surface is measured along separate lines using a measuring Converter and the corresponding profilograms of the measured cross-sections are recorded in the polar or Cartesian coordinate system [3].

In modern devices, the measurement in each selected section is carried out discretely and the software allows you to automatically calculate the deviation from the cylindrical shape from the measured coordinates of points [4].

As a rule, the deviation from roundness and cylindricity is measured by the contact method of measuring the deviation of the side surface of the measured part during precision rotation [5-7].

![Figure 4](image)

**Figure 4.** Contact method for measuring the deviation of the side surface of the measured part during precision rotation.

But even precision rotation affects the measurement results. In modern automatic round meters for working with critical parts, the ultra-high-precision turntable has a margin of error \((0.02 + 0.00035 \text{ H})\) microns. In some cases, this error is half of the total measurement error.

The article [8] was chosen as a prototype, where a laser goniometer constructed from various types of triangulation methods is analyzed. Triangulation is based on the use of the mirror component of the reflected light beam [1]. The device covered in this article is like the well-known Schack-Hartmann sensors [9].

The device covered in this article is similar to the well-known Schack-Hartmann sensors[9], which work to determine the change in the wave front and can achieve a measurement accuracy of \(5\times10^{-4}\) microns, which exceeds the GOST for measurement.

This means that their sensitivity ensures compliance with the requirements and is comparable to the best models of round meters.

The developed measurement technology has a measurement accuracy of \(5\times10^{-3}\) microns, which also corresponds to GOST for measurement, but does not use such expensive sensors.

To improve the accuracy of measurements, it is necessary to select a technology for high-precision measurement of the position of the light spot (SP), which will be taken from the light beam coming from the object of rotation, which represented on figure 5.
Figure 5. The technology of high-precision measurement of the position of the light spot (LS).

The spatial angle between the light beam and the optical axis of the measuring camera, which falls on the "zero" pixel of the photo-receiving device (FPU), is calculated by the formula:

\[ \tan \varphi = \frac{R}{f} \]

where \( R \) is the radius of the circumscribed circle following the light spot, represented on figure 6, \( f \) is the rear focal plane of the measuring camera lens that coincides with the FPU plane.

Figure 6. Circumscribed circle following the light spot.

A trace described by a light spot in the rear focal plane of the measuring camera lens on the FPU plane, where \( \Psi \) is the angle of rotation of the spindle; \( \omega \)-angular speed of rotation of the spindle; \( t \) – time relative to the initial time;

The article [10] describes the technology for obtaining the coordinates of the position of a light spot (SP) with accuracy at the level of thousandths of a pixel on the plane of the CCD matrix (Space-Charge Coupling).

If at the current level of development of photodetector matrix technology there are matrices with a pixel size of 5 microns or less, then the coordinates of the photo-energy center of the jointventure can be found by the formula:
\[ C_x = \frac{\sum_{n=1}^{N} \sum_{m=1}^{M} l_{n,m} n}{\sum_{n=1}^{N} \sum_{m=1}^{M} l_{n,m}} \]
\[ C_y = \frac{\sum_{n=1}^{N} \sum_{m=1}^{M} l_{n,m} m}{\sum_{n=1}^{N} \sum_{m=1}^{M} l_{n,m}} \]

where \( C_x, C_y \) – coordinates of the center of gravity on the x and Y axes, respectively; \( l_{n,m} \) – elements of the brightness matrix; \( N, M \) – number of columns and rows in the brightness matrix; \( n, m \) – ordinal indexes on columns and rows of the matrix.

The total measurement error is calculated as:
\[ \Delta n = 2 \cdot \sqrt{(\sigma)^2 + (\Delta f)^2 + (\Delta k)^2} \]

where \( \sigma \) – average square random error of measurement, \( \Delta f \) – additional measurement error caused by changes in external conditions, \( \Delta k \) – the standard uncertainty of the calibration.

Modern photodetector screens have a pixel size even smaller than 2 microns[7] and use CMOS rather than CCD technology, which is more expensive but also more accurate, since this technology has less noise. On this basis, it can be argued that the photodetector screen can measure the accuracy of moving the center of the light spot with an accuracy of 50 ... 5 nm.

Such measuring equipment meets modern requirements for the most high-precision instruments. The use of this technology can significantly improve the accuracy of measuring parts, and therefore the quality of work of machine parts and devices. In addition, this method is non-contact and completely eliminates the possibility of damage to the surface of the controlled or measured object, as well as allows you to control not only individual local zones, but also the entire surface of the part.

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