Determination of reliable techniques for carrying out measurements on coordinate-measuring machines

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Abstract. Coordinate measuring machines (CMM) are gaining popularity in manufacturing enterprises among the most universal means of determining the geometric characteristics of parts. Among a large number of CMM manufacturers' offerings, a suitable model can be purchased based on the dimensions of the monitored product, the accuracy of the measurement and a number of additional functions. Some manufacturers claim that the location of the part in the measuring zone and the location of the calibration of the measuring tip do not affect the measurement result. In this paper, experimental studies of the measurement of the reference ring on hexopod (six-axis) CMM in different positions, different distances from the calibration site along the sphere, and different positions of the calibration of the measuring tip are presented. From the results obtained, one can see the most approximate values of the obtained values of the diameter of the ring and the deviation from roundness, depending on the position of the calibration sphere and the calibration angle of the measuring tip. The work shows the difference in the results of multiple measurements of the reference ring, depending on the measurement technique.

1. Introduction

The quality of engineering products, radio electronics and instrumentation is largely determined by the geometric precision of manufacturing parts. A significant proportion of all measurements in modern production is the measurement of linear dimensions. As a wide-universal means of determining geometric characteristics, measurement tools have become widespread, in which a coordinate method is used, the essence of which is to sequentially find the coordinates of a series of surface points in space, and then calculate the dimensions of the product. A special feature of coordinate measurements is the direct measurement of individual points of the surfaces of the elements of the part and calculation of the normalized geometric parameters from the results obtained.

Such devices not only allow measuring various geometric characteristics (including deviations of the shape and arrangement of surfaces) of various types of parts, but are also well suited for automating the control and measurement process. This is what determined the use of coordinate measuring machines in modern flexible production systems.

Existing coordinate measuring devices include, as a rule, linear measuring systems that operate in Cartesian coordinates. In some coordinate meters, a measurement of the angular coordinate is provided. In most cases, all measuring instruments measure the coordinates, only in a one-dimensional or two-dimensional plane. In previous works [1], instruments for monitoring linear dimensions during processing were considered. CMM is most often used in laboratory conditions, which does not allow us to quickly evaluate the dimensions of products on the machine, but the authors of the article are working on the creation of a portable mobile coordinate measuring machine in the form of a stylus.

2. Formulation of the problem

All means of measurement have random and systematic components of error. CMM also includes these errors. A regular change in the results with repeated measurements or a constant error indicate the presence of a systematic error. The appearance of a systematic error is caused by the deviation of one of
the parameters of the measurement condition from a specified value, or by the mechanical wear of parts and the aging of the electronic components of the measuring means. An example is the wear of the touch point on the measuring tip. Such an error is easy to identify and exclude from the measurement results. To do this, enter a correction factor or calibrate the measuring instrument. As a result of the calculations and corrections of the systematic error, an insignificant residue can be observed. Random errors, unlike the systematic ones, do not have regularities and can’t be excluded. It is possible to detect a random error after repeated measurements [2] of the same physical quantity under the same external conditions by one measuring instrument [3].

In the reviewed sources, the measurement processes [6], the processing of the results [2] are described in detail, taking into account the compensation of some errors and errors [4] and the assessment of the accuracy of specific equipment [5]. But in studies [3,4,5,6,7] calculations are given for one type of part. Consequently, the results are not universal and for each individual case there will be additional errors due to the peculiarities of the geometry of the part and the equipment used. For the most accurate measurement, it is important to analyze the results considered taking into account the location of the part on the working area of the CMM. The results of this article help to reduce the methodological error and stabilize the data due to the optimal position of the probe tip and taking measurements near the calibration site.

The following errors may affect the accuracy of the measurement using CMM (Figure 1):

| I | Components of the errors of coordinate movements, measurements and counting of the surface. |
|---|--------------------------------------------------------------------------------------------|
|   | Mechanical design: - non-compliance with the Abbe principle; - deviation from the straightness of coordinate movements; - angular deviations with coordinate displacements; |
|   | Measuring systems: - accumulated error; - interpolation error; - convergence of the count; - Discreteness of counting; - electric and mechanical inertia. |
|   | Measuring heads: - convergence count; - uneven sensitivity in different directions of measurement; - errors in the shape of the measuring tips; - mechanical and electrical inertia; - calibration error. |

| II | The error of coordinate measurements; |
|    | Factor factors: - surface defects; - dustiness and contamination of the surface; - modulus of elasticity and hardness; |
|    | - deviation from the form; - roughness; - temperature deviations; - weight. |

| III | Environmental factors: - temperature deviations; - vibrations and deformation of the floor; - electromagnetic interference; - dustiness and contamination of the coolant; - change in pressure; - change in humidity. |

| IV | Factors of exploitation: - aging; - wear and tear; - de-setting; - corrosion. |

| V | Processing and presentation of measurement results: - measurement order; - determination of base surfaces for evaluation of measurement results; - formulation of measurement tasks; - algorithms and programs for calculating the GE; - limited accuracy of calculations. |

Figure 1. Generalized scheme of measurement errors
3. Methodological errors - this error is very important when measuring at CMM, because the measurement of individual points in space by different methods yields different results. It is impossible to get to the same point in the same way, as well as to measure absolutely all points of the surface. In connection with this, possible surface protrusions can be missed during measurement and are not approximated when constructing the surface. As an example, we can consider a circle. To construct a circle, at least three points on the surface are required. Given the deviation from roundness, the diametrical dimensions will also change constantly depending on the location of the contact points. This means that the methodological component of the error depends on the technique used, which affects the determination of the actual size of the component parts. Moreover, the methodical error will be affected by the deviation of the form. To reduce the effect of deviation of the shape, it is necessary to shoot more points from the surface. Another factor that influences the methodical error is the algorithm for processing the results of measuring the points of the real surface of parts having a deviation of shape.

3. Theory

After measuring the set of points in the majority of CMMs, the average size of the measured element is calculated (depending on the installed metrological software, it is possible to choose between the calculation based on the average principle or "minimum - maximum"). However, when normalizing the accuracy of geometric characteristics, which refer to dimensions, deviations of shape and location, the adjacent surface is assumed as the basis. So, the size of an ideal cylinder that passes through the protruding points of a real cylinder (adjacent or described cylinder) is taken as the largest shaft size. When calculating the results of a measurement on a CMM, the dimensions and positions of non-adjacent, and medium surfaces are determined. Most often, the axes of the adjacent cylinders and middle cylinders do not coincide, therefore, because of the inaccuracy of the algorithm used to calculate, the result of the mathematical processing will include a methodological error. The calculation of medium surfaces instead of adjoining ones is due to the fact that this measurement is the simplest and takes less computer time (it is often called the least squares method). In addition, the methodical error of measurement also occurs with other types of measurements. That is, by measuring the diameter of the shaft using a micrometer, you can’t find the diameter of the adjacent cylinder to determine the maximum diameter. But with these measurements, the operator is not bound by measuring a
limited number of points, but produces a certain number of measurements aimed at revealing the limiting dimensions. For the same details, the sequence of measurements and the number of measured cross sections can be different. But for CMM, where the measurement technique is mostly programmed in the majority of cases, and the measurement process refers only to individual points, the methodological component of the measurement error is therefore specific and, as a rule, the dominant error.

According to the international Guideline on the expression of the uncertainty of the GUM measurement, in most cases the measured value of \( Y \) is calculated from \( N \) other quantities \( X_1, X_2, \ldots, X_N \), related by the following functional relationship: \( Y = f(X_1, X_2, \ldots, X_N) \). The standard uncertainty of the function \( f \) can be defined as:

\[
u(Y) = \sqrt{\sum_{i=1}^{n} \left( \frac{\partial f}{\partial X_i} \right)^2 \nu^2(X_i)}
\]

This function is used in the measurement and processing of results. Depending on how the uncertainty is calculated, the values of \( X_N \) can be conditionally divided into two types:

- calculation of uncertainty, based on statistical observations of multiple measurements;
- calculation of uncertainties that are not based on statistical observations of multiple measurements (for example, previous measurement data, reference data of the manufacturer's specification) \[11\].

The accuracy characteristic of CMM itself is, in most cases, the magnitude of the MPE error (Maximum Permissible Error - the limit of the basic tolerable error), which is determined in the group of standards ISO 10360. This characteristic has the form \( \text{MPE} = A + \frac{L}{R} \), where \( L \) - length of the measured object, mm; \( A, K \) are constants that characterize CMM. Thus, for the LAPIK coordinate measuring machine CMM-750 MPE is \( \pm 2.0 + L / 280 \) μm.

Most CMM fix the coordinates (x, y, z) of the center of the probe, so the accuracy characteristics of the CMM itself can lead to uncertainty in measuring the coordinates of the points (x, y, z).

To assess the uncertainty of measurements, the results of interlaboratory studies on STB ISO 5725 and ISO / TC 12748 "Guidelines for the application of estimates of repeatability, reproducibility and accuracy in estimating uncertainty of measurement" are generally used. Interlaboratory studies are most often conducted in assessing the accuracy of methods for performing measurements and their validation. The estimation of accuracy and bias is the result of interlaboratory studies that can be typical for performing a certain measurement procedure and therefore can be used by any laboratory that applies this measurement method if the tests are conducted in accordance with a standard (documented) procedure. The measurement conditions and control samples must be consistent with those used for interlaboratory comparison. Correctness and precision of measurements when the laboratory conducts test procedures are comparable with interlaboratory comparisons. For standard test procedures, accuracy and accuracy should be determined through interlaboratory comparisons (STB ISO 5725-2). The main characteristics of accuracy, which are obtained in such studies:

- \( s_r \) – standard deviation parameter of repeatability;
- \( s_R \) – is the standard deviation parameter of interlaboratory reproducibility.

To estimate the measurement uncertainty, the standard deviation of the reproducibility \( s_R \) is used, including the number of components of uncertainty that is larger than the standard deviation parameter of the repeatability \( s_r \).

4. Experimental results

The measurements were carried out in three calibration positions of the CMM measuring head: 180°, 90° and 45°. Taking into account that the accuracy of the CMM increases from the measured length or diameter and amounts to ± 2.2 μm in our case, we determine from the graphs the reliability of the results obtained. In the graph of Fig. 2 that when multiple measurements of the diameter of the reference ring hole at different points of the measuring table, we obtain the dispersion of the sizes within the permissible CMM errors. It should be noted that at a distance from the zero point, in which the calibration was carried out on the reference sphere, the values of the diameter measurement results go to the lower side.
Figure 2. Results of measuring the diameter of the reference ring at the position of calibration of the measuring head 180°

Figure 3. Results of measuring the diameter of the reference ring at the position of calibration of the measuring head 90°

Figure 4. Results of measuring the diameter of the reference ring at the position of calibration of the measuring head 45°

Figure 5. Results of measuring the cylindricality of the reference ring at the position of calibration of the measuring head 180°

Figure 6. Results of measuring the cylindricality of the reference ring at the position of calibration of the measuring head 90°

Figure 7. Results of measuring the cylindricality of the reference ring at the position of calibration of the measuring head 45°
In addition to measuring the diametrical size, the deviation from cylindricality was monitored. In Figures 5, 6 and 7 show the results, depending on the angle of calibration of the measuring tip and the position on the measuring table relative to the initial calibration point on the sphere.

5. Discussion of the results

Carrying out of experimental researches was carried out on a stationary heterocomposite CMM produced by LAPIK (Figure 8). The working measuring area of the table was divided into sectors with an interval of 100 mm (Figure 9). At each point, the diameter of the hole in the reference ring was measured. Calibration of the measuring tip was carried out at the starting point of the X and Y axes. After calibration, the ring was displaced along the marking and measured 10 times. The measurements were carried out automatically. The cylinder was divided into 3 sections with 12 measuring points each.

The results of the experimental studies were carried out on one CMM and the authors do not certify that other CMM will have similar results. Due to the research of the KAPM with the reference part, it is possible to obtain the most approximate values to the real geometric characteristics of the part. After carrying out of researches it is possible to choose the authentic technique for carrying out of measurements of other nomenclatures of details on manufacture. When carrying out measurements of the reference ring, some results exceeded the range of CMM error. The result of the experiment showed that the removal from the calibration site affects the measurement result. Thus, in order to determine a reliable measurement procedure at a CMM, it was necessary to carry out a number of experiments presented in the article, which show a methodological error significantly influencing the measurement result.

6. Conclusions and conclusion

Coordinate measuring machines (CMM) have become a necessary part of modern production and in metrology have made the same revolution as CNC machines in technology. The opportunity to dispense with standards, mandrels, sleeves, other highly specialized rigging gives the same benefits as the rejection of the system of conductors in technology. The ability of CMM to accurately and quickly evaluate the data and provide the operator with exhaustive information on the state of the production process, and is what distinguishes CMM from hand-held measuring devices of all kinds.

In order to be able to verify the results of measurements of CMM, taking them for real, the methodological component of the measurement error at the CMM and the measurement uncertainty estimation, which showed the greatest accuracy and stability of the measurements at the tip position, were considered 90°. The worst results were obtained when measuring in the vertical position of the measuring tip.
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