Model and software module for predicting uncertainties of coordinate measurements using the NX OPEN API

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Abstract. In CAM-systems (Computer-aided manufacturing), it is possible to simulate the process of measurement by the machine and coordinate measuring machine and generate measurement commands in the control program. Measurements can become the basis for the implementation of various adaptive processing schemes. The main advantage is an ability to adjust automatically the machining process basing on the measurement results without removing the parts from the machine. During measuring complex parts (stamps, engine blades) by the machine and coordinate measuring machine, measurement uncertainties significantly increase. It is not calculated in modern CAM-systems (for example, NX from SIEMENS and CATIA from Dassault Systèmes). This feature can lead to a degradation of processing precision (due to inadequate measurement accuracy) with program seemed definitive. The paper proposes a model and a software module for the prediction of measurement uncertainties, implemented with use of the NX OPEN API, which can be integrated into the CAM module.

1. Introduction

Three-axis coordinate measuring machines (CMM) equipped with measuring tips (MT) of spherical shape, or optical probes are used to measure the complex surfaces of parts. In optical probes an important role is given to the problems of optics [1,2]. Figure 1 shows the scheme for measuring a complex surface using an MT of spherical shape on the CMM.

Coordinate measurements of complex surfaces are carried out in the following sequence:
1. The advance of the MT to the measured surface is carried out at the defined coordinates of the nominal point until it contacts with the actual cover.
2. When the measuring tip and the actual surface come into contact, the coordinates of the sphere center of MT are stored.
3. The coordinates of the tangency point of the sphere are calculated from the coordinates of the center of the measuring tip and the normal vector at the nominal surface.

During measuring the surface by the CMM an error in determination of point position occurred because of the deviation of the direction of the normal of the real profile at the measured point from the nominal direction (compensation error of the radius MT).

2. Model and software module of coordinate measurements

To assess the accuracy and optimization of manufacturing processes widely used computer and mathematical modeling [3]. To solve the problem of ensuring the accuracy and productivity of coordinate measurements, it is necessary to have a mathematical description of the process. Furthermore, it can be necessary to compare different approaches of parameters calculation. The arising errors can be estimated using the
"Virtual CMM" approach [1], which involves creating a mathematical model and software algorithms of coordinate measurements for its implementation.

![Figure 1. Scheme for measuring a complex surface.](image)

To assess the errors, we create a model that allows calculating the coordinates of the point of contact, the coordinates of the center of MT and the coordinates of the measured points in contact with the part surface.

Figure 2 shows a flowchart of the steps involved in the created model.

![Figure 2. A flowchart of the estimate method of measurement error.](image)

Thus, the created model allows calculating the coordinates of the point of tangency between MT and the real surface C, the coordinates of the point O, which is the center of MT, and the coordinates of the measured points E [2].

The coordinates of the measured points E are calculated at the radius of the measuring tip R in the normal direction from the points O by the equation:

$$ E = O + R \cdot N_{\text{comp}} $$

where $ N_{\text{comp}} $ is radius compensation normal.

The considered model does not take into account the random components of the measurement error of $\pm 2 \mu m$. These errors are thought of as noise, there are various methods for removing it during the operation of measured data processing [3, 4]. In the case of measurement when there is a reference CAD model, the coordinates of the measured points are calculated at the intersection of the normals $ N_{\text{comp}} $ to the surface of the CAD model and the sphere of the measuring tip (for example, measuring the ring gear). In the case of measuring the surface of a geometric primitive (sphere, cone, cylinder,
plane), the equidistant surface is described by the equation of the corresponding primitive by the least squares method (LSM) in the array of points \( O \). The direction vectors of the normals \( N_{\text{comp}} \) are redefined by the equidistant surface equation at the points \( O \).

Thus, it is possible to estimate the errors in the compensation of the radius of the measuring tip using the developed model. The error in measuring the radius of the MT in the \( i \)-th measuring point is calculated by equation:

\[
\delta_{\text{comp}} = |C_i - E_i|.
\]

(2)

The developed model is implemented as a software application in the NX / Open API module written in the programming language, Visual Basic. Thus, a software product is developed using the NX / Open API module and it works as a fully integrated "embedded" NX function with the extension *.dll.

![Figure 3. Virtual measurement of a point on a surface.](image)

To solve the optimization problem of the contact point search, the following optimization methods are used: the uniform search method and the golden section method. Difference from the existing NX solutions in the area of setting measurement operations (probing operation in the NX CAM module) is the calculation of the actual measurement error, while the standard CAM tools only implement automatically the generation of the measurement control program without taking into account the occurring errors.

Figure 3 shows the screen of the software interface and the results of its operation by the example of measuring a point on the surface of a rotor blade of a centrifugal compressor.

In a separate data window, information about the coordinates of the points and the measurement error is displayed. The module also implements the possibility of automated generation of a real surface having geometric deviations.

3. Estimation of gear wheel measurement accuracy

The developed model and the software application implementing it are applied to study the errors of the process of measuring the spur gear wheel [6] by the CMM. Table 1 shows the main geometric dimensions and tolerances of the gear wheel having accuracy degree of 6-5-5 of state standard 1643-81 [7] (industry standard 1.41671-77 [8]).

The virtual measurement of the involute surfaces of the teeth is performed with a space of 5% from the boundaries of these surfaces to eliminate the influence of irregularities occurring on the surface boundary [9]. In the process of measurement modeling, a strategy is applied in which the points are arranged as a grid (Figure 4), with the number of \( N \) points along the involute tooth profile and
$M$ sections along the width of the ring gear. In modeling, the lateral surfaces of the teeth are measured with the parameters $N = 10$ and $M = 5$.

Table 1. Geometrical parameters and tolerances of the gear.

| Parameter                        | Notation | Value  | Parameter                        | Notation | Value  |
|----------------------------------|----------|--------|----------------------------------|----------|--------|
| Number of teeth                  | $z$      | 24     | Initial-circle diameter, mm      | $d_w$    | 126,295|
| Module, mm                       | $m$      | 5.6    | Tooth thickness over             | $S_T$    | 12.47  |
|                                   |          |        | pitch-circle arc, mm             |          |        |
| Engagement angle, deg            | $\alpha$| 20     | Pitch, deg                       | $\tau$   | 15     |
| Gear face, mm                    | $b$      | 78.89  | Tolerance of radial runout of gear rim, $\mu$m | $F_r$    | 50     |
| Displacement coefficient         | $x$      | 0.90116| Limiting deviation of engagement pitch, $\mu$m | $\pm f_p$| ±9     |
| Splitting-circle diameter, mm    | $d$      | 134.4  | Tolerance of tooth profile error, $\mu$m | $f_f$    | 8      |
| Tooth-tip diameter, mm           | $d_a$    | 155.693| Standards of backlash, $\mu$m     | $E_{cs}$ | 110    |
| Tooth-space diameter, mm         | $d_f$    | 130.493|                                    | $T_c$    | 100    |

The radius of the measuring tip CMM for the measurement is selected 0.5 mm.

Modeling of 50 gears with deviations of shape and location from the nominal CAD-model is carried out within the tolerances specified in Table 1. For each case, a computer simulation of the contact measurement and calculation of errors in determining the point of the surface of the gear rim $\delta_{R_{comp}}$ (2) are carried out.

Figure 4. The strategy of measuring the involute tooth surface.

Figure 5 shows the histograms of the distribution of measurement errors $\delta_{R_{comp}}$ of the left and the lateral sides of the teeth during 50 experiments when all the teeth of each wheel are measured.

Analyzing the histograms of Figure 5, it is established that the error of compensation is distributed according to the $\beta$ law.

Table 2 shows the mathematical expectation and standard deviation ($\mu$; $\sigma$), as well as the limiting absolute values (minimum - $Min$, maximum - $Max$) of errors $\delta_{R_{comp}}$ for the sample of gears with a confidence level of 99.73%.

Table 2. Absolute values of the gear measurement error $\delta_{R_{comp}}$.

| Tooth face | $\mu$, $\mu$m | $\sigma$, $\mu$m | $Min$, $\mu$m | $Max$, $\mu$m |
|------------|----------------|------------------|---------------|---------------|
| Left       | 1.6            | 0.6              | 0.7           | 3.4           |
| Right      | 1.6            | 0.6              | 0.7           | 3.2           |
As shown in the table, the measurement errors do not exceed 4 μm. Thus, it can be concluded on account of the computer simulation that the coordinates of the tooth points for the chosen measurement strategy and the geometry deviations are determined quite accurately and further calculations of the wheel accuracy parameters can be carried out basing on the results of obtained data.

4. Conclusion
This paper considers a model for predicting errors of the radius compensation of the measuring tip of a spherical shape in monitoring surfaces by the CMM. The model is implemented as a software module using the NX OPEN API. It can be integrated into the CAM module during development of control programs for taking into account the measurement errors. In the future, it is planned to simulate the remaining components of the error and compare the simulation results with the results of the experiments.

5. References
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