Uncertainty evaluation for coordinate metrology by intelligent measurement

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Abstract

In coordinate metrology, the evaluation methods of uncertainties of measurements in a specific measuring strategy are key techniques. In this article, we formulate the uncertainty evaluation methods by intelligent measurement. First, the relationship between uncertainties of measured results and a measuring strategy are described. Second, ISO/TC 213/WG 10 activities to development of the standards for CMM as ISO 15530 series for uncertainty estimations are introduced. Then, the novel calculation method by uncertainty propagation of the CMM software is proposed. This method deals the CMM software as the black box and uses the offline mode of the CMM software. The methods deals with the variances of point coordinates and the covariance by handling the error propagation simulation reflecting kinematic error of CMM, kinematic error of a probing system and form deviations of the measured workpiece.

Keywords: CMM, coordinate measuring machine, uncertainty, CMM software, error propagation

1. Introduction

In coordinate metrology, the evaluation methods of the uncertainties of measurements in a specific measuring strategy are key techniques. The role of uncertainty estimation methods and the relationship between the uncertainty of measured results and a measuring strategy are described. We also describe ISO/TC 213/WG 10 activities to development of the standards for CMM as ISO 10360 and ISO 15530 series. In ISO 15530 series, the part 4 defines the method to estimate the uncertainties by computer simulation [1, 2, 3].

Then the novel calculation method by uncertainty propagation of the CMM software is proposed. This method deals with the CMM software as the black box and uses the offline mode of the CMM software. In the proposed method, the error propagation method with the Jacobian matrix of CMM software is formulated, and the Monte Carlo simulation is not used. Therefore, the properties of uncertainties are easy recognized and the calculation time of the simulation is small.

2. Uncertainty estimation in coordinate metrology

For the next generation production system, the three dimensional complex machine parts with high accuracy and high function are used to perform the high functional machining and nano-based mechanical system (Fig. 1). There are three key technologies in intelligent measurements for the next generation production system as follows;

1. Uncertainty of measurement is utilized to decide proving conformance in industry,
2. 3D complex machine parts are keys for high accuracy and high function, and
3. Uncertainty in coordinate metrology has large difficulties.

From the above items, the uncertainty estimation in coordinate metrology is the key technology.

Figure 2 shows an example of the uncertainty estimation in coordinate metrology. In this figure, the angle (88.52 arc-degree) between the axis of the cylinder and the normal vector of the plane can be easily measured and calculated by CMM. However the uncertainty of the angle (0.25 arc-degree) is difficult to estimate. Because the uncertainty estimation method evaluates the uncertainty contributors from the uncertainty of each coordinate, effects of form deviations, effects of environmental conditions and so on [4, 5]. And, the relationship between uncertainty and strategy of measurement is very complex. Figure 3 shows the positional deviation of the center coordinate of a measured circle. The positional deviation is deference by the number and the positions of measured points [6].

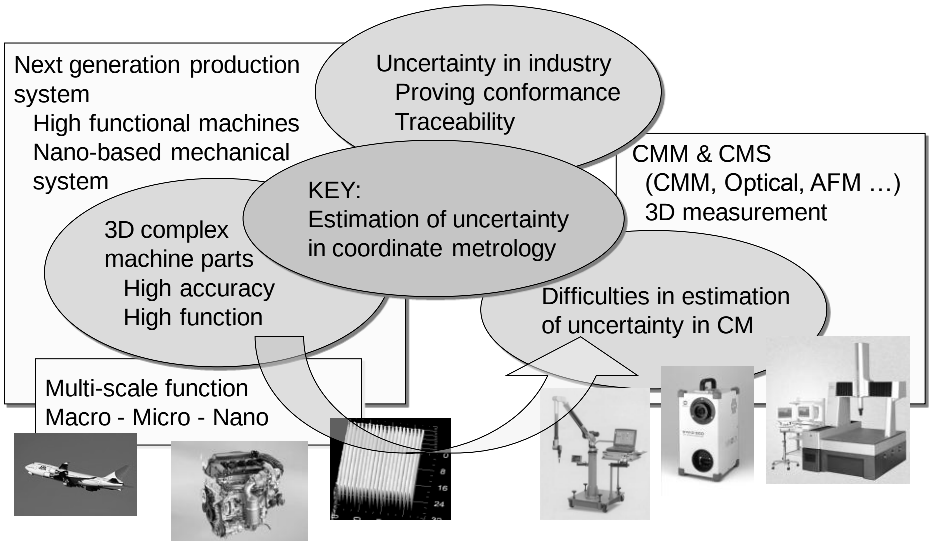


Fig. 1. Estimation of uncertainty in coordinate metrology in the next generation production system.

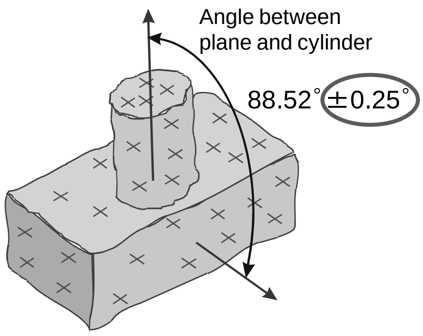


Fig. 2. Uncertainty in coordinate metrology.

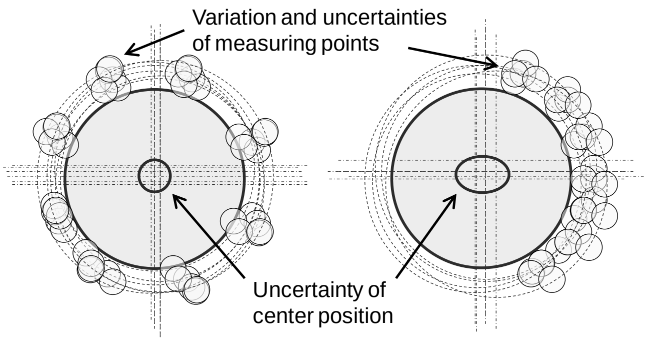


Fig. 3. Relationship between uncertainties and a strategy of measurement.

3. Methods to estimate uncertainty in ISO standard

ISO TC 213/ WG 10 (coordinate measuring machine) is developing the standards related to CMM. ISO 10360 series focus on the acceptance test of CMM [2, 3]. Then, ISO 15530 series are "Techniques for determining the uncertainty of measurement" by 4 parts (see Table 1). Figure 4 illustrates the example of multiple measurements in ISO 15530 Part 2. The artefact is measured in 4 orientations which the user accepts as “natural positions”, i.e. in which no bigger or additional uncertainty sources are present. 5 different randomly selected point distributions are used in each orientation.

Figure 5 shows the procedure of substitution measurement by a measuring cycle (ISO 15530-3). In the substitution method, uncertainties from the calibration of the calibrated workpiece, measurement procedure (repeatability) and, variations due to the expansion coefficient, form errors, roughness are evaluated. The measured object and the standard are measuered by the same measuring strategy and the geometrical features, form deviationas, surface roughness, material of them are similar due to the functional properties (see Fig. 5 (b)). The main and flexible method for determining the uncertainty is the computer simulation method (ISO 15530-4). A novel computer simulation method is proposed in the next section.

Table 1. ISO 105530 series: Techniques for determining the uncertainty of measurement [2].

part	content
1	Overview and metrological characteristics
2	Used of multiple measurement strategies
3	Used of calibrated workpieces or standards
4	Use of computer simulation

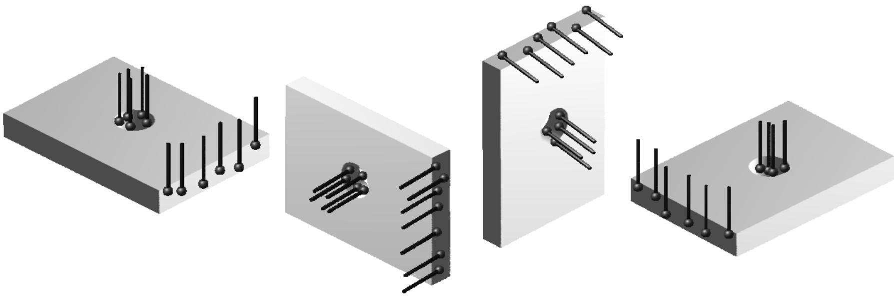
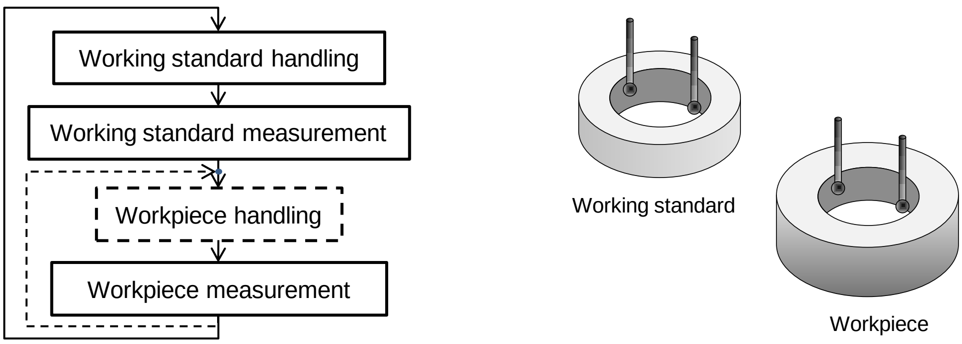


Fig. 4. The artefact is measured in 4 orientations which the user accepts as “natural positions”. 5 different randomly selected point distributions are used in each orientation (ISO 15530-2).



(a) (b)

Fig. 5. Procedure of substitution measurement of a measuring cycle (ISO 15530-3). The measured object and the standard are measured by the same measuring strategy.

4. Uncertainty propagation in coordinate metrology

A noble computer simulation method using error propagation of the CMM software for evaluating a task specific uncertainty in coordinate metrology is proposed. In the proposed method, the error propagation method with the Jacobian matrix of CMM software is formulated, and the Monte Carlo simulation is not used. Therefore, the properties of uncertainties are easy recognized and the calculation time of the simulation is small. Provided that specification or test result conforming to ISO 10360-2 is available, both variance of point coordinates and covariance expressing the mutual influence is handled to perform error propagation simulation reflecting kinematic error of CMM, kinematic error of a probing system and form deviations of measured workpieces [7, 8].

The uncertainty of the specified measuring task is calculated using the error propagation method. The proposed method is processed in the three steps as follows (Fig. 6) [9, 10];

1. The Jacobian matrix **A** as the error propagation of the measured results from the uncertainties of the point coordinates is calculated.
2. An uncertainty matrix **S** as the variance and covariance matrix of the point coordinates is estimated.
3. An uncertainty matrix **T** of the measured results is calculated by the Jacobian matrix **A** and the uncertainty matrix **S**.

In this figure, **P** is the vector of measured coordinates and **D** is the vector of measured results such as sizes, angles and diameters shown at equations (1) and (2).

$$\mathbf{P} = \begin{pmatrix} P_{1x} & P_{1y} & P_{1z} & \cdots & P_{nx} & P_{ny} & P_{nz} \end{pmatrix}^t \tag{1}$$

$$\mathbf{D} = \begin{pmatrix} D_1 & \cdots & D_m \end{pmatrix}^t \tag{2}$$

The Jacobian matrix **A** by the specified measuring task **F** is defined by equation (3). The Jacobian matrix **A** is calculated by the partial differential of **F** (equation (4)). In this method, the Jacobian matrix **A** of error propagation on CMM software is calculated using a black box method. In the black box method, the series of CMM software is handled as the black box. The factor a_{ij} of the Jacobian matrix between one of measured results D_i and one of coordinate P_j of measured points is calculated by the numerical differential of the CMM software in offline mode. The Jacobian matrix **A** defines the relationship of the propagation between the measure results **D** and the point coordinates **P** in the specific measured strategy.

$$\mathbf{D} = \mathbf{F}(\mathbf{P}) \tag{3}$$

$$\mathbf{A} = \frac{\partial \mathbf{F}}{\partial \mathbf{P}} \tag{4}$$

The uncertainty matrix **S** of uncertainties of the point coordinate is estimate by the following contributors as variance of point coordinate and covariance between two of the point coordinates. The uncertainty matrix **S** is defined the sum of the variance and covariance matrixes of all contributors as the follows;

1. Kinematic error of CMM: kinematic errors such as straightness, yawing and pitching of each CMM axis, and squareness between CMM axes,
2. Kinematic error of the probing system and
3. Form deviation of the measured workpiece.

Finally, the evaluation of the uncertainties of measured results **T** is calculated by the Jacobian matrix **A** and the uncertainty matrix **S** by equation (5), where $\mathbf{A}^t$ is the diagonal matrix of **A**.

$$\mathbf{T} = \mathbf{A}^t \mathbf{S} \mathbf{A} \tag{5}$$

The method of evaluating the uncertainties on the specified measuring tasks is formulated in the coordinate metrology to perform error propagation simulations reflecting kinematic error of CMM, kinematic error of probing system and form deviation of measured workpieces.

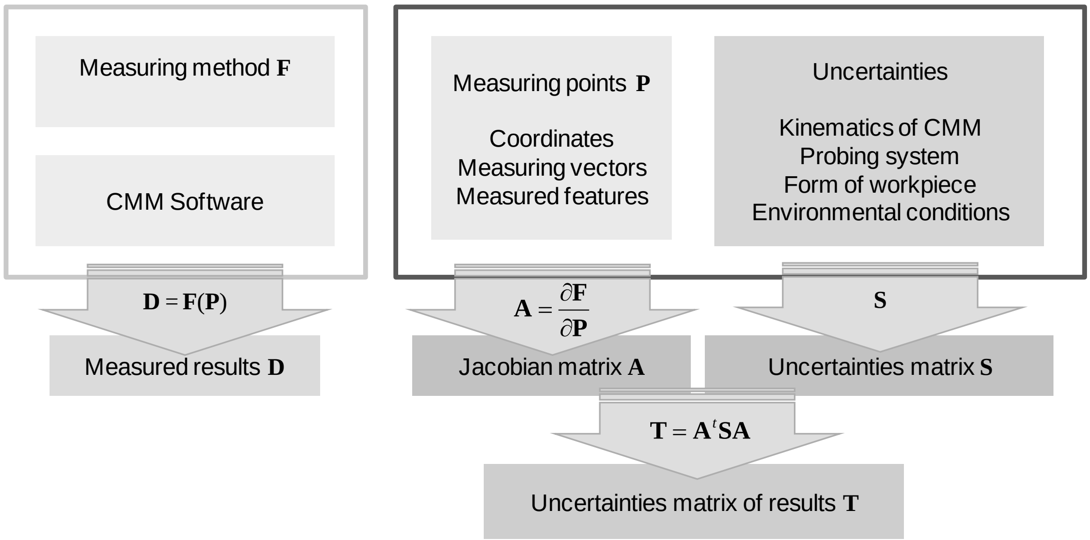


Fig. 6. Method of uncertainty estimation by propagation of the CMM software: **P** is measured coordinates, **D** is measured results, and **F** is function defined by measuring strategy. Uncertainties matrix of measured values **T** is calculated by the Jacobian Matrix **A** and uncertainties matrix of measuring points **S**.

5. Conclusion

In this article, we formulate the uncertainty evaluation methods by intelligent measurement. The novel calculation method by uncertainty propagation of the CMM software is proposed. This method deals the CMM software as the black box and uses the offline mode of CMM software. The methods deals with the variances of point coordinates and the covariance by handling the error propagation simulation reflecting kinematic error of CMM, kinematic error of a probing system and form deviations of the measured workpiece.

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