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ROUND ROBIN TESTS OF UNCERTAINTY ESTIMATION FOR COORDINATE METROLOGY BY SOFTWARE ERROR PROPAGATION

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Abstract: In coordinate metrology, the estimation methods of uncertainties in a specific measuring strategy are key techniques. In this article, we formulate the novel uncertainty evaluation methods using software error propagation. The proposed method deals with the CMM software as the black box and the variances and covariance of point coordinates uncertainties are estimated by CMM kinematic error, probing system error and form deviations of the measured workpiece. The round robin tests of uncertainties estimating are carried out and the results are evaluated. We confirm the availability of the proposed method by comparisons the measured results and the estimation values.

Keywords: Coordinate Measuring Machine, Uncertainty, CMM software, Error Propagation.

1. INTRODUCTION

In coordinate metrology, the estimation methods of the uncertainties in a specific measuring strategy are key techniques. First, the role of uncertainty estimation methods and the relationship between the uncertainty of measured results and a measuring strategy are described. For ISO standards developments, the standards for CMM as ISO 10360 and ISO 15530 series are issued. 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 short. And furthermore, ISO 15530 Part 4 requires the some specifications and a checklist for an uncertainty evaluating software (UES). The proposed method will satisfy the specifications required by ISO 15530 Part 4.

For validation of ability of the proposed method, we planned the round robin tests by 15 CMMs in 13 institutes in Japan. In these tests, a simple rectangular solid type workpiece with 2 holes are measured. The positions and diameters of the holes are evaluated in specified measuring strategies. Then, the variations and deviations of the measuring results are evaluated and compared with the proposed method. We confirmed the availability of the proposed method by comparisons between the measured results and the estimation values by the proposed method.

2. UNCERTAINTY ESTIMATION IN COORDINATE METROLOGY

For the next generation production system, the uncertainty estimation in coordinate metrology is the key technology. Fig. 1 shows an example of the uncertainty estimation in coordinate metrology. In this figure, the angle (88.52 arc-degrees) between the axis of a cylinder and the normal vector of a plane can be easily measured and calculated by CMM and CMM software. However the uncertainty of an angle (0.25 arc-degrees in the case) 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 uncertainties and strategy of measurements is very complex [6].

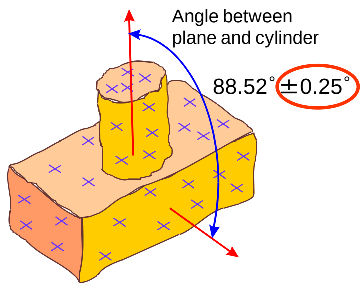


Fig. 1 Example of uncertainty in coordinate metrology for the uncertainty of angle between plane and cylinder.

3. 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 [7]. 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 short. 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 [8][9].

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. 2) [7][10][11][12]:

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

In this procedure, **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).

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

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

The Jacobian matrix **A** by the specified measuring task **F** is defined by equations (3) and (4). The Jacobian matrix **A** is calculated by the partial differential of **F**. 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 each factor of the Jacobian matrix between one of measured results and one of coordinate 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.

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

$$\mathbf{A} = \frac{\partial \mathbf{F}}{\partial \mathbf{P}} \quad (4)$$

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 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**.

$$\mathbf{T} = \mathbf{A}^t \mathbf{S} \mathbf{A} \quad (5)$$

In the proposed method, the method of evaluating the uncertainties on the specified measuring tasks is formulated. And, the uncertainties of measured results are calculated straightforwardly by the proposed method.

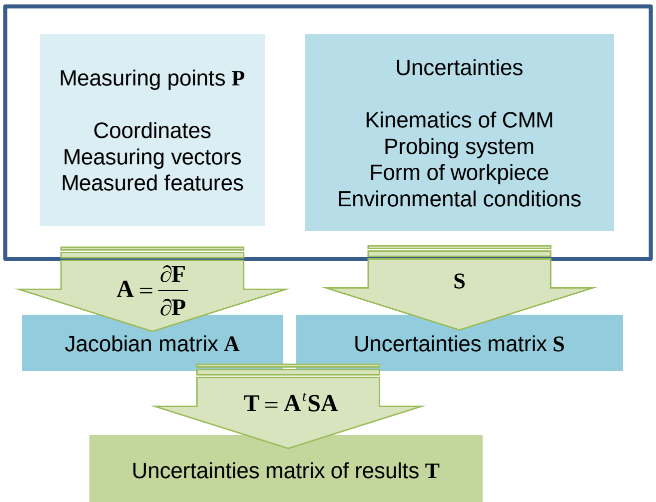


Fig. 2 Method of uncertainty estimation by propagation of the CMM software: **P** is measured coordinates and **F** is function defined by measuring strategy. Uncertainties matrix of measured values **T** is calculated by the Jacobian Matrix **A** and uncertainties matrix of measuring points **S**.

4. ROUND ROBIN TEST

4.1 Workpiece and Measuring Strategy

We performed round robin tests by a simple rectangular solid made of SUS420J2 with 2 holes as shown in Fig. 3. Size of the workpiece is 200 mm × 120 mm × 50 mm, and the diameters of Circle A and Circle B are 70 mm. The form deviation of Circle A is better than that of Circle B.

For the workpiece, we measured the items by the following strategy:

1. Z axis as the normal vector of Plane A,
2. Y axis as the line by Plane B,
3. Origin as the cross point of Plane B and Plane C, and
4. Diameters and center coordinates of Circle A and Circle B are measured.

The workpiece are placed on 3 positions and 3 directions of the workpiece are set as 0°, 45° and 90° from X axis. Then measurements are repeated 3 times on each position and direction. The number of points of circle measurement is 16 on total around, 1/2 around and 1/4 around of the circle. Fig. 4 shows two examples of measuring strategies; (a) illustrates the workpiece direction of 0° and measured total around of the circles, and (b) illustrates the workpiece direction of 45° and measured 1/4 around of the circles.

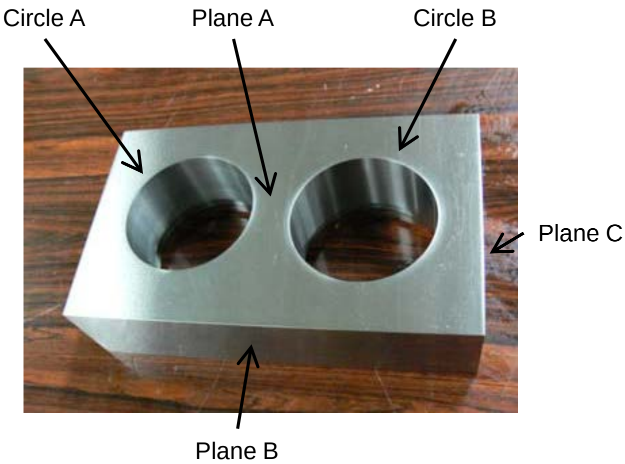


Fig. 3 Rectangular solid type workpiece with 2 holes. Size of the solid is 200 mm × 120 mm × 50 mm and diameters of circles are 70 mm.

4.2 Measuring Results and Estimated Uncertainty

First, the Jacobian matrix **A** is calculated the proposed method. Then, the uncertainty matrix **S** is estimated the following assumptions:

1. Form deviations (standard deviations) of each form are assumed from the form measuring on each form:
   - Plane B: 0.26 μm
   - Plane C: 0.27 μm
   - Circle A: 0.18 μm
   - Circle B: 0.84 μm
2. Random errors (standard deviations) include the other factor of uncertainties as defined by types of CMMs from MPE_E (Maximum Permissible Error of length measurement) the CMMs:
   - High accuracy CMMs: 0.48 μm
   - Low accuracy CMMs: 1.45 μm

Finally, we calculated the estimated uncertainties **T** from the Jacobian matrix **A** and the uncertainty matrix **S** by the proposed method.

Fig. 5 illustrates an example of measured results and estimated uncertainties for the diameter of Circle A: (a) is measured by CMM1 (high accuracy type) and (b) is measured by CMM2 (low accuracy type). In the figure, points ○ and + are measured results and bars are estimated uncertainties (k = 2) by the proposed method. The true values in these figures are estimated by high accuracy CMM with high precision strategies. Three small graphs in each figure illustrate the measured results by measuring area of circle of total around, 1/2 around or 1/4 around.

Fig. 6 illustrates other example of the results of Y coordinate of center of Circle B measured by CMM1 (high accuracy type) and CMM2 (low accuracy type).

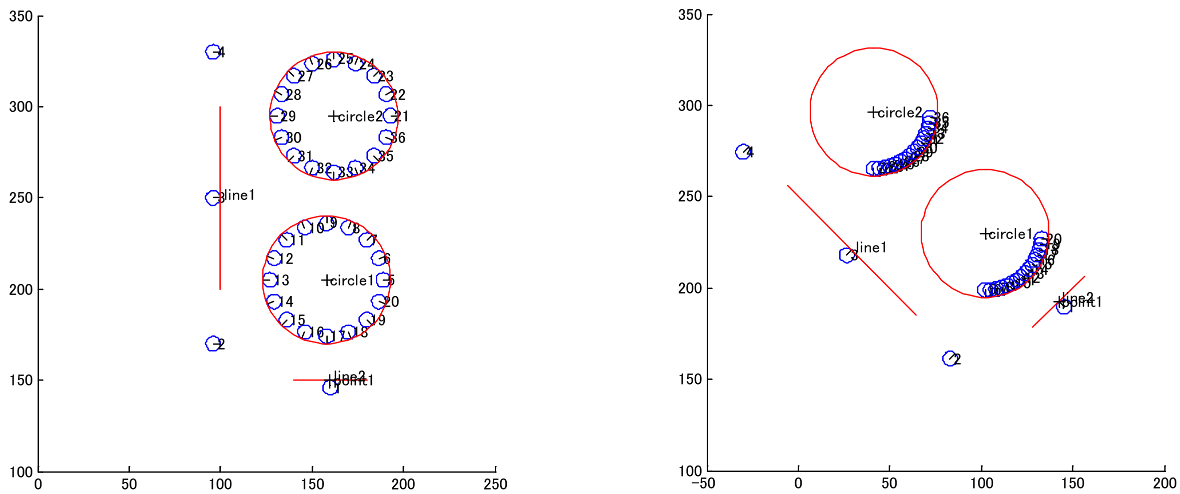
4.3 Discussions of the Results

The round robin tests are performed under the following conditions:

1. CMMs and probing systems are well calibrated,
2. Environmental conditions (ex. temperature variations) are well controlled,
3. Size of the workpiece is small, and
4. Form deviations of the workpiece are not good.

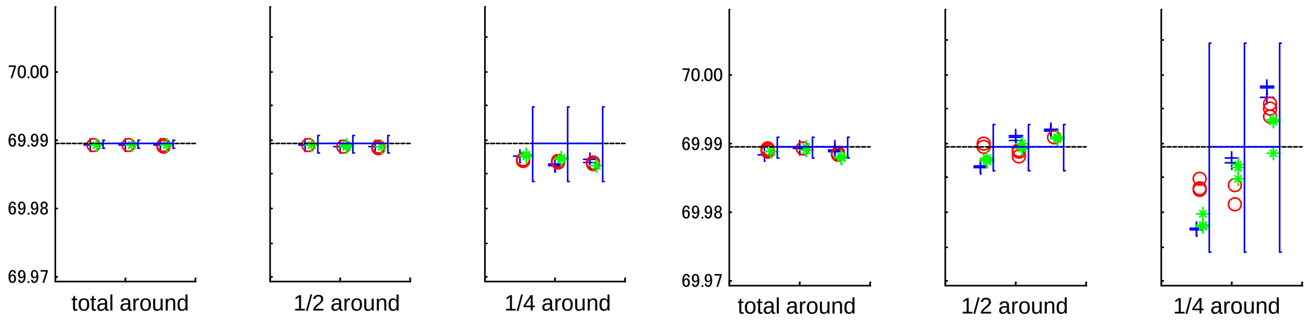
In above conditions, the main factors of uncertainty are random errors from CMMs and probing systems and form deviations of the workpiece under the specified measuring strategy. The proposed method can deal with the measuring strategy, form deviations and random errors. Therefore, the measured errors and estimated uncertainties are good agreements.

Therefore, we confirmed that our proposed method deals with measuring strategy, random errors and form deviations. The uncertainty matrix can be estimated from form deviations of each form and random errors by MPE_E of CMMs under the conditions of good environment and a small workpiece, and the proposed method can calculate the good estimations in these conditions.



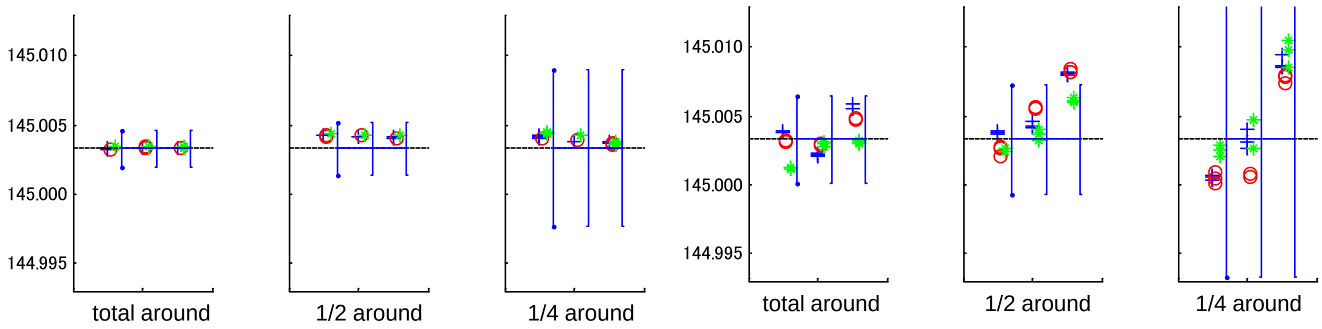
(a) (b)

Fig. 4 Two examples of measuring strategies: (a) workpiece direction of 0° and measured total around of the circles, and (b) workpiece direction of 45° and measured 1/4 around of the circles.



(a) CMM1 (High accuracy type) (b) CMM2 (Low accuracy type)

Fig. 5 Examples of measured results and estimated uncertainties. Diameter of Circle A measured by CMM1 and CMM2. Points are measured results and bars are estimated uncertainties (k = 2).



(a) CMM1 (High accuracy type) (b) CMM2 (Low accuracy type)

Fig. 6 Examples of measured results and estimated uncertainties. Y coordinates of Circle B by CMM1 and CMM2. Points are measured results and bars are estimated uncertainties (k = 2).

5. CONCLUSION

In this article, 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 CMM software, and 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. The round robin tests of uncertainties estimating are carried out and the results are evaluated. We confirm the availability of the proposed method by comparisons the measured results and the estimation values.

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