Evaluation of Measurement Uncertainty for Fourth Axis Error Calibration of Coordinate Measuring Machines

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Abstract. According to the calibration method defined in the specification, a measurement uncertainty evaluation method for the fourth axis error calibration results of coordinate measuring machines is proposed. Establish a measurement uncertainty evaluation model based on calibration methods and analyze the sources of each uncertainty. Based on measurement examples, the evaluation process of measurement uncertainty for the fourth axis error calibration of coordinate measuring machines is elaborated.

Keywords: metrology; coordinate measuring machine; forth axis error; uncertainty in measurement.

1. Introduction

Coordinate Measuring Machine (CMM) is a measurement system composed of a mechanical host, displacement sensors, detection systems, control parts, and measurement software. By measuring the relative motion of the object being measured with a probe, it can measure the surface coordinates of various complex three-dimensional components. CMM usually has three motion axes in the X, Y, and Z directions. For coordinate measuring machines equipped with rotating workbenches, the rotation axis of the rotating table is referred to as the fourth axis. In the international standard ISO 10360-3[2] and the calibration specification JJF 1064-2010 "Calibration Specification for Coordinate Measuring Machines"[3], the measurement indication error E of the measurement characteristic size mainly characterizes the metrological performance of the X, Y, and Z axes of CMM, and the four axis error reflects the metrological characteristics of the CMM rotating workbench. The four axis error has three components, radial four axis error *FR*, tangential four axis error *FT*, and axial fourth axis error *FA*. JJF1064-2010 does not provide an example of measuring uncertainty evaluation for four axis errors. In relevant research, literature [4] uses angular polygon, autocollimators to calibrate the optical turntable matched with CMM, and evaluate its measurement uncertainty. However, the turntable calibration method used by this research institute is different from the four axis error calibration method defined in JJF 1064-2010 "Coordinate Measuring Machine Calibration Specification", and the measurement uncertainty evaluated is not the measurement uncertainty of fourth axis error calibration. Therefore, this article attempts to analyze the uncertainty of four axis error measurement according to the calibration method defined in standard JJF1064-2010.

2. Calibration method

The principle of CMM fourth axis error calibration is to evaluate whether the measurement capability of CMM meets the specified maximum allowable error (MPE_{FR}, MPE_{FT}, MPE_{FA}) by measuring the changes in the coordinates of the two ball centers of the detection ball group installed on a rotating workbench. The center position of the detection ball is in the workpiece coordinate system on the rotating workbench. For an ideal fourth axis coordinate measuring machine, the center position of the detection ball should be kept constant when the workbench rotates. The center of each detection ball is determined by three directions: radial, tangential, and axial. A series of measurements are taken at different angle positions of the workbench at the center of each detection ball installed on the workbench. Calculate the range of maximum and minimum measurement results for each detection ball's indication error (*FR*, *FT*, *FA*) in three directions separately [3].

Before calibration, install the detection ball A at the radius r on the rotating workbench, as close as possible to the surface of the workbench, and at a height of h_A from the workbench. Install the detection ball B on the rotating workbench with the same radius as the detection ball A. Try to align it with the diameter on the surface of the workbench at a height of h_B from the workbench. The height difference between the two balls is Δh. Installation diagram of CMM fourth axis calibration balls is shown in Figure 1[3].

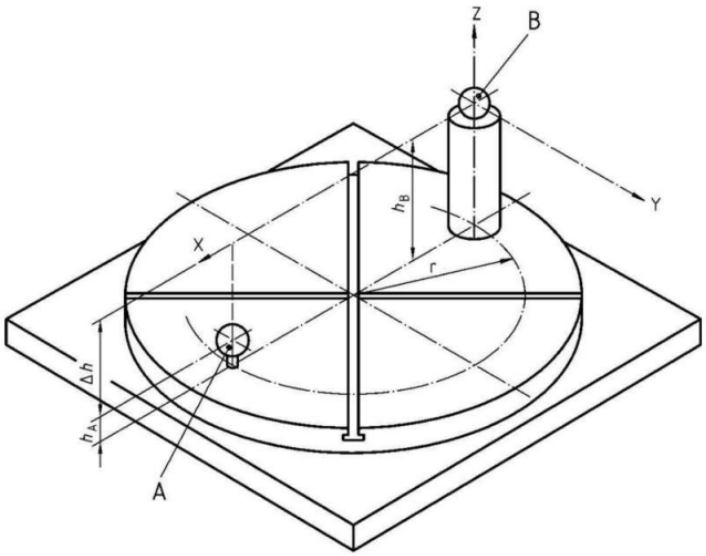


Figure 1. Installation diagram of CMM fourth axis calibration balls [3]

When compiling the CMM fourth axis error calibration program, a right angle workpiece coordinate system is defined on the rotating workbench, which should meet the following requirements, (1) establish the origin of the coordinate system at the center of the detection ball B (away from the surface of the workbench); (2) The reference axis Z must be parallel to the axis of the rotating workbench; (3) The second axis X must be in the plane containing the reference axis and the center of the detection ball A. After establishing the workpiece coordinate system, start measuring and measure the center of the detection ball B at the origin. There are a total of 14 sets of measurement angle positions for the rotating workbench, as detailed in Table 4 of Specification JJF1064-2010 [3]. After the measurement is completed, calculate the peak to peak values of the radial, tangential, and axial errors of the centers of the detection balls A and B, and use the maximum values of the three sets of results as the calibration results for the fourth axis errors *FR*, *FT*, and *FA*, respectively.

3. Evaluation of measurement uncertainty

3.1 Measurement result

Under laboratory environmental conditions, calibrate the four axis error of CMM using the above calibration method. The maximum permissible error of the calibrated CMM is $\pm(0.4\mu m+1.2\times10^{-6}L)$. The calibration process is shown in Figure 2.

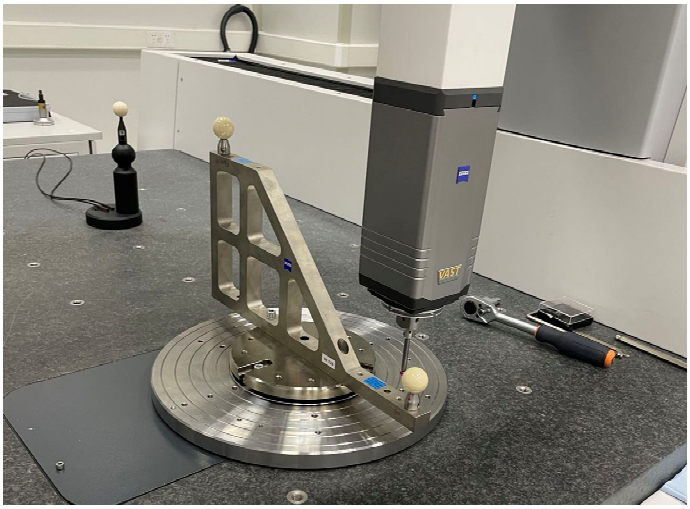


Figure 2. Schematic diagram of the fourth axis error calibration process for CMM

The measurement results of the maximum and minimum values of the center coordinates of balls A and B at different rotation angles are shown in Table 1. According to the measurement results in Table 1, the four axis error calibration results can be calculated as

$$FR = 2.2\mu m,\ FT = 2.1\mu m,\ FA = 0.5\mu m \tag{1}$$

Table 1. Coordinate extreme measurement results for CMM's fourth axis error calibration (unit: μm)

No. of ball	X axis (max)	X axis (min)	Y axis (max)	Y axis (min)	Z axis (max)	Z axis (min)
A	-1.8	0.4	-0.2	1.9	-0.2	0.3
B	-0.4	1.2	-1.4	0.6	0.1	0.5

3.2 Measurement model

According to the calibration method, it can be seen that the measurement model for CMM's fourth axis error calibration is

$$\begin{cases} FR = \max[(\max(X_A) - \min(X_A)), (\max(X_B) - \min(X_B))] \\ FT = \max[(\max(Y_A) - \min(Y_A)), (\max(Y_B) - \min(Y_B))] \\ FA = \max[(\max(Z_A) - \min(Z_A)), (\max(Z_B) - \min(Z_B))] \end{cases} \tag{2}$$

Due to the strong correlation between the coordinate values X, Y, and Z of the balls A and B, and the uncertainty introduced by the three is equal, the combined standard uncertainty is [5]

$$u_{FR} = 4 \cdot u_x;\ u_{FT} = 4 \cdot u_y;\ u_{FA} = 4 \cdot u_z \tag{3}$$

Where u_x, u_y, and u_z are the measurement uncertainties introduced by the X, Y, and Z coordinate values of the measurement ball, respectively.

Considering that the sources of uncertainty for u_x, u_y, and u_z are the same, the maximum value among them can be taken as the composite standard uncertainty u_{FC} for the fourth axis error calibration results of CMM. The u_{FC} is shown below

$$u_{FC} = \max(u_{FR},\ u_{FT},\ u_{FA}) \tag{4}$$

3.3 Sources of standard uncertainty

According to equation (2), the measurement uncertainty of the fourth axis error calibration results of CMM mainly comes from the measurement process of the ball center coordinate value of the

detection ball. Referring to the technical specification JJF1859-2020 "Calibration Specification for Standard Ball Bars" [6], the standard uncertainty of the fourth axis error calibration results mainly comes from the repeatability of ball center coordinate measurement, error of indication of the CMM for size measurement, and the impact of temperature changes on the position of the ball center during measurement. When measuring, the range of temperature changes in the laboratory environment is less than ±0.2℃, and the influence of temperature on the position of the ball center is very small, so the measurement uncertainty introduced by the influence of temperature changes on the position of the ball center can be ignored. The source analysis of the standard uncertainty components for the fourth axis error calibration results of CMM is shown in Table 2.

Table 2. Source of standard uncertainty components for CMM's fourth axis error calibration results

u_i	Source of u_i	Evaluation method
u_1	Standard uncertainty components introduced by repeatability in spherical coordinate measurement	Type A
u_2	Standard uncertainty components introduced by error of indication of the CMM for size measurement	Type B

3.4 Calculation of standard uncertainty

3.4.1. Calculation of u_1

Under the same conditions, the center coordinates of balls A and B with the same turntable angle were selected for 10 repeated measurements. The standard deviations of single measurement experiments for ball A's X, Y, and Z axis coordinates were calculated to be 0.28μm, 0.19μm, and 0.22μm, respectively. The standard deviations of single measurement experiments for ball B's X, Y, and Z axis coordinates were calculated to be 0.09μ m, 0.16μm, and 0.11μm. During the calibration process, each detection ball was measured 14 times, and the maximum value of 6 sets of data was taken as the standard uncertainty component u1 introduced by measurement repeatability. The standard uncertainty u_1 introduced by repeatability in spherical coordinate measurement is

$$u_1 = 0.28\mu m/\sqrt{14} \approx 0.08\mu m \tag{5}$$

3.4.2. Calculation of u_2

According to the maximum permissible error for CMM size measurement, the rotation diameter of the corresponding detection ball is 412mm, and the corresponding MPE is calculated to be ±0.88μm. Since the size is calculated as the square root of three coordinate values, assuming a uniform distribution, the standard uncertainty component u_2 introduced by CMM spatial size measurement error is

$$u_2 = 0.88\mu m / (\sqrt{3} \times \sqrt{3}) \approx 0.30\mu m \tag{6}$$

3.5 Combined standard uncertainty

Based on the above analysis, according to equation (2), the composite standard uncertainty u_{FC} for the fourth axis error calibration results of CMM is as follows

$$u_{FC} = 4 \times \sqrt{u_1^2 + u_2^2} \approx 1.24\mu m \tag{7}$$

3.6 Expanded uncertainty

The calibration result of the indication error of the hydrostatic level is to take the peak to peak values Taking the inclusion factor k=2, the expanded uncertainty of the fourth axis error calibration results for CMM is

$$U = ku_{FC} \approx 2.5\mu m \tag{8}$$

4. Conclusion

According to the calibration method defined in the specification, a measurement uncertainty evaluation model for CMM fourth axis error calibration results is established, and the sources of each uncertainty are analyzed. Based on measurement examples, this paper elaborates on the evaluation process of measurement uncertainty in the fourth axis error calibration of coordinate measuring machines, calculates the expanded uncertainty of CMM's fourth axis error calibration results, and provides a reference for the evaluation of measurement uncertainty in CMM's fourth axis error calibration results.

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