Discussion on Fast Calibration Method of Coordinate Measuring Machine

LongChen¹, TingtingRen¹*, LeiTao¹, JunXiong¹, and ChunyanGu¹

¹Center of Length Metrology, Chongqing Academy of Metrology and Quality Inspection, Chongqing, 401123, China
*Corresponding author’s e-mail: cd@cqjz.com.cn

Abstract. This article presents a novel design of a device with simple structure, convenient operation and stable performance for fast calibration of coordinate measuring machines (CMMs). The purpose of the design is aiming at the solving the problems of long time-consuming, high cost and high requirements for calibration personnel during the traditional calibration process of CMMs. The technical specifications of the designed calibration device complies with ISO 10360-2-2009 Geometrical Product Specifications (GPS)-Acceptance and reverification tests for coordinate measuring machines (CMM)-Part 2: CMMs for measuring linear dimension and ISO 10360-5-2020 Geometrical Product Specifications (GPS)-Acceptance and reverification tests for coordinate measuring machines (CMM)-Part 5: Coordinate measuring machines (CMMs) using single and multiple stylus contacting probing systems using discrete point and/or scanning measuring mode. The device can complete the calibration of the CMMs quickly, obtain the size error and probing error of the CMM in a short time, and provide data support for users to determine whether the CMM meets the application requirements.

1. Introduction
Coordinate measuring machine (CMM) has been widely used in manufacturing industry due to its characteristics of simple operation, high degree of automation, strong universality and high accuracy of measurement results.¹ CMM must be calibrated regularly in order to ensure the accuracy and reliability of its measurement results. The calibration of CMM is mainly completed on-site by a third party, who mainly adopts two traditional methods to calibrate CMM. One method is completed by using high-precision measuring instruments such as laser interferometer as calibration standards, while the other is by using material standards, such as gauge block, step gauge, etc as calibration standards². High-precision measuring instrument is expensive, time consuming, and has high requirements for operators, while material standard has high requirement for environmental conditions and needs to be calibrated regularly³.

In order to solve the problems of the two traditional methods mentioned above, a fast calibration device is proposed in this paper, which is easily operated and highly efficient. Calibration of CMM can be completed within ten minutes by using the device, in the meantime, the measurement method and procedure of which entirely meet the requirements of ISO 10360-2-2009⁴ and ISO 10360-5-2020⁵.
2. Commonly adopted calibration method for CMM
At present, CMM is generally calibrated according to the requirements of ISO 10360-2-2009 and ISO 10360-5-2020. The physical standards, such as gauge blocks, step gauges, and test spheres are selected as the calibration standards[6]. The size indication error and probing error of CMM are obtained by measuring the physical standards, in order to evaluate the measurement capability of CMM. In order to obtain the size indication error, five material standards of different sizes (the minimum length is no more than 30mm, while the maximum is greater than 2 / 3 of the spatial diagonal) are placed in seven different directions (x-axis direction, Y-axis direction, z-axis direction and four spatial diagonals) in the measuring volume of the CMM. Each length shall be measured three times, and a total of 105 measurement values are obtained. Compare the measured values with the standard values of the material standards, the difference of which is the dimensional indication error. In order to obtain the probing error, use the CMM to probe 25 points on the test sphere, and calculate the centre coordinate of the sphere by software. Record the range of radial distances of 25 points, i.e. $R_{\text{max}} - R_{\text{min}}$, the valve of which is the probing error.

3. Design of fast calibration device for CMM
The fast calibration device is composed of industrial ceramic reference spheres, carbon fibre sphere shafts and carbon fibre base. Nine industrial ceramic reference spheres are connected to the carbon fibre base through carbon fibre sphere shafts. The reference sphere placement structure of the rapid calibration device is designed according to the measurement requirements of ISO 10360-2-2009 and ISO 10330-2-2020 in order to complete the axial and spatial measurement at the same time. The structure of the fast calibration device is shown in figure 1, with a carbon fibre base of 400 mm × 500 mm, sphere shaft height of (2 ~ 400) mm, sphere distance of (394 ~ 623) mm. The diameter of the industrial ceramic reference sphere is 25.4mm, with the roundness of less than 0.2um.

![Figure 1. Structure diagram of the fast calibration device for CMM](image1)

4. Calibration method
Place the fast calibration device stably on the workbench of the calibrated CMM, and establish the Cartesian coordinate system with the bottom of the device as the surface, the short end face of the device as the line and the long end face of the device as the point (as shown in figure 2).

![Figure 2. Sketch map of Cartesian coordinate system](image2)
25 points of each reference sphere are probed by stylus. These points shall be evenly distributed over the upper hemisphere. The distribution of points shall be at the discretion of the users, the following probing pattern is recommended (see figure 3): one point on the pole (defined by the discretion of the stylus shaft) of the reference sphere; four points (equally spaced) 22.5° below the pole; four points (equally spaced) 67.5° below the pole and rotated 22.5° relative to the previous group; eight points (equally spaced) 90° below the pole (i.e. on the equator) and rotated 22.5° relative to the previous group. Using all 25 measurements, compute the Gaussian (i.e. least-squares) associated sphere. For each of the 25 measurements, calculate the Gaussian radial distance with respect to the least-squares sphere centre, and the difference between the maximum and minimum radial distance, i.e. \( R_{\text{max}} - R_{\text{min}} \) is the probing error of the CMM. In the mean time, the centre coordinate of the reference sphere is obtained.

![Figure 3. Target points distribution diagram](image)

Calculate the sphere centre distances, and compare the calculated values with the standard distance values of the rapid calibration device to obtain the size indication error. By obtaining the nine spherical centre coordinates, 37 data can be calculated at the same time as demonstrated in table 1, which include: 3 X-axis errors, 3 Y-axis errors, 1 indication error in each of four directions of space, 1 indication error in each of 6 XY planes, 1 indication errors in each of 6 XZ planes, 1 indication error in each of YZ planes, and probing error MPEP.
Table 1. Sphere centre distance statistics

| Sphere 1 | Sphere 2 | Sphere 3 | Sphere 4 | Sphere 5 | Sphere 6 | Sphere 7 | Sphere 8 | Sphere 9 |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Sphere 1 | MPEp1    | X1       | /        | /        | Y1       | /        | K1       | /        |
| Sphere 2 | XZ1      | MPEp2    | /        | /        | Y2       | /        | /        | /        |
| Sphere 3 | /        | XZ2      | MPEp3    | /        | Y3       | /        | /        | K2       |
| Sphere 4 | /        | XY2      | YZ3      | MPEp4    | /        | /        | X2       | /        |
| Sphere 5 | XY1      | /        | /        | YZ4      | MPEp5    | X3       | /        | K3       |
| Sphere 6 | /        | /        | XY5      | XZ4      | MPEp6    | /        | /        | /        |
| Sphere 7 | /        | XZ4      | /        | /        | YX5      | /        | /        | K4       |
| Sphere 8 | YZ1      | XY3      | /        | /        | XY6      | ZY6      | MPEp9    | /        |
| Sphere 9 | /        | YZ2      | XZ3      | /        | YZ5      | XZ6      | MPEp9    | /        |

The obtained 28 specific size indication errors out of 37 in table 1 can not only judge the measurement performance of the calibrated CMM in four directions of space, as well as in X axis and Y axis, but also analyze the angle swing error of X axis through Y1, Y2 and Y3, the straightness error of Y axis through X1, X2 and X3, the perpendicularity error between X axis and Y axis through XY1 and XY2, the perpendicularity error between Y axis and Z axis through YZ2 and YZ5, and the perpendicularity error between X-axis and Z-axis through XZ3 and XZ6.

5. Uncertainty analysis of measurement results

5.1. Measurement Model

\[ \delta_i = L_i - L_s \] (1)

Where \( \delta_i \) is the indication error, \( L_i \) is spherical centre distance value obtained by the calculated CMM, and \( L_s \) is the standard spherical centre distance value of the fast calibration device.

5.2. Measurement uncertainty component

5.2.1. Standard uncertainty introduced by measurement repeatability

Utilize the calibrated CMM to measure the spherical centre distance between sphere 1 and sphere 2, repeat the procedure 10 times, and the obtained values are 236.6772mm, 236.6773mm, 236.6771mm, 236.6770mm, 236.6772mm, 236.6772mm, 236.6770mm, 236.6771mm, 236.6768mm, 236.6771mm. Calculate the standard deviation with Bessel formula:

\[ u_i = \sqrt{\frac{\sum V_i^2}{n-1}} = 0.2 \mu m \] (2)

5.2.2. Standard uncertainty introduced by the traceability of the fast calibration device

The standard spherical centre distance values of the fast calibration device are provided by a certified metrology inspection institution, and the uncertainty of the value is \( U = 2 \mu m + 2.5 \times 10^{-6}L \), \( k = 2 \) (where \( L \) refers to the standard spherical centre distance: 236mm). Hence the uncertainty component introduced by the traceability of the calibration standard is:

\[ u_2 = U / 2 = 1.4 \mu m \] (3)
5.2.3. Standard uncertainty introduced by the thermal expansion coefficient of the fast calibration device

If the calibration is carried out on site, the standard uncertainty shall be introduced by the temperature deviation from 20°C, which is calculated as follow (where \( L \) refers to the standard spherical centre distance: 236mm, \( \alpha \) refers to the thermal coefficient of carbon fiber: \( 1.5 \times 10^{-6} \, \text{L/°C} \), and \( t \) refers to the on-site temperature: 21.0°C):

\[
u_3 = L \times \alpha \times \left| \left( t - 20°C \right) \right| = 0.8 \mu m
\]  

(4)

5.2.4. Standard uncertainty introduced by the form error of the reference sphere

The center coordinate is calculated by probing or scanning the surface of the reference sphere in order to obtain the spherical centre distance, therefore, the roundness of the reference sphere will affect the measurement results. The roundness of the reference sphere is no more than 0.5μm, so the standard uncertainty introduced by the form error is \( u_4 = 0.5 \mu m \).

5.3. Synthetic standard uncertainty and extended uncertainty

5.3.1. Synthetic standard uncertainty

\[
u_c = \sqrt{\sum_{i=1}^{4} u_i^2} = \sqrt{u_1^2 + u_2^2 + u_3^2 + u_4^2} = 1.2 \mu m
\]  

(5)

5.3.2. Extended uncertainty

Take the inclusion factor \( k=2 \) (confidence probability is 95%), the extended uncertainty is:

\[U = u_c \times 2 = 2.4 \mu m\]

(6)

6. Conclusion

The traditional calibration methods for CMM are time consuming and have very high requirements for operators and measurement environment. This article presents a fast calibration device of high efficiency and easily operated. The calibration of CMM can be rapidly completed within ten minutes by using the fast calibration device, while the measurement methods and procedures of the device completely meet the requirements of ISO 10360-2-2009 and ISO 10360-5-2020. Both of the two methods can measure size indication errors and probing error of CMM according to ISO 10360-2-2009 and ISO 10360-5-2020. The difference between the traditional method and the fast calibration method is demonstrated in table 2.

| When CMM is calibrated by gauge blocks or step gauges | When CMM is calibrated by fast calibration device | Comparison result |
|-----------------------------------------------------|-----------------------------------------------|-------------------|
| Measurement time | More than 2 hours | Within 10 minutes | The fast calibration device is much faster. |
| Measurement range | (30~1000) mm | (30~625) mm | Gauge blocks have wider measurement range. |
| Calibration interval | 12 months is recommended | Any time needed | The fast calibration device is more convenient and practical. |
| Requirements for operator | Highly experienced | None | |

Table 2. Difference between two calibration methods
Compared with the traditional method, the fast calibration method is easily operated, high efficient and of low cost. It is a more suitable choice for the users to conduct internal self-inspection to determine whether the performance of the CMM meets the application requirements.

References
[1] Xu, H., Ren, N. (2006) Working principle and system calibration of ATOS optical scanner. J. Tool Engineering, 40: 82–86.
[2] Wang, H. (2007) The research of detecting equipment on coordinate measuring machine. J. Journal of Test and Measurement Technology, 21 Supp: 103–107.
[3] Zhang, G. (2000) Development trend of coordinate measuring machines. J. China Mechanical Engineering, 11: 222–226.
[4] ISO-10360-2. (2009) Geometrical Product Specifications (GPS) - Acceptance and Reverification Tests for Coordinate Measuring Machines (CMM) - Part 2: CMMs Used for Measuring Linear Dimensions. Geneva.
[5] ISO-10360-5. (2020) Geometrical Product Specifications (GPS) - Acceptance and Reverification Tests for Coordinate Measuring Machines (CMM) - Part 2: CMMs Using Single or Multiple Stylus Contacting Probing Systems. Geneva.
[6] Ni, Y., Wang, W. (2000) Guide to the Estimation of Uncertainty in Calibration of Geometrical Measuring Equipment. China Metrology Publishing, Beijing.