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Abstract. In industry, the coordinate measuring machine (CMM) is the most confident instrument in length metrology. The device must conduct systematic precision calibration during installation and before measurement in order to ensure the measurement quality. However, the complete calibration procedure is multifarious. It requires many standard gauges and an experienced worker to finish the job. The expenditure is considerable. The purposes of this study are, first, to develop a CMM calibration tool, the 1-D space ball array plate, to carry out the calibration process, and secondly, to propose the “1-D space ball array coordinating algorithm” to compute the CMM spacial measurement error. From the actual measuring experiments, the proposed 1-D ball array plate has good repeatability and has similar functions of a step gauge. In addition, the proposed methodology conforms to the calibration specification of ISO 10360-2, and has the advantages of low fabrication cost and short calibration time. It provides a new and efficient procedure for CMM calibration.

1. 1-D space ball array coordinating algorithm

1.1. Measurement principle

In the precision calibration of a CMM machine, the well known standards include the CMMA[1], ANSI/ASME B89.4.1[2], JIS B7440[3], BS 6808[4], ISO 10360-2[5] and VDI/VDE 2617[6]. These standards have layed out the examination items, the calibration processes, the standard gauges, and the precision calculation method. They provide common criteria to be followed for all CMM manufacturers.

The “1-D space ball array coordinating algorithm” is based on a standard 1-D space ball array, under the condition that one of the center distances on the ball array is given. A symmetric assembly comparison measurement is executed according to the point-array formed by the standard ball plate and measured by a CMM. The measurement error of the examined CMM can then be derived by the least squares method.

The 1-D ball plate is designed as an assembly with six standard steel balls. The center distance of the neighbor balls is 25mm. A total of 16 measurement points are set on the measuring lines. According to the scheme shown in Figure 1 and Figure 2, the comparison measurements between the ball array and the point distance on the measuring lines are executed. The subsequent error of each point examined on the measuring line can be derived.
1.2. Measurement equations
Let \( \lambda_1, \lambda_2, \ldots, \lambda_5 \) be the correction of the center distance between the balls 1’, 2’, \ldots, 5’ and their corresponding position \((25 \times j)\). Then, the actual value, \( L_j \), is the sum of \( L_{nj} \) and \( \lambda_j \), that is, \( L_j = L_{nj} + \lambda_j \) \((j=1 \sim 5)\). The measurement equations can be derived as the frame lines in Equation (1).

\[
\begin{align*}
L_{nj} + \lambda_j &= d_j, \\
\Rightarrow L_j &= L_{nj} + \lambda_j, \\
\lambda_j &= L_j - L_{nj}
\end{align*}
\]

In Equation (1), \( a_{ij} = d_j - j \times 25 \) and \( d_j \) is the measuring value of the center distance of \( j \)th examined line. \( \lambda_1 \) is the given datum. Then we can infer the normalized equations of \( I_{1,1} \sim I_{1,5} \). According to the above method, the solutions of the 2nd~16th equations sets can also be obtained.

1.3. Theoretical measuring values and accuracy
Based on the measurement equations, we derive twenty sets of center distance correction, which can be used to calculate the average weighting value \((p_1, \ldots, p_5)\). Let \( \lambda_i \) to be the given datum. From the function error, we synthesize:

\[
\sigma_i^2 = \sigma_{h,1}^2 + \left( \frac{\partial h_{1,1}}{\partial L_{1,1}} \right)^2 \sigma_{h,1}^2 + \left( \frac{\partial h_{1,1}}{\partial L_{1,2}} \right)^2 \sigma_{h,1}^2 + \cdots + \left( \frac{\partial h_{1,1}}{\partial L_{1,5}} \right)^2 \sigma_{h,1}^2 = \frac{1}{2} A^2
\]

where \( A \) is the precision of the examined CMM. Then the weights of each correction are presented as:

\[
p_1 = \frac{1}{\sigma_{h,1}},
p_2 = \frac{1}{\sigma_{h,1}},
p_3 = \frac{1}{\sigma_{h,1}},
p_4 = \frac{1}{\sigma_{h,1}},
p_5 = \frac{1}{\sigma_{h,1}}
\]

Then, the measurement results can be expressed as:

\[
\begin{align*}
\bar{I}_1 &= L_{1,1} - L_{1,5} \\
\bar{I}_2 &= L_{1,2} - L_{1,6} \\
\bar{I}_3 &= L_{1,3} - L_{1,7} \\
\bar{I}_4 &= L_{1,4} - L_{1,8} \\
\bar{I}_5 &= L_{1,5} - L_{1,9} \\
\bar{I}_6 &= L_{1,6} - L_{1,10} \\
\bar{I}_7 &= L_{1,7} - L_{1,11} \\
\bar{I}_8 &= L_{1,8} - L_{1,12} \\
\bar{I}_9 &= L_{1,9} - L_{1,13} \\
\bar{I}_{10} &= L_{1,10} - L_{1,14} \\
\bar{I}_{11} &= L_{1,11} - L_{1,15} \\
\bar{I}_{12} &= L_{1,12} - L_{1,16} \\
\bar{I}_{13} &= L_{1,13} - L_{1,17} \\
\bar{I}_{14} &= L_{1,14} - L_{1,18} \\
\bar{I}_{15} &= L_{1,15} - L_{1,19} \\
\bar{I}_{16} &= L_{1,16} - L_{1,20}
\end{align*}
\]

2. 1-D space ball array plate
The structure of the “1-D space ball array plate” developed is shown as Figure 3. To achieve the requirement of seven spatial measuring lines defined in ISO 10360-2, a support frame is designed with angular adjustment function. A linear rail, which carries the ball plate, is fastened on the rotatable frame. Then the ball array plate can comply with the objective of three dimensional calibration.

3. Uncertainty evaluations of the center distance measurement

The instruments used in the standard datum measurement include the laser interferometer, the inductor micrometer and the gauge block et al. Figure 4 shows the measuring system. The displacement of the moving platform is measured by the laser interferometer.

3.1. Uncertainty of the measuring device

The uncertainty of the measuring device is determined by four measuring errors due to the laser interferometer ($e_1$), the moving platform ($e_2$), the gauge block and the measuring line ($e_3$) and the inductor micrometer ($e_4$). The uncertainty data are listed in Table 1.

| Data source                                      | Uncertainty value |
|-------------------------------------------------|-------------------|
| Due to the laser interferometer [7]             | $e_1 = 0.5 \times (0.025 + l \times 10^{-2}) = 0.0125 \, \mu m$ |
| Due to the moving platform                       | $e_2 = (l/2) \times (5.8/1000l)^2 = 6.728 \times 10^{-4} \, \mu m$ |
| Due to the gauge block and the measuring line    | $e_3 = \pm \Delta h \cdot \tan \Delta \alpha = 9.95 \times 10^{-5} \, \mu m$ |
| Due to the inductor micrometer                   | $e_4 = 0.3 \, \mu m$ |

In this system, the uncertainty is synthesized by $e_c = \sqrt{e_1^2 + e_2^2 + e_3^2 + e_4^2} \approx e_4 = 0.3 \, \mu m$.

3.2. Uncertainty of the ball center distance measurement

The roundness error of the steel ball ($e_d$) must be considered in this stage. The maximum roundness of the steel balls is $0.37 \, \mu m$. Thus, the uncertainty can be derived by:

$$\sigma_i = \sqrt{\left(\frac{\partial l_i}{\partial l_1}\right)^2 \sigma_i^2 + \left(\frac{\partial l_i}{\partial l_2}\right)^2 \sigma_i^2 + \left(\frac{\partial l_i}{\partial l_3}\right)^2 \sigma_i^2 + \left(\frac{\partial l_i}{\partial l_4}\right)^2 \sigma_i^2 + e_d^2} = 0.48 \, \mu m$$

where $\sigma_i$ is the uncertainty of $l_i$ ($i=1,2,3,4$). In this case, $\sigma_i^2 = \sigma_i^2 = \sigma_i^2 = e_c$, denoted by $e_c$.

4. Measurement experiments and discussions

4.1. Measurement experiments

After measurements, the dimensions of the two data of 25 mm and 125 mm are 24.9889 mm and 124.9808 mm. The examined CMM in this study is a bridge frame type machine, Mitutoyo BHN506.

4.1.1. Analyses of the calibrating datum of 24.9889 mm

1. Uncertainty of center distance between ball-1 and ball-5

   (i) The average of the calculated center distance between ball-0 and ball-5 is 124982.7 \, \mu m (L_3).
(ii) From Equation (2), the uncertainty of the calculated center distance between \textit{ball-0} and \textit{ball-5} is 
\[ 2.24 \, \mu m \quad (\sigma_{L_5} = \sqrt{25\sigma^2 + 6.4^2}/12 = 2.24 \, \mu m) . \]

2. Analytical results. Four items have been derived as follows:

(i) Measurement uncertainty of \( L_5 \) is \( 0.48 \mu m \) (\( \sigma_{L_5} \)).

(ii) Calculated uncertainty of the ball center distance of \( L_5 \) is \( 2.24 \mu m \) (\( \sigma_{L_5} \)).

(iii) Calculated average of \( L_5 \) is \( 124982 \, .7 \mu m \) (\( L_{(5\text{(cal)})} \)).

(iv) Standard calibrating item of ball center distance of \( L_5 \) is \( 124980 \, .8 \mu m \) (\( L_{5\text{(cal)}} \)).

The limiting error is set as \( \delta = 3\sigma \). Thus the error can be compounded as:

\[ E = \sqrt{(3\sigma_{L_5})^2 + (3\sigma_{L_5})^2} = 6.9 \, \mu m \tag{6} \]

The difference between the calculated average (\( L_{(5\text{(cal)})} \)) and the ball center distance of the standard calibrating item (\( L_5 \)) is \( |L_{(5\text{(cal)})} - L_5| = |124982.7 - 124980.8| = 1.9 \mu m < E = 6.9 \mu m \).

4.1.2. \textit{Analyses of the calibrating datum of 124.9808mm.} The difference between \( L_1\text{(cal)} \) and \( L_1 \) is \( |L_{1\text{(cal)}} - L_1| = |124985.2 - 124988.0| = 0.4 \mu m < E = 2 \mu m \). It is also within the error range of \( E \). From the above analyses, the feasibility of using the proposed methodology to calibrate the CMM precision is proved.

4.2. CMM axial accuracy calibration

The longer standard datum of 124.9808 \( \mu m \) was selected in the calibrating process. The measured axis was \( Y\text{-axis} \). Two examinations were executed. The correction data of the 12 examined positions are listed in Table 2, that is, the measurement error of the examined CMM.

\[
\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline
\text{Measuring positions (mm)} & 25 & 50 & 75 & 100 & 125 & 150 & 175 & 200 & 225 & 250 & 275 & 300 \\
\hline
1^{st} \text{ calibration} & 1.87 & 2.26 & 4.50 & 3.65 & 4.00 & 3.49 & 5.43 & 5.52 & 5.95 & 6.30 & 5.43 & 4.91 \\
2^{nd} \text{ calibration} & 1.32 & 4.35 & 4.08 & 4.38 & 4.66 & 3.95 & 4.95 & 5.54 & 5.29 & 4.65 & 5.70 & 5.25 \\
\text{Laser interferometer} & 1.0 & 1.5 & 2.5 & 4.0 & 4.5 & 4.9 & 5.5 & 6.6 & 8.3 & 9.1 & 9.6 & 10.5 \\
\hline
\end{array}
\]

5. Conclusions

This study has successfully developed a CMM calibration system by using the “1-D ball array plate” and the “1-D space ball array coordinating algorithm”. The ball array plate has similar functions of a step gauge. In addition to calibrating the axial accuracy, it can also be used to examine various machines based on the calibrating standard of ISO 10360-2.

References

[1] CMMA (Coordinate Measuring Manufacturers Association), 1981, “Final version of the CMMA accuracy specification,” Approved on September 21th.

[2] ANSI/ASME (American Society of Mechanical Engineers), 1997, B89.4.1 “Methods for performance elevation of coordinate measuring machines,” New York.

[3] JIS (Japanese Standards Association), 1987, B7440 “Test code for accuracy of coordinate measuring machine,” Tokyo.

[4] BS (British Standards Institute), 1987, 6808 “British Standard – coordinate measuring machines, Parts 1-3,” London.

[5] ISO (International Organization for Standardization), 1994, 10360 “Coordinate metrology, Parts 1-2,” Geneva.

[6] VDI/VDE, 1989, 2617 “Accuracy of coordinate measuring machines, Part 3, Components of measurement deviation of the machine”.

[7] Renishaw Company, 1991, “Renishaw Laser Measurement System,” UK.