A Self-calibration Method for Coordinate Measuring Machines

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1. Introduction

Nowadays, Coordinate Measuring Machines (CMM) are widely used not only in temperature controlled measuring rooms, but also in manufacturing lines, which are severe environments for CMMs. Temperature variation, vibration, and so on will make it difficult to keep CMMs to be accurate; accordingly, frequent calibration is required. However, conventional calibration method of using ball-plates is not easy to setup and takes long time. Moreover, calibrated artifact like a ball plate is expensive and it is difficult to use many artifacts. Although, self-calibration methods of using uncalibrated ball plate have been proposed[1)], these methods also require complex calibration procedure. Here, we propose a calibration technique for CMMs based on the self-calibration concept[2) 3)]. This method is simple, takes only short time and there is no need to use expensive artifact like ball-plates. It is therefore suitable for frequent calibration of CMMs.

In this paper, the authors show the principle and some experimental results of the self-calibration methods. In addition, unequal pitch calibration methods, which can use the parts that are measured in manufacturing lines as the artifacts, are also proposed.

2. Principle

Errors of a CMM are classified into the mean sensitivity error and the linearity error. At first, before calibrating the linearity error, the mean sensitivity error is calibrated by a reference artifact or a calibrated gauge like a gage block.

Next, the linearity error calibration is carried out without using any calibrated artifact. In Fig. 1, the vertical axis shows real coordinate x, the lateral axis shows output value of CMM m, $h(m)$ shows the calibration curve. The object placed at left of the vertical axis shows an artifact that has some measuring points indicated with circles. First, coordinates of the measuring points are measured and values $a[1],a[2],\ldots,a[n]$ are obtained. Relation between x_i and $a[i]$ is expressed by the following equation.

$$x_i = h(a[i]) \qquad i=1,2,\ldots,n \tag{1}$$

After shifting the artifact parallelly with a distance D, measurement is carried out again and values $b[1],b[2],\ldots,b[n]$ are obtained to establish the next equation.

$$x_i + D = h(b[i]) \qquad i=1,2,\ldots,n \tag{2}$$

If the linearity error is 0, difference between output values at the same measuring point before and after the shift (cf. $b[1]-a[1]$) becomes D. However, if there is the linearity error, the difference between output values becomes slightly different from D. In other word, it is possible to obtain the local derivative of calibration curve $h'(m)$ from the difference between output values as follows:

$$h'[i] = \frac{D}{b[i]-a[i]} \qquad i=1,2,\ldots,n \tag{3}$$

where, D is obtained by equation (4).

$$D = \frac{1}{n}\sum_{k=1}^{n}\left(a[k]-b[k]\right) \tag{4}$$

In using equation (3) position of $a[i]$ can be compensated for and the compensated position $a_c[i]$ is obtained by equation (5)

$$a_c[i+1] = a[i] + h'[i]\left(a[i+1]-a[i]\right) \qquad i=1,2,\ldots,n \tag{5}$$

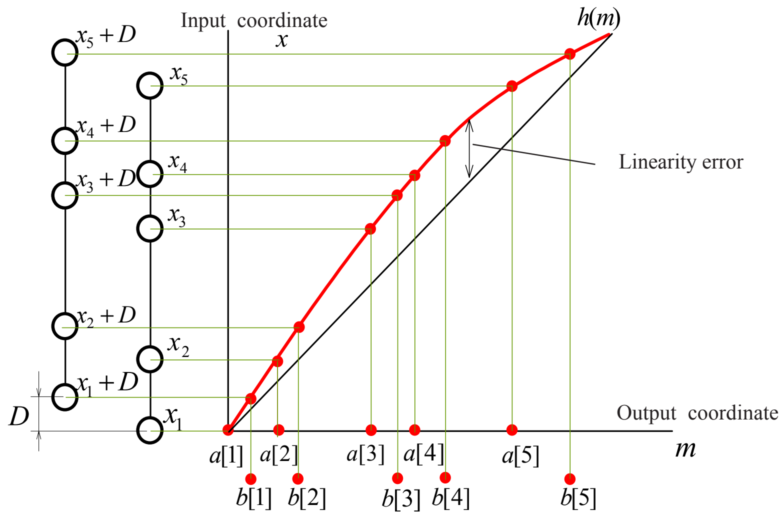

Fig.1 Calibration curve and calibration procedure

On the other hand, it is possible to obtain the calibration curve *h(m)* by integrating the derivative in equation (3).

$$h[i] = \sum_{k=2}^{i} h'[k-1](a[k]-a[k-1]), \qquad h[1]=0 \qquad i=2,3,\ldots,n \tag{6}$$

As described above, this method is very simple and there is no need to use calibrated artifacts like the ball-plates in the linearity calibration process. It can be applied to two-dimensional calibration with using an uncalibrated two-dimensional ball plate or hole plate. Moreover, measuring points are not required to have equal pitch. Therefore, unequal pitch calibration can be realized and workpieces themselves can also be used as artifacts for calibration.

3. Equal pitch self-calibration experiments

To confirm effectiveness of the proposed method, one-dimensional calibration experiments were carried out. A prototype of a CMM "m-job" by Dai-Ichi Sokuhan Works Co. is used as a target for calibration. This CMM has a good repeatability of 1.1μm in the standard deviation, but relatively large errors at the end of measuring range. As an artifact, a commercial available step gauge was used. The step gauge consists of 22 gauge blocks with a length of 10mm, aligned with an equal interval of 10mm (total length of the step gauge was 450mm). The calibrated values of this gauge ware not used in the experiments. As a reference CMM, a commercially available one (Mitutoyo Corp. Model: Bright Apex504, accuracy: 2.9+4L/1000μm) was adopted.

Data correction was carried out by the following sequence. First, the left side position of the gauge surface and positions of all gage blocks were sampled to obtain 23 position data with a pitch of 20mm. In addition, to reduce the affect of dispersion, the measurements were carried out 10 times sequentially and the averaged value was adopted as *a[i]*. Next, the artifact was shifted by approximately 20mm parallel along the gauge axis. Though the shifting distance can be arbitrarily selected, the shift distance was selected to be equal to the pitch of the measuring points. After that, the same sampling process was carried out again and *b[i]* was obtained. At this time, the mean sensitivity error was compensated for by comparing the distance between the positions of the left-side surface of the gauge and the gage block at 440mm. In the next process, the self-calibration method mentioned in section 2 was applied. The result is shown in Fig.2. The lateral axis shows the positions of gage blocks and vertical axis shows the linearity error of the CMM. Before calibration, the CMM has a linearity error of maximum 27μm. In contrast, the residual error after calibration was reduced to 3.4μm peak-to-valley. This was almost the same as the level of the measurement repeatability of the CMM. From this result, the effectiveness of proposed method, which does not need any calibrated artifacts as references, has been confirmed. In other words, handmaid uncalibrated artifacts can be used for calibration. This is a large merit for frequent calibrations in manufacturing lines.

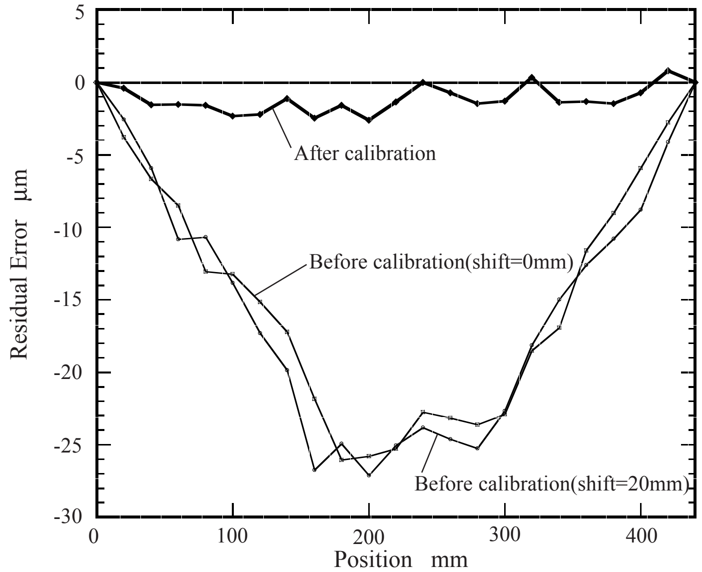

Fig.2 Calibration result of equal pitch self-calibration method

4. Unequal pitch self-calibration experiments

In the next step, we consider to use the parts themselves that are measured in the manufacturing line as artifacts for calibration. In many cases, measuring points of the parts, however, are with unequal pitches. Because pitch equality of measuring points is not required in the self-calibration method as shown in equations (5) and (6), basic experiments of unequal pitch self-calibration were carried out.

As the unequal pitch coordinate data, we chose coordinate data of 12 positions with unequal pitches from the coordinate data obtained in the experiment in section 3, which were data of 0, 40, 60, 120, 140, 180, 220, 240, 320, 340, 400, 440mm. In this case, pitches of measuring points varied from 20mm to 80mm. For comparison, calibration experiments of 12 data with an equal pitch of 40mm were also carried out.

The results of calibration experiments are shown in Fig. 3. In the case of equal pitch calibration, the residual error was reduced to maximum 9.9µm. On the other hand, in the case of unequal pitch calibration, the residual error was reduced to 8.9µm peak-to-valley. This results shows that the error reduction effects were approximately the same in both cases.

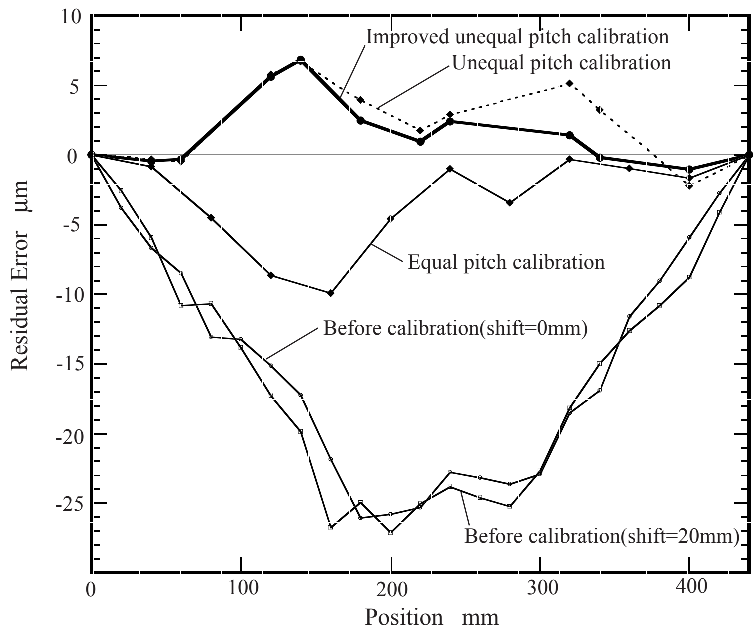

Fig.3 Residual errors of each calibration method

5. Improved unequal pitch self-calibration

In section 4, it is shown that compensation of linearity error by unequal pitch self-calibration is accomplished. However, in the unequal pitch calibration, the shift distance and pitches are sometimes quite different. Therefore, it can be predicted that deviation between *a[i+1]* and *a[i]* is quite different from that between *b[i]* and *a[i]*. To reduce the calculation error caused from the difference mentioned above, we propose an improved unequal pitch calibration technique. This method uses both deviations of near *a[i]* and near *a[i+1]* in integration when compensating linearity errors. In this method, compensated coordinate and calibration curve are described as follows:

$$a_c[i+1] = a[i] + h'[i](b[i] - a[i]) + \frac{h'[i] + h'[i+1]}{2}(a[i+1] - b[i]) \qquad i=1,2,\ldots,n \qquad (7)$$

$$h[i] = \sum_{k=2}^{i} h'[k-1](b[k-1] - a[k-1]) + \frac{h'[k-1] - h'[k]}{2}(a[k] - b[k-1]), \qquad h[1] = 0 \qquad i=2,3,\ldots,n \qquad (8)$$

A broad line in Fig.3 shows the result of applying the improved method. The residual error was reduced to 7.9μm peak-to-valley and the sum of residual errors at each point was also reduced comparing with the unequal pitch calibration shown in section 4. From this result, efficiency of the improved unequal pitch calibration was confirmed.

6. Conclusions

1) A new self-calibration method for CMMs was proposed. From the results of basic experiments, it is confirmed that this method can reduce the linearity error to the level of repeatability without using calibrated gauges.
2) Instead of equal pitch calibration that is conventionally performed, an unequal pitch calibration of self-calibration method is proposed and the effectiveness was confirmed from the experimental result. This method has the feasibility of using the parts in measurement for calibration.
3) To reduce the error of unequal pitch self-calibration, an improved technique was proposed and the efficiency was confirmed by experiments.

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