

# Error compensation for Coordinate Measuring Machine

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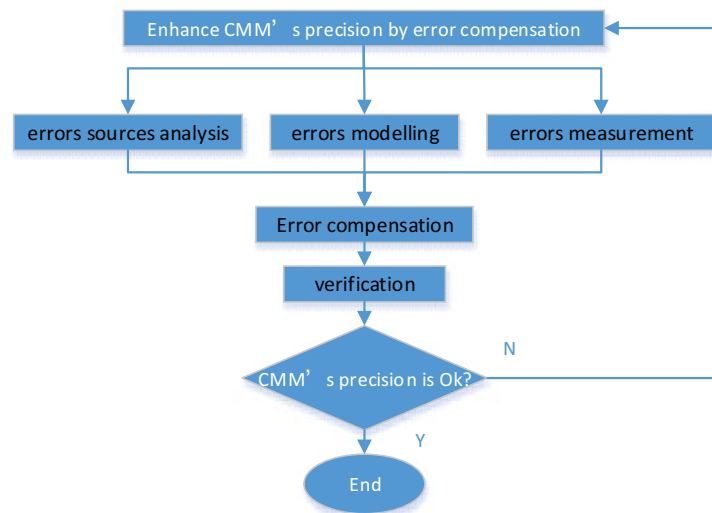
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**Abstract.** In order to improve the precision of Coordinate Measuring Machine(CMM), error compensation method is researched, especially the basic steps of error compensation, which are errors sources analysis, errors modelling and errors measurement, the experiment is done which proves the feasibility.

## 1. Introduction

With the fierce competition, products become more complex, more diversity and more exquisite, which calls for higher precision processing equipment and inspection equipment. As the delegation of test equipment, Coordinate Measuring Machine(CMM) has used in variety field for its features of high precision and quick measurement. Especially, high accuracy is the key character, so it is important to hunt for higher precision of CMM to meet the need of competition.



**Figure 1.** The process to enhance CMM' precision by error compensation method

There are two ways to enhance the accuracy, one is error avoiding and the other is error compensation. Error avoiding costs a lot because it needs perfect design, accuracy machining and careful installation, thus the method is given up[1]. Error compensation method is much cheaper, it improves accuracy by bringing in new errors to offset system errors. There are 3 basic steps for compensation: errors sources analysis, errors modelling and errors measurement, showing as Fig.1



## 2. Errors sources analysis

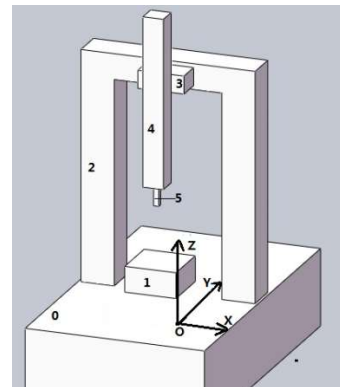
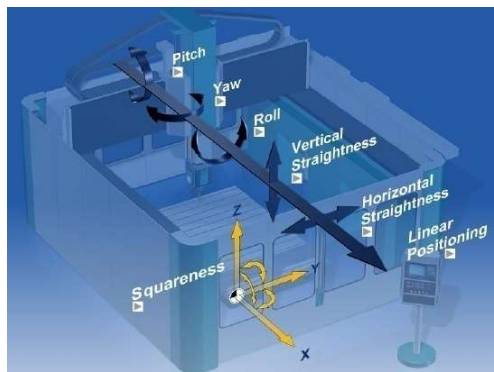
There are many errors may influence the accuracy of CMM, especially geometric errors[2], so the paper focuses geometric errors. Each CMM has three axes, including X-axis, Y-axis and Z-axis. Each axis has 6 errors---3 translational errors and 3 angular errors. Take X-axis for example, 3 translational errors are linear positioning error  $\delta_x(x)$ , horizontal straightness error  $\delta_y(x)$  and vertical straightness error  $\delta_z(x)$ ; 3 angular errors are roll angular error  $\varepsilon_x(x)$ , pitch angular error  $\varepsilon_y(x)$  and yaw angular error  $\varepsilon_z(x)$ , shown in Fig.2. Bracketed letter means the motion direction and the subscript means the error direction.

Therefore, Y-axis and Z-axis have 6 errors, respectively, shown as follows

Y-axis:  $\delta_y(y)$ ,  $\delta_x(y)$ ,  $\delta_z(y)$ ,  $\varepsilon_y(y)$ ,  $\varepsilon_x(y)$ ,  $\varepsilon_z(y)$ ;

Z-axis:  $\delta_z(z)$ ,  $\delta_x(z)$ ,  $\delta_y(z)$ ,  $\varepsilon_z(z)$ ,  $\varepsilon_x(z)$ ,  $\varepsilon_y(z)$ ;

Besides each single axis errors, it still has errors between axes, which are named straightness errors. So there are total 3 straightness errors,  $S_{xy}$ ,  $S_{yz}$  and  $S_{xz}$ , respectively.

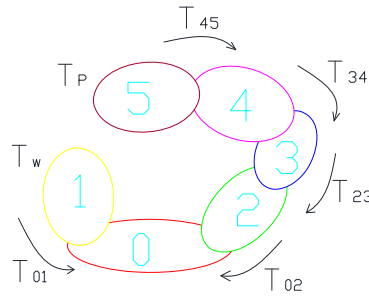


**Figure 2.** Geometric errors of X-axis    **Figure 3.** the structure of CMM

## 3. Errors modelling

Model depends on the structure of CMM. Generally speaking, most of CMMs' structures are as Fig.3, where 1 represents workpiece, 0 is marble table, 2 is frame which moves along Y-axis, 3 is sliding block which goes along X-axis, 4 is stand column which can run along Z-axis and 5 is the probe. When CMM is working, in ideal situation, the workpiece should coincide with the probe at the specific point, but due to the errors, they may meet at other point. According to the difference of two points, the model can be established.

Suppose  $T_w$  is the matrix which reflects the position and posture of the measuring points W in the workpiece coordinate system, while  $T_p$  reflects the position and posture of the probe in the probe coordinate system. These matrixes cannot compare with each other in the different coordinate system, so they should transform to the one coordinate system—marble table 0 coordinate system, shown as Fig.4.



**Figure 4.** The transfer chain

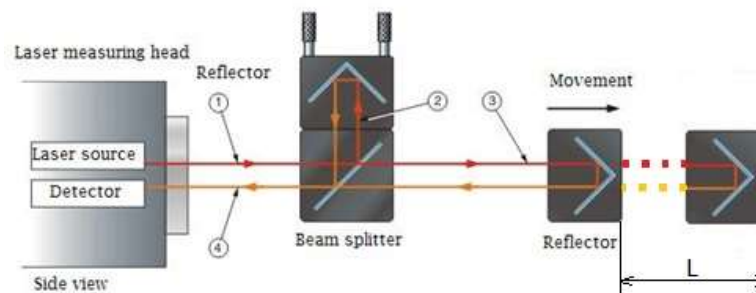
Therefore, the errors matrixes are given in Eq.1, where  $T_{ab}$  means transform matrixes between two adjacent coordinate systems, exactly speaking,  $T_{ab}$  reflects the coordinate system b transform to the coordinate system a;  ${}^0T_W$  shows the position and posture of the measuring points W in the marble table 0 coordinate system and  ${}^0T_P$  is the position and posture of the probe in the marble table 0 coordinate system.

$$\left\{ \begin{array}{l} {}^0T_W = T_{01}T_W \\ {}^0T_P = T_{02}T_{23}T_{34}T_{45}T_P \\ \begin{bmatrix} E \\ 1 \end{bmatrix} = {}^0T_W - {}^0T_P \end{array} \right. \quad (1)$$

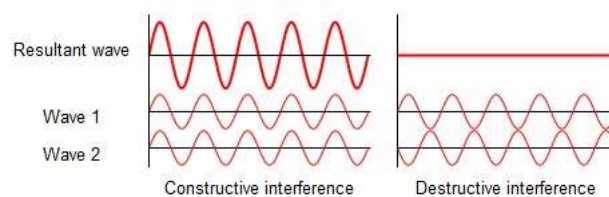
#### 4. Errors measurements

All of 21 geometric errors of CMM can be obtained by laser interferometer, except roll error of vertical axis  $\varepsilon_z(z)$ . The principle of laser interferometer is shown as Fig.5. A laser beam comes from interferometer's head, then goes to splitter. By splitter, the beam is separated into two beams. One (the beam②) goes up to the fixed reflector and returns to the splitter, while the other beam (the beam③) goes through the splitter, reaches to the mobile reflector and turns back. Two returned beams meet again and combine into one beam, finally the beam returned to the detector where can observe the interference phenomenon. If the mobile reflector moves, the optical path difference between the beam ② and the beam ③ changes[3]. When the difference is integer multiples of laser's wave length, the constructive interference will happen and the detector will capture the bright fringe; if the difference is half of the wave length(except the integer multiples), the destructive interference will occur and detector will catch the dark fringe, shown as Fig.6[4]. So when the mobile reflector moves the distance L, the detector will find that the bright fringe and dark fringe appear alternately. The times of alternation (N) will be recorded and the distance L will be calculated by the times of alternation and the wavelength of the laser( $\lambda$ ), given in Eq.1.

$$2 * L = N * \lambda \Rightarrow L = N * \lambda / 2 \quad (2)$$



**Figure 5.** The principle of laser interferometer



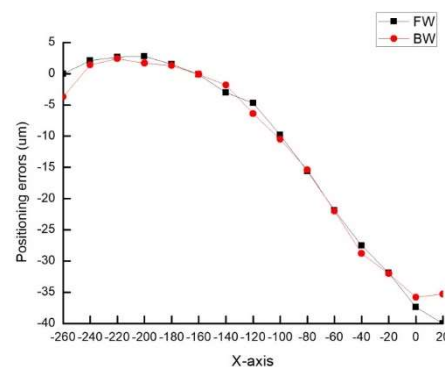
**Figure 6.** The phenomenon of interferometer

## 5. Experiments

In order to avoid redundancy, only one geometric error of CMM is selected to elaborate, which is the X-axis positioning error  $\delta_x(x)$



**Figure 7.** The measurement process



**Figure 8.** The results of X-axis' positioning errors

The CMM for experiments is made by own lab which is aimed to teaching. Generally speaking, there are 30~35 students in one class at the college. To ensure teaching effect, at most 6 students share the same CMM, so 6 CMMs are needed in the students' lab, due to space limitation of the lab, each CMM's volume should be small. Actually speaking, its work volume is 300mmX300mmX200mm. The equipment for measurement is Renishaw's laser interferometer, if the mirrors are enough, it can gather information about positioning errors, straightness errors, angular errors and squareness errors. X-axis's range is from -270 to 30mm, due to the installation of mirrors, the measurement is done from -260 to 20mm and the step is 20mm. When measuring, the laser beam is fixed as close to the X-axis, in order to reduce the influence of Abbe error [5].

The results are given in Fig.8, the CMM moves along X-axis from -260mm to 20mm which is in forward direction (FW), the positioning errors increases to max positive value(2.8um) at -200mm of X-axis, then decrease to zero, after that the errors rise to max negative value (-40um) at 20mm of X-axis. The return trip(BW) is from 20mm to -260mm, the results are similar with forward ones, the max positive value is 2.4um occurring at -220mm and max negative value is -37.7um at 20mm.

## 6. Conclusion

The paper has analysed the errors source affecting CMM and has found out 21 geometric errors which are key errors; error modelling has been established which has built the bridge between errors and compensation; the errors measurement method has given, which has been proved the feasibility by experiments.

## Acknowledgments

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