# *A Calibration and Data Analysis Method for Five-Axis Machine Tools*

*Wen-Yuh Jywe, Tung-Hui Hsu, Mu-Cheng Ji*
*Department of Automation Engineering, National Formosa University, No. 64, Wunhua Rd., Huwei Township, Yunlin Country 632, Taiwan, R.O.C.*
*jywe@nfu.edu.tw, tunghui.hsu@gmail.com, viewsonic7717@gmail.com*

*Abstract - A multi-axis CNC machine tool combined with several rotary axes (rotary tables and/or swivelling axes) and linear axes allows machining along multiple directions. Due to increased complexity, the number of errors of a multi-axis CNC machine tool is higher than that for a three-axis CNC machine tool. This study proposes a simple calibration method to improve the accuracy of five-axis CNC machine tools. Reducing the eccentricity error of the two rotary axes of a five-axis CNC machine tool is the main focus. An optical calibration system is used to simultaneously obtain the errors of multi-axis movement. The proposed calibration method is implemented to calibrate three types of multi-axis CNC machine tool from 14 manufacturers. The calibrating results are presented and discussed.*

*Keywords: multi-axis CNC machine tool, ISO/CD 10791-6, calibration, eccentricity error*

## *I. INTRODUCTION*

A multi-axis CNC machine tool has two or more rotary axes, giving it multiple machining directions to manufacture complex workpieces. When workpieces with a free-form surface, such as dies, turbo blades, and cams, are manufactured using three-axis CNC machine tools, they must be loaded and discharged. Thus, the produce is time-consuming and inaccurate. The number of loads and discharges can be decreased using five-axis CNC machine tools, which have thus become widely applied.

For five-axis CNC machine tools, the position error of each axis, including the linear and rotary axes, can be obtained using various techniques. However, the eccentricity error of the rotary axis center, which is an important source of error in multi-axis CNC machine tools, is more difficult to measure. For five-axis CNC machine tools, eccentricity error accounts for about 70% of the total error. If the rotary axis center can be calibrated, the accuracy of multi-axis CNC machine tools will greatly increase.

## *II. STRUCTURE AND OPERATING PRINCIPLE OF PROPOSED SYSTEM*

The proposed optical calibration system is composed of a master detector module, a ball lens module, and a signal module. In order to obtain signals in three directions, the master detector module comprises two two-dimensional quadrant detectors, QD, and two laser sources, LS, which are vertically assembled. The ball lens module is composed of a ball lens, BL, and a holder. The signal module comprises two amplifiers, a 16-bit analog-to-digital (A/D) converter card, and a computer. The structure of the optical calibration system is shown in Fig.1.

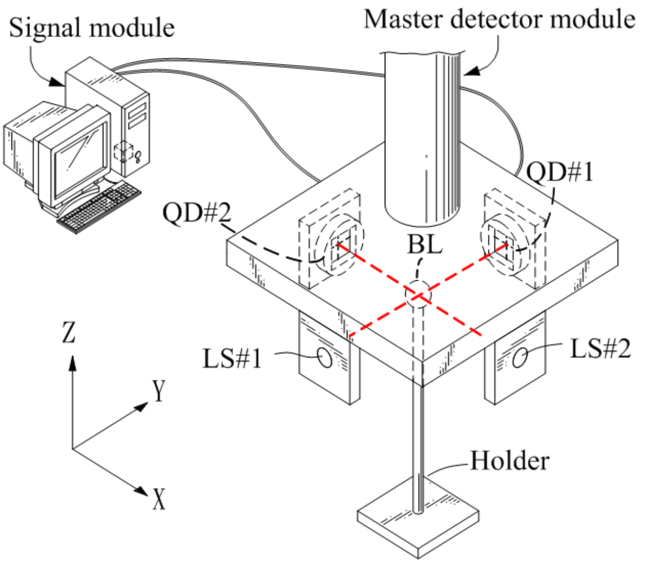



Fig.1, Structure of the optical calibration system[17]

Before a multi-axis CNC machine tool can be calibrated, its error must be obtained and analysed. A reliable measurement tool is thus needed for quantifying the error. Numerous measurement systems and techniques have been developed, including the optical calibration system (OCS), the double ball bar, the R-test, the rotary axis calibrator, and Swivelcheck, etc. [1-16] Although these methods can be used to rapidly obtain the eccentricity error of the two rotary axes, there are no specific data analysis and calibration methods for multi-axis CNC machine tools. A simple data analysis and calibration method for the OCS are presented in this paper. The proposed method was recently implemented to calibrate three types of multi-axis CNC machine tool, namely A-type, B-type, and C-type, from 14 manufacturers of machine tools. The calibrating results are shown and discussed in details. The results are discussed in the next section.

## III. *CALIBRATION METHOD AND ERROR DATA ANALYSIS*

In general, a multi-axis CNC machine tool has several linear axes and two or more rotary axes. A five-axis CNC machine tool has three linear axes and two rotary axes. According to the definition of ISO-230-1, for the A-axis, the eccentricity errors of the rotary centers corresponding to the two axial directions are YOA and ZOA, respectively. For the B-axis, these errors are XOB and ZOB, respectively. For the C-axis, these errors are XOC and YOC, respectively. A diagram is shown in Fig. 2.

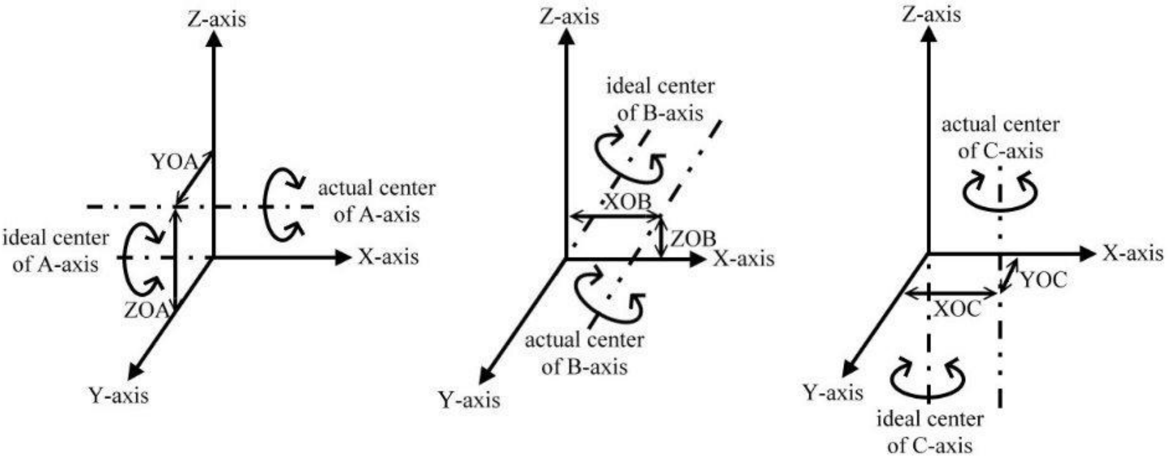



Fig. 2, Schematic diagram of eccentricity error defined in ISO-230-7[18].

A multi-axis CNC machine tool uses a geometric error calibration table or the control's built-in parameters to obtain information such as the center of the rotary axis and the relative displacement between the axes. Some controllers have a built-in geometric error calibration table, called the kinematic table, which describes some geometric parameters, especially those of the rotary axis. These calibration parameters can be used with the error measured by the OCS to increase the accuracy of multi-axis CNC machine tools.

Following ISO/CD 10791-6, the OCS was implemented with measurement path K2. The eccentricity error of the two rotary axes was obtained. During measurement, the detector module was fixed on the spindle head and the ball lens module was fixed on the table. Detailed parameters are shown in Table 1.

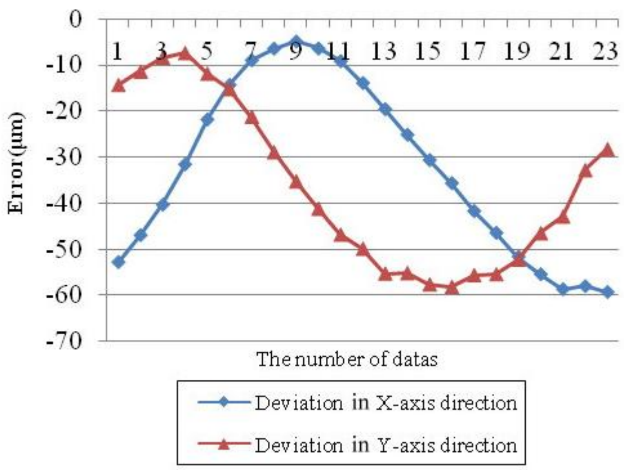
Table 1. Measurement parameters of B-type tool

| Measurement path | K2 |
|---|---|
| Rotary axis | C |
| Interpolation axes | X and Y |
| Feedrate (degrees/min) | 360 |
| Sampling rate (points/s) | 100 |

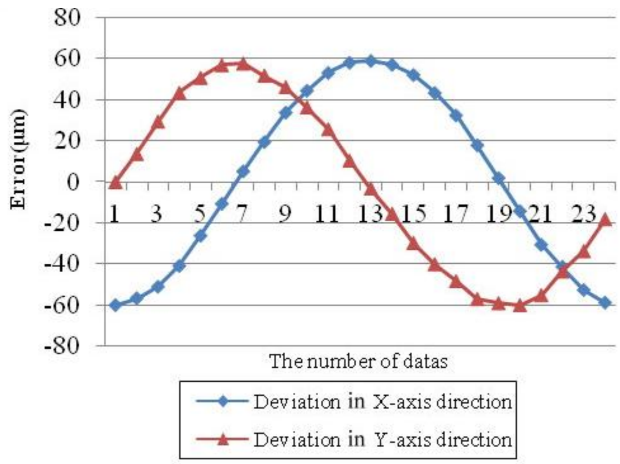
For the K2 path, the table was divided into 15° sections and the data were sampled using a self-developed static measurement program. The data which measured were estimated using the least-squares method to obtain the eccentricity error of the C-axis. The error value was used to calibrate the parameters of the controller.

As shown in Fig. 3(a), [19], the error signals in three directions were obtained using the OCS. The K2 path has X-, Y-, and C-axis movement simultaneously. The error signals correspond to the X- and Y-axis directions. The error signals before calibration shown in Fig. 3(a) have sine and cosine forms, respectively, representing a circle in the X-Y plane. The center deviates from the ideal center is -32.86 μm in the X-axis direction and -32.68 μm in the Y-axis direction. The eccentricity error value of the C-axis obtained by the OCS was verified. The value calculated by the program can thus be used to update the eccentricity error value by incremental calculation. The results after calibration are shown in Fig. 3(b) . [19]

The X- and Y-axis direction error signals are a sine or cosine wave, indicating that they form a circle in the X-Y plane. Since the center of the circle is located at zero, the eccentricity error of the axis is very small, These wave form is caused by the center be changed.




(a) Error in X- and Y-axes before calibration



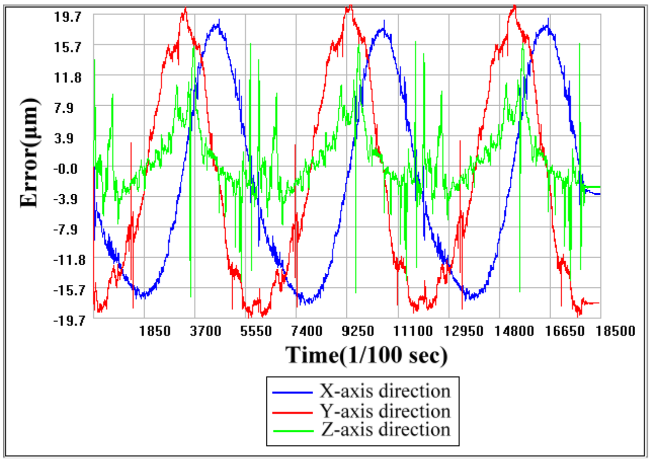

(b) Error in X- and Y-axes after calibration

Fig. 3, Error in X- and Y-axes before and after calibration.[19]

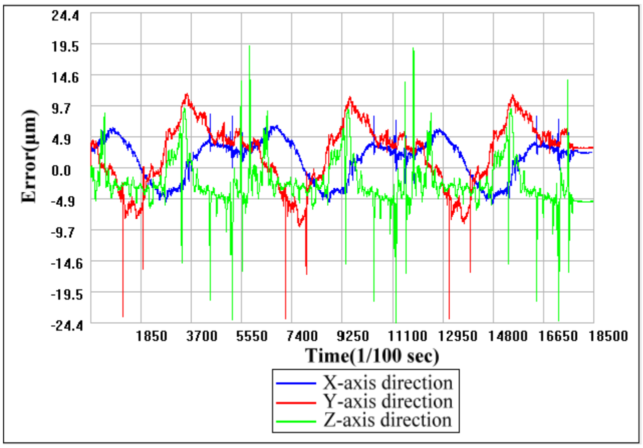
## IV. EXPERIMENT AND RESULTS

A five-axis CNC machine tool has three linear axes and two rotary axes. According to the assembled positions of the two rotary axes, five-axis CNC machine tools can be divided into three types, namely A-type (rotary axes are assembled on the spindle head), B-type (rotary axes are respectively assembled on the spindle head and the table), and C-type (rotary axes are assembled on the table). For details, see ISO/CD 10791-6. The measurement path of a five-axis CNC machine tool can be found in Annex A, Annex B, and Annex C in ISO/CD 10791-6.

Take a B-type five-axis CNC machine tool with XYZAC as an example. The sampling results of the K2 path are shown in Fig. 4. [19]




(a) K2 path dynamic measurement before calibration




(b) K2 path dynamic measurement after calibration

Fig. 4 K2 path dynamic measurement results before and after calibration.[19]

## CONCLUSION

An effective calibration method and data analysis method were presented. The OCS is used to determine error and the measurement paths, parameter settings, and standard error range of ISO/CD 10791-6 are adopted. The simple calibration method reduces the error of multi-axis CNC machine tools effectly. The proposed methods increase the precision of multi-axis CNC machine tools and reduce process time.

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