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Measurement of the Angular Errors of a Multi-Axis Machine Tool by Using A Novel Optical Rotary-Axis Calibrator

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Keywords：rotary axis; angular positioning errors; machine tool; indexing table.

ABSTRACT

Based on the theory of laser measurement, this work presents a novel optical rotary-axis angular errors calibrator to measure the angular positioning errors of a multi-axis machine tool. The proposed calibrator integrates a laser-based angular measuring system and a high accuracy rotary stage. The control method of the optical rotary-axis angular errors calibrator is based on autofocusing technology. Additionally, based on the quadrant detector (QD) of the laser-based angular measuring system, the angular positioning signal is detected from the indexing table. Moreover, an angular position for autofocusing the laser spot at QD is provided using the high accuracy rotary stage. The proposed optical rotary-axis angular errors calibrator is verified using commercial instrument autocollimator and laser interferometer. Experimental results indicate that the proposed optical rotary-axis angular errors calibrator detects the angular positioning with an accuracy of approximately ±1 arcsec. Furthermore, the angular accuracy of a multi-axis machine tool can be adjusted within ±1 arcsec, based on the indexing resolution of 0.0001°.

INTRODUCTION

Rotary components have been widely used in multi-axis machine tools in recent years as an alternative to the conventional three-axis machine tool. Thus, developing efficient approaches to verify the performance of a rotary axis is of priority concern when attempting to enhance the accuracy and quality assurance for users and manufacturers. Three linear positioning errors $(\delta_x(\theta), \delta_y(\theta), \delta_z(\theta))$, one wobble angular error $(\alpha(\theta))$ and one angular positioning error $(\delta_{index}(\theta))$ of a rotary axis incur errors in the position of a workpiece. In particular, eliminating the angular positioning error $(\delta_{index}(\theta))$ is of priority concern when attempting to improve the indexing table performance.

The conventional means of measuring the angular indexing of a rotary axis uses an autocollimator and a high precision polygon. This measurement method provides an efficient set up for measurement and yields reliable results. However, this method feasible for verifying the specific angles (typically every 30° with a 12-side polygon), seventy-two sided polygons have been used, yet are commercially unavailable owing to the cost of manufacture. To overcome this problem, this measurement method has been improved by incorporating a high precision serrated table with a plane reflector. Laser interferometer systems have been extended to include angular indexing calibration [1-2]. To calibrate the accuracy of angular indexing over a circle of 360°, an accuracy reference table is still required, in addition to the standard angular optics. Despite the claim that the precision table has an extremely high accuracy within 0.1 arcsec, the prohibitively high cost of this indexing table is the main limitation of this measurement method for most organizations.

Some optical methods also have been developed for angular error measurement. Ikram and Hussain (1999) developed a precision angle measurement based on Michelson interferometer. Optical methods using a right-angle prism and a glass strip were developed for improving the measurement error and nonlinearity. Yuana and Long (2003) developed a charge-coupled device (CCD) small-angle measurement system based on the autocollimator principle. By using a cold-light source and unique data processing arithmetic, the

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measurement resolution of the autocollimator has been significantly improved. Liu, Jywe and Chen (2005) developed an angular indexing measurement system based on the diffractive principle. Optical methods using a laser, diffractive grating and two position sensor detectors were also developed for measuring the angular errors with a small range of the indexing table. Liu, Jywe and Chen (2005), Liu et al.(2005), Liu, Huang and Lee (2009), Huang et al.(2007), (2009), (2010), Chen, Jywe and Wang (2017) and Gao et al. (2011) also developed a multi-degree-of-freedom measurement system for a linear stage. that can simultaneously detect those system integrated multiple optical components with custom designed optical paths for simultaneously measuring the linear and angular error motions of a linear stage. Jywe, Liu and Hsu (2012) developed a Non-Bar system based on the optical imaging theory. A system consisting of a master detector module, ball lens module and signal module were developed for simultaneously measuring all errors associated with multi-axis movement of five-axis machine tools. Li, Kuang, and Liu (2013) developed a small range angular measurement system based on the autocollimator and common-path compensation principle. The system integrates a CCD detector with uniquely designed optical paths, capable of improving the angle measurement resolution. Arellano et al. (2013) developed an angular motion measurement system based on polarization interference. The optical layout incorporates carefully designed cat's eye retroreflectors that maximize the measurable range of angular motion and facilitate the initial alignment.

This work presents a novel laser-based system to measure the indexing errors of the rotary stage. The proposed systems has the following features: the proposed method can measure both the indexing error of a rotary stage and the angular errors of a single-axis linear stage. Additionally, cost of the proposed system can be reduced because all of its components are inexpensive and common. Moreover, calibration results indicate that the indexing measurement results have a relatively high accuracy. Furthermore, the eccentric effect of the proposed system set up can be disregarded.

SYSTEM CONFIGURATION AND MEASUREMENT PRINCIPLES

Overall System Layout

Figure 1 shows the instrument configuration of the optical rotary-axis angular errors calibrator, which consists of a laser-based angular measurement system and a highly accurate rotary stage. Figure 2 shows the laser-based angular measurement system, including a laser diode [17], beam splitter [18], lens [19] and QD [20]. According to Figure 3, the highly accurate rotary stage includes a plane mirror [21], rotary encoder [22-23], servo motor [24], mount and rotary stage [25]. The laser source used in this study is a collimating laser diode with a wavelength of 632.8 nm. The laser beam of the collimating laser diode passing through the beam splitter is divided into two laser beams. The transmitted beam is projected onto the plane mirror. The return beam from plane mirror is reflected by the beam splitter, subsequently passing through the lens and focusing on the QD.

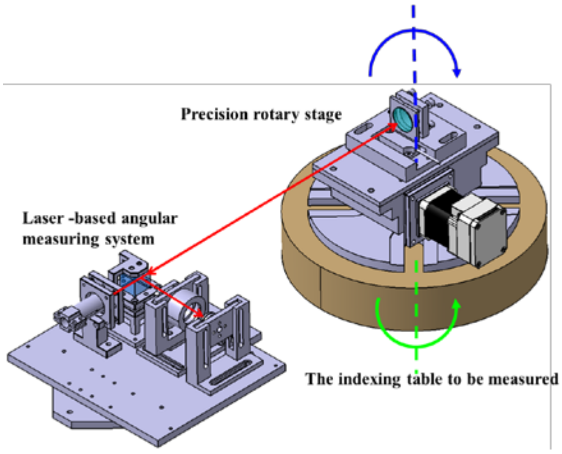


Fig. 1. Sketch of the novel optical rotary-axis angular errors calibrator

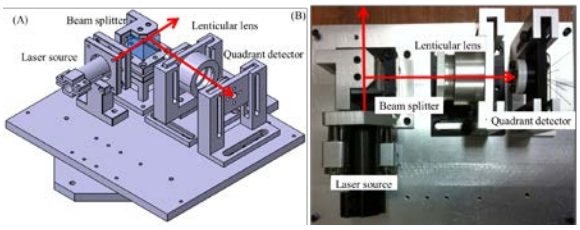


Fig. 2. Sketch and picture of the laser -based angular measuring system

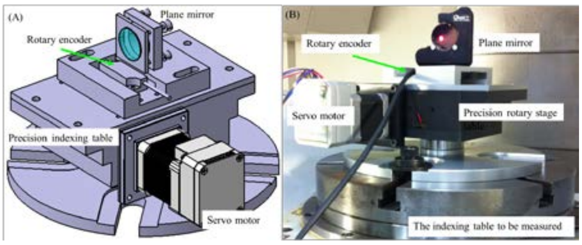


Fig. 3. Sketch and picture of the precision rotary table

Figure 4 shows the control flow chart of the optical rotary-axis calibrator. The control method is based on autofocusing technology. The QD of the laser-based angular measurement system is then set up for measuring the angular position signal of the indexing table. The interface dSPACE [26] receives the signals from the DAQ card [27] and drives the servo motor of the highly accurate rotary stage.

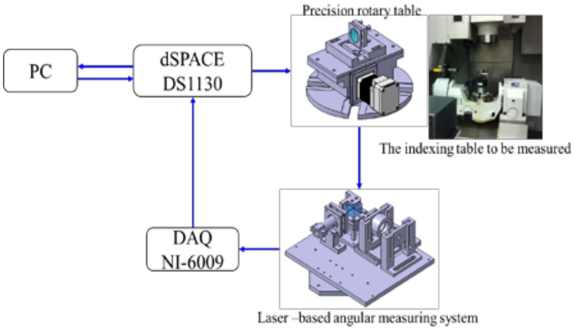


Fig. 4. Control flow chart of the optical rotary-axis angular errors calibrator

Principles of the proposed system

Figure 5 shows the measurement principles of the optical rotary-axis angular errors calibrator, which are based on the autocollimator. Measuring the angular positioning error is limited by the linear zone of the QD. The angular positioning error is determined using the beam reflected by the plane mirror of the highly accurate rotary stage and projected onto the QD of the laser-based angular measurement system. The QD is placed away from the focal point of the lens to generate a light spot with a width of w on the QD. The position of the laser spot can be derived as

$$X_{QD} = \frac{(I_1 + I_4) - (I_2 + I_3)}{I_1 + I_2 + I_3 + I_4} \times 10 = \frac{2}{W} \Delta x \qquad (1)$$

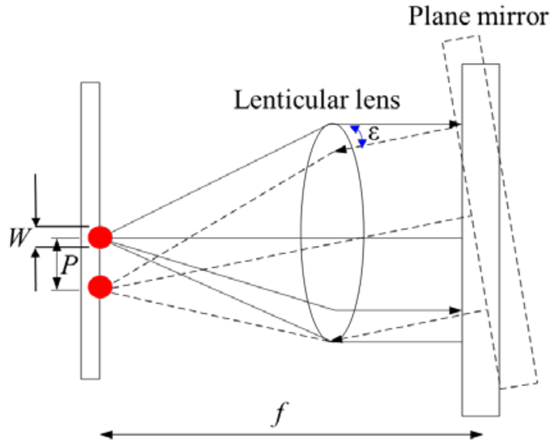
$$Y_{QD} = \frac{(I_1 + I_2) - (I_3 + I_4)}{I_1 + I_2 + I_3 + I_4} \times 10 = \frac{2}{W} \Delta y \qquad (2)$$

Where I_1, I_2, I_3 and I_4 represent the photoelectric currents from the four quadrants of the QD. The yaw and pitch angular error can then be derived as

$$\text{Yaw angular error: } \varepsilon_{yaw} = \frac{wX_{QD}}{4f} = kX_{QD} \qquad (3)$$

$$\text{Pitch angular error: } \varepsilon_{pitch} = \frac{wY_{QD}}{4f} = kY_{QD} \qquad (4)$$

where f represents the return beam path length from the plane mirror to the beam splitter, in addition to the distance from the beam splitter to the QD.



f: Distance from plane mirrir to QD

$\mathcal{E}$: Angular error

W: Diameter of laser spot

P: Position of the laser spot

Fig. 5. Sketch of the measurement principles of proposed system

Initial set-up error analysis of the eccentricity of the proposed optical rotary-axis calibrator

This section describes the effect of the eccentricity of the optical rotary-axis angular errors calibrator. The simple homogeneous transform matrix can explain how the incident ray and optical rotary-axis angular errors calibrator are related, as shown in Figure 6.

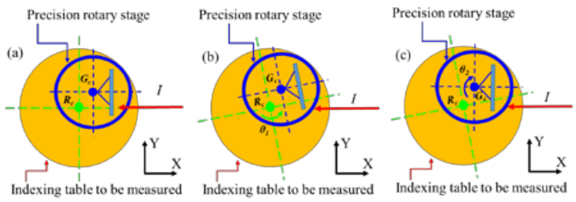


Fig. 6. Sketch of the spatial relationship between the incident ray and optical rotary-axis angular errors calibrator, (a) initial setup error, (b) indexing table with rotational angle θ_1, (c) precision rotary stage with rotational angle θ_2.

A plane mirror coordinate G_c is fixed to the highly accurate rotary stage of the optical rotary-axis angular errors calibrator. Where R_c represents a reference coordinate of the indexing table. The plane mirror original coordinate G_c coincides with that of the reference coordinate R_c. Notably, the Z_c-axis refers to the movement direction of the indexing table, and the X_c-axis is the incident ray direction of the laser diode. Let unit vector ${}^{R_c}I$ of an incident ray in the reference coordinate system R_c be represented as

$$^{R_C}I = [I_x, I_y, I_z, 1] \tag{5}$$

The plane mirror is fixed on the highly accurate rotary stage of the optical rotary-axis angular errors calibrator. When the indexing table and high accuracy rotary stage moves, the transform matrix between the reference coordinate and the new plane mirror coordinate due to the motion error of the rigid body can be expressed as

$$^{R_C}T_{G_C} = \begin{bmatrix} cos(\theta_1-\theta_2) & -sin(\theta_1-\theta_2) & 0 & acos(\theta_1-\theta_2)-bsin(\theta_1-\theta_2) \\ sin(\theta_1-\theta_2) & cos(\theta_1-\theta_2) & 0 & asin(\theta_1-\theta_2)+bcos(\theta_1-\theta_2) \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

Where $^{R_C}T_{G_C}$ denotes the coordinate system G_c relative to the coordinate system R_c; and {a, b, c} represent the eccentric parameters of the X-Y-Z axis respectively. In this work, the rotational parameters $\{\theta_1, \theta_2\}$ are represented as the motion of Z-axis Euler angles of the indexing table and highly accurate rotary stage, respectively. Thus, the directional change of the incident ray related to the plane mirror can be expressed as

$$^{C_C}I' = {}^{G_C}T_{R_C}\ {}^{R_C}I = [I'_x, I'_y, I'_z, 1]^T \tag{7}$$

where $^{G_C}T_{R_c} = {}^{R_C}T_{G_C}^{-1}$ and ^{R_C}I refers to the unit incident vector ray.

In this work, the control method of the optical rotary-axis calibrator is based on autofocusing technology. The rotational parameters $\{\theta_1, \theta_2\}$ can be adjusted to the similar angle ($\theta_1 \approx \theta_2$). Thus, the plane mirror surface is almost perpendicular to the y-axis. The effect for the eccentricity of the optical rotary-axis calibrator approaches to zero, and can be disregarded.

EXPERIMENT RESULTS AND DISCUSSION

Calibration test of the proposed optical rotary-axis calibrator

Figure 7 shows the physical setup of the calibration test of the proposed optical rotary-axis angular errors calibrator. Calibration tests for optical rotary-axis angular errors calibrator were conducted by the autocollimator measurement system. The QD of the optical rotary-axis angular errors calibrator detects the beam from polygon. The linearity of the QD was made in direct comparison with the autocollimator. The resolution of the autocollimator is 0.1 arcsec for the angular measurement.

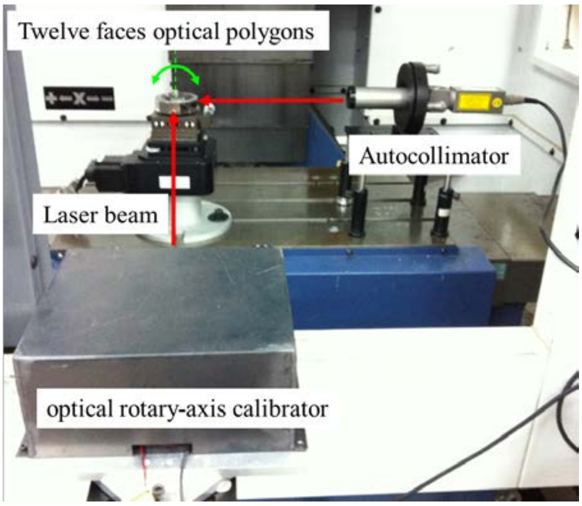


Fig. 7. Physical setup of the calibration test of the proposed optical rotary-axis angular errors calibrator.

Experimental results indicate that the average of the three tests of the calibration curve for the QD is almost coincidental with that of the autocollimator within ±35 arcsec (Fig. 8). The residual error of QD is within ±0.9 arcsec for a calculated range of ±35 arcsec (Fig. 9).

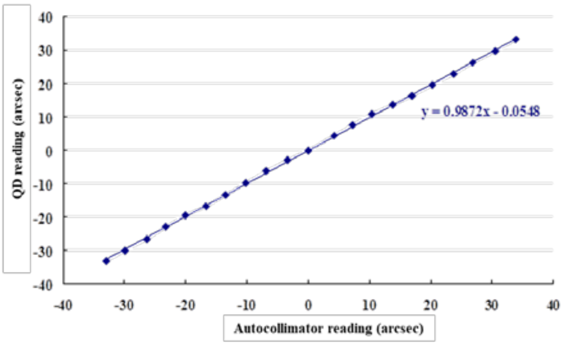


Fig. 8. Calibration result of the QD of the proposed optical rotary-axis angular errors calibrator.

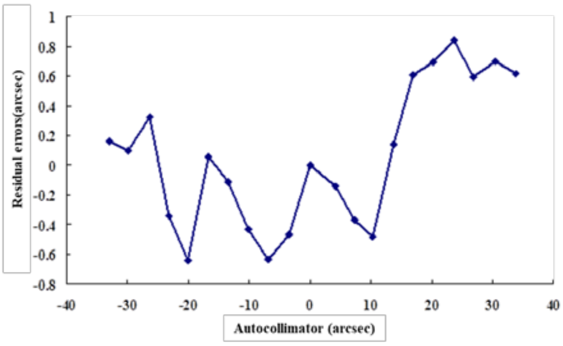


Fig. 9. Residual error of the QD of the proposed optical rotary-axis angular errors calibrator.

Verification test of the proposed optical rotary-axis calibrator

Figure 10 shows the physical setup of the verification test of the proposed optical rotary-axis angular errors calibrator. The optical rotary-axis angular errors calibrator was verified using the HP laser interferometer angular measurement system. Resolution of the HP laser interferometer angular measurement system was ± 0.36 arcsec. Here, the optical rotary-axis angular errors calibrator and HP laser interferometer angular measurement system were setup on the indexing table, respectively. Tests were performed by moving the indexing table with each step 30° for a circle of 360°.

Experimental results indicate that the average of three tests for the clockwise (CW) and counter-clockwise (CCW) is almost coincidental with that of the HP interferometer angular measurement system for a circle of 360° (Fig. 11). The residual errors of CW and CCW are within ±6 arcsec and ±4 arcsec for a circle of 360°, respectively (Fig. 12).

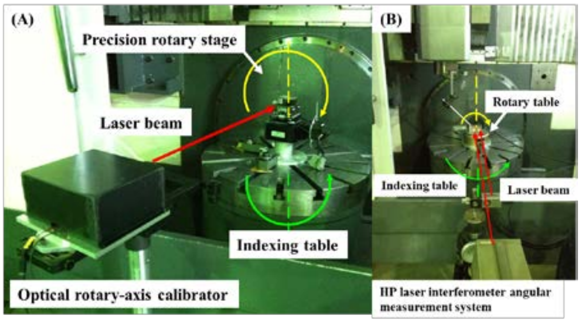


Fig. 10. Physical setup of the verification test of the proposed optical rotary-axis angular errors calibrator, (a) proposed optical rotary-axis angular errors calibrator, (b) HP laser interferometer angular measurement system.

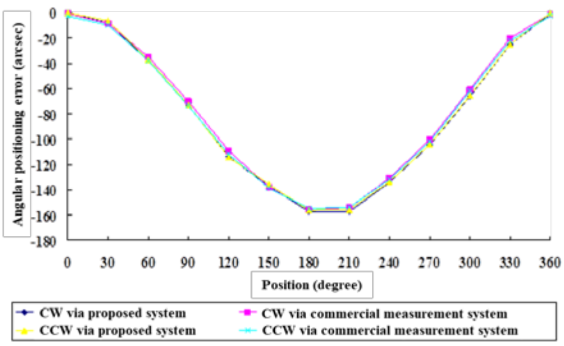


Fig. 11. Verification result of the CW and CCW measurement of the proposed optical rotary-axis angular errors calibrator.

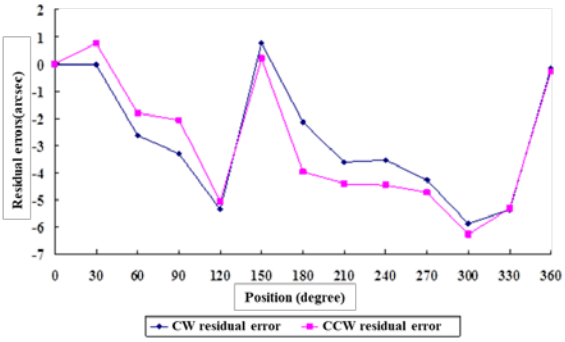


Fig. 12. Verification result of the CW and CCW measurement of the proposed optical rotary-axis angular errors calibrator.

Error measurement of five-axis machine tool using the proposed optical rotary-axis calibrator

The proposed optical rotary-axis angular errors calibrator was also used to measure and compensate for the angular positioning error of the C-axis of five-axis machine tool (Fig. 13). Based on the measurement results, the C-axis parameter of the controller can be adjusted, and the angular positioning error can be reduced as well. In this experiment, three tests were performed by moving the C-axis of a five-axis machine tool with each step 30° for a circle of 360°. According to Fig. 14, the average of three tests of the angular positioning error of the five-axis machine tool before compensation is less than ±3 arcsec for a calculated range of 360°. Table I shows the compensation value of the controller for the C-axis of the five-axis machine tool. According to Fig. 15, the average of three tests of the angular positioning error of a five-axis machine tool after compensation is less than ±1 arcsec for a calculated range of 360°. Therefore, the accuracy can be adjusted within ±1 arcsec, based on the indexing resolution of 0.0001°.

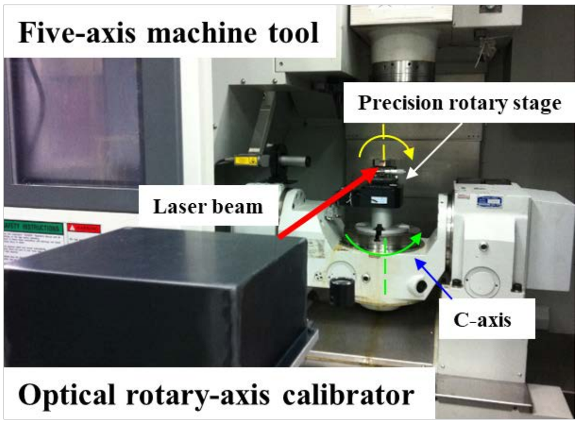


Fig. 13. Physical setup of the angular positioning error measurement of the indexing table (C-axis) of the five-axis machine tool using the proposed optical rotary-axis angular errors calibrator.

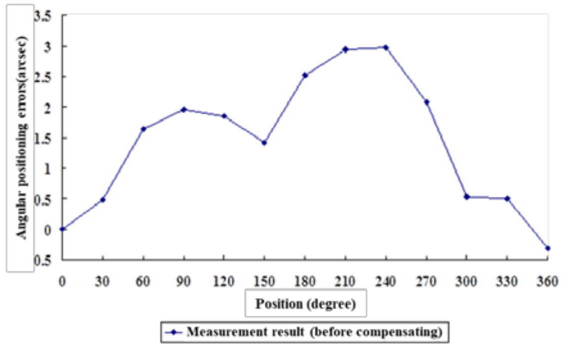


Fig. 14. Measurement result of the angular positioning error of five-axis machine tool before compensating.

Table I. Compensation value of the controller for the C-axis of the five-axis machine tool

C-axis angular (degree)	Compsation value (degree)
0	0
30	0
60	-0.0004
90	-0.0005
120	-0.0005
150	-0.0004
180	-0.0006
210	-0.0008
240	-0.0008
270	-0.0006
300	0
330	0
360	0

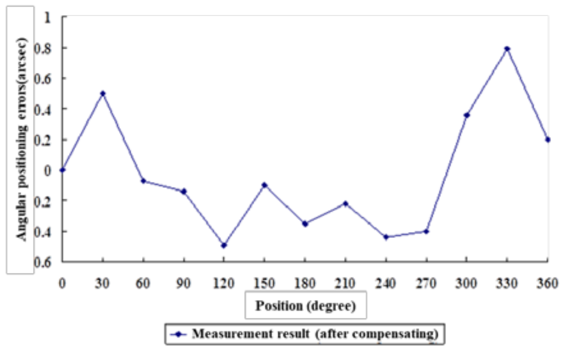


Fig. 15. Measurement result for the angular positioning error of five-axis machine tool after compensating.

The proposed optical rotary-axis angular errors calibrator can measure both the angular positioning error of the indexing table and also the yaw and pitch errors of the linear platform. The yaw and pitch errors of the stage were evaluated by the optical rotary-axis angular errors calibrator and autocollimator (Fig. 16). The resolution of the autocollimator is 0.1 arcsec for the angular measurement. In this experiment, was measured by moving the linear platform along the single-axis of a five-axis machine tool for a distance of 600 mm. Figures 17 and 18 show the average of three tests for the linear platform is nearly coincidental with that of the autocollimator within 600 mm. Figures 19 and 20 indicate that the average error differences of three tests of the yaw and pitch angular errors between optical rotary-axis angular errors calibrator and autocollimator are less than 0.8 arcsec and 1 arcsec, respectively.

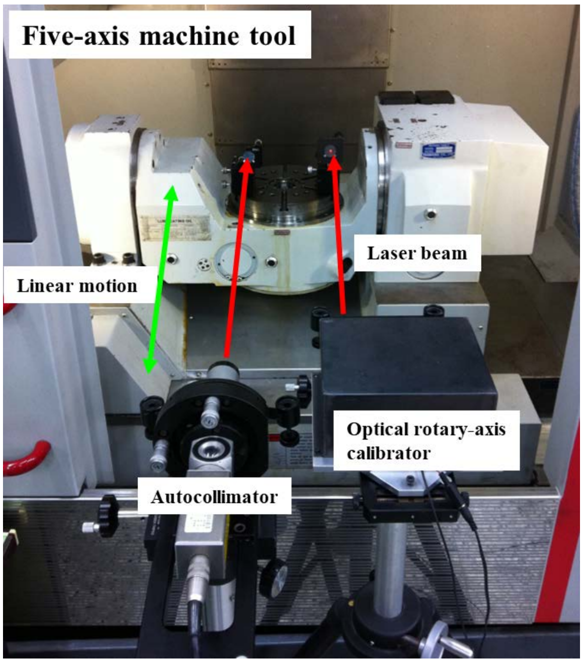


Fig. 16. Physical setup of the yaw and pitch error measurement of the linear platform of the five-axis machine tool using the proposed optical rotary-axis angular errors calibrator.

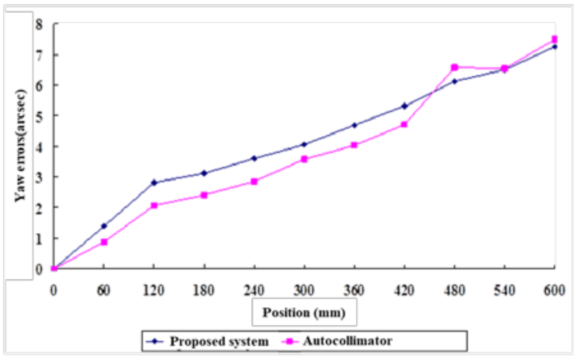


Fig. 17. Measurement result of the yaw error of the linear platform of the five-axis machine tool.

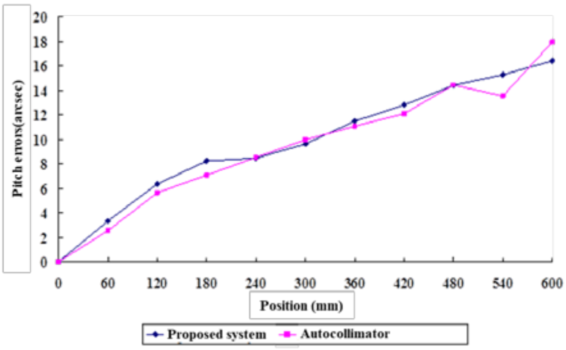


Fig. 18. Measurement result of the pitch error of the linear platform of the five-axis machine tool.

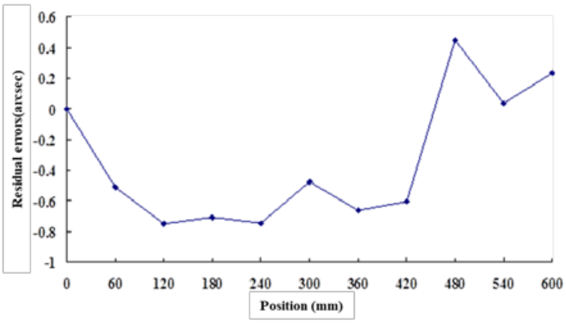


Fig. 19. Residual error of the yaw error of the linear platform of the five-axis machine tool.

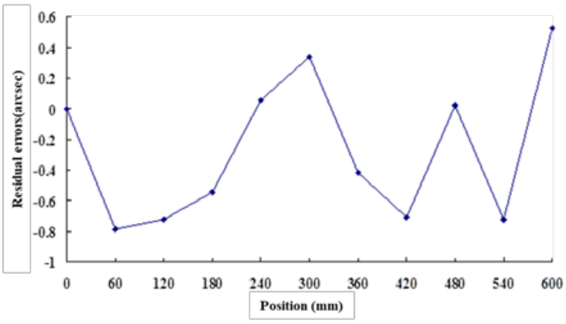


Fig. 20. Residual error of the pitch error of the linear platform of the five-axis machine tool.

CONCLUSIONS

This work presents a novel optical rotary-axis angular errors calibrator to measure the angular errors of a multi-axis machine tool. Our results verify the proposed calibrator system is and demonstrate its excellent performance, the system accuracy: ±0.5 arcsec, repeatability: ±1 arcsec. The proposed system can calibrate the accuracy of angular position over a circle of 360°. Additionally, the rotary-axis calibrator can measure both the angular positioning error of the indexing table and also the angular errors of the linear platform. Efforts are underway in our laboratory to design a rotary-axis calibrator based on multi-parameters and wireless measurements, a calibratory which will be more powerful in terms of quality control of the multi-axis machine tool.

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Model RESM-20U-S-A-52 of Angle encoder Specifications, Renishaw.
Model T2021-30A of Read head Specifications, Renishaw.
Model Cool Muscle 1 of Servo motor Specifications, Muscle Corporation.
Model RM-3 of Rotary stage Specifications, Newmark.
Model DS1103 of Interface Specifications, dSPACE.

新型光學式多軸工具機旋轉軸角度定位誤差量測系統

陳柏宇 王明習
國立成功大學 工程科學系

黃學良 覺文郁
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摘 要

本文提出一種新型光學式旋轉軸量測系統用於多軸工具機的角度定位誤差。本量測系統包含雷射角度測量系統和高精度的旋轉台，光學量測系統採用自動對焦技術的控制方法。本系統的將雷射光點自動對焦於四象限感測器(QD)來量測高精度定位平台的角度定位信號，本系統之驗證採用市售之高精度自動視準儀及雷射干涉儀。根據實驗結果，本文所提出的光學式多軸工具機旋轉軸角度定位誤差量測系統之定位精度為±1 角秒。在旋轉平台之解析度 0.0001 以下，多軸工具機的角度定位精度可在±1 角秒內。