Measurements of tilt error and eccentric error of rotary stages

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Abstract. Rotary indexing devices are widely used in industries, such as robotic arms, machine tools and coordinate measuring machines (CMM). The main error sources of a precision rotary stage are the tilt error and eccentric error during rotation. Traditional contact type dial gauge method to measure the tilt error is only the wobble displacement, and to measure eccentric error contains the eccentric error of the standard sphere.

This study aims at developing tilt error and eccentric error measurement systems by non-contact optical method. The tilt error measurement system is based on the principle of autocollimator. The autocollimator is calibrated by the HP5529A laser interferometer and the residual error is less than 1 arc-sec in the measuring range of ±150 arc-sec. Tilt error and setting error can be separated by mathematical analysis. The eccentric error measurement system consists of a laser source, a quadrant photodetector (QPD) and a corner cube reflector. The QPD is calibrated by the HP5529A and the residual error is less than 0.3 μm in the measuring range of ±40 μm. It is known that the tilt error also results in eccentric error if the measured point is not at the center. This study analyzes the error of rotary axis more precisely by using the measurement results between eccentric error and tilt error.

Introduction

Rotary indexing device is widely used in industry, such as in robotic arm, machine tool and coordinate measuring machines (CMM). Multi-axis machine tool has more degrees of freedom in mechanism, which are mostly for rotation. In multi-axis real-time movement control, the cutting tool can be operated in the normal direction to cut the freeform curved surface. Indexing table is also applied to CMM for measuring components which are of complicated shape. In a multi-axis machine, the rotational accuracy of the rotary axis is as important as those of the linear axes. Consequently, how to measure the accuracy of rotary devices is essential. The basic terminology used in the rotary measurement is based on the ASME B89.3.4 "Axes of Rotation and ISO 230-7 Geometric Accuracy of Axes of Rotation" standards [1, 2] (about the radial error motion, axial error motion and tilt error motion). In recent studies, optical measurements for angle and displacement have widespread application in spindle tilt and eccentric measurement. Jywe et al. [3] proposed a high-speed spindle measurement system for utilizing a rotational fixture with built-in laser diode and a PSD, but the measurement value has compound errors of motion error and the tilt angular error of the spindle. Liu et al. [4] proposed a spindle error measurement system utilizing a rotational fixture with a built-in laser diode, a beam splitter and two PSDs. Compound errors can be separated into two radial errors and tilt angular errors by theoretical analysis. Later on, he used a PSD and rotational fixture with a corner cube [5]. The feature of using the corner cube is not sensitive to the tilt angle error of the spindle. The same group applied the diffraction grating and two PSDs to simultaneously measure the angular displacement [6], but the angle measurement system is incapable of measuring indexing table of long-working range. Kengo Fujimaki et al. [7] proposed an optical measurement method based on autocollimation, which evaluates the radial error motion according to the movements of a laser beam reflected from a target sphere attached to the spindle end. This optical measurement method is suitable for radial error measurements of miniature ultra-high-speed spindles because of its applicability to a small target sphere. Castro [8] applied the high-precision sphere and laser interferometer to measure radial and axial error motions of spindles, respectively. Park et al. [9] applied a laser diode, a reflector, two beam-splitters and two PSDs to measure the geometrical errors of rotary axis of miniaturized machine tool by two measurement step. The measurement system includes two modules. The compound errors can be separated into six geometrical errors by theoretical analysis. Anandan et al. [10] proposed a ultra-high-speed miniature spindles error measurement system utilizing two laser Doppler vibrometer (LDV) systems. It is shown that the average radial motion, synchronous radial error motion value and the standard deviation of the asynchronous radial error motion vary significantly with the spindle speed due to dynamic effects. They also applied three LDVs and rotary axis with a custom-fabricated sphere-on-stem precision artifact to simultaneously measure three-dimensional displacements [11]. The measured motion data are post-processed to obtain the synchronous and asynchronous components of the axial and radial error motions in both fixed-sensitive and rotating-sensitive directions, as well as the synchronous error motion values and the standard deviation of asynchronous error motions. Aketagawa et al. [12] introduces a measurement system for spindle radial, axial and angular motions using concentric circle grating and phase modulation interferometers. Using three optical sensors, three radial displacements and three axial displacements of the proper observed position of the grating can be measured. Wang et al. [13] proposed a method with laser tracker on the basis of multi-station and time-sharing measurement principle. In order to maintain high measurement accuracy, laser tracker measures the target points successively at different base stations, and only distance is involved in the measurement, which is called “multi-station and time-sharing measurement”. Based on the GPS principle, the actual coordinates of each measuring point during the turntable rotation can be determined by the measured data at different base stations. Then the motion error of turntable at different rotational angle can be determined by comparing the actual coordinates of each measuring point with its theoretical coordinates. Murakamia et al. [14] proposed an optical measurement system for the simultaneous measurement of the five-degrees-of-freedom error motions of high-speed micro spindles utilizing two laser diodes, two PDs, two QPDs and some optical components. Measurement errors can be separated into three-dimensional (X, Y, Z) errors and two angular (θ_X, θ_Y) errors by theoretical analysis.

Geometric errors of rotary table

Rotary table has a rotational axis. It is known that there are six geometric errors, including three linear errors and three angular errors. Linear errors can be separated into axial errors and eccentric errors; angular errors can be separated into tilt error and rotation error. As shown in Fig. 1, δ_X, and δ_Y are radial errors, δ_Z is axial error; ε_x and ε_Y are tilt errors, ε_z is rotation error.

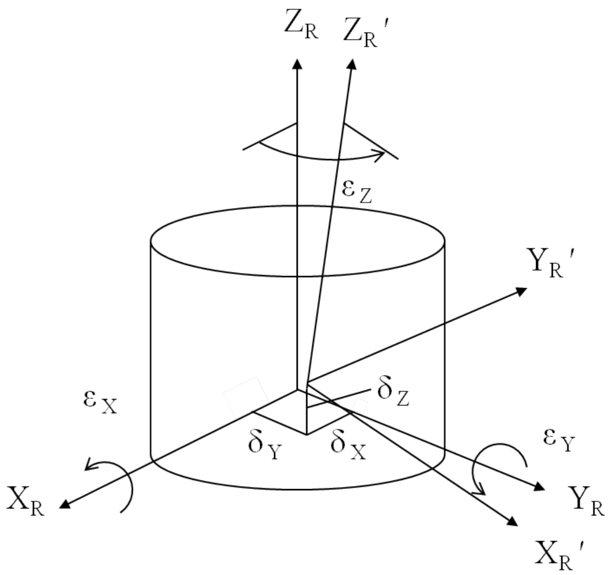

Fig. 1 Geometry errors in rotary axis

System setup of the developed measuring device

Setup of the tilt error measurement. As shown in Fig. 2 (left), the tilt error measurement system is composed of an autocollimator, an optical flat and a Grade I gauge block. The autocollimator contains a laser diode, goniometer stage, optical elements and a QPD. The use of optical flat is to remain the same surface as the tabletop, while the gauge block is assure the parallelism with the flat and to reflect the laser beam. The autocollimator was calibrated by the HP5529A angular interferometer and the residual error is less than 1 arc-sec in the measuring range of ±150 arc-sec. The autocollimator was installed vertically and the laser beam was properly aligned by the goniometer stage. Thus, the tilt error can be measured when rotating.

Setup of the eccentric error measurement. As Fig. 2 (right) , the eccentric error measurement system contains a QPD and corner cube reflector. The QPD sensor was calibrated by HP5529A displacement interferometer and the residual error is less than 0.3 μm in the range of ±40 μm. An X-Y stage was used to adjust the reflector as near to the rotary axis as possible, reducing the radial motion when rotating.

Experiment results

Tilt error measurement. When the rotary table rotates, the tilt error or eccentric error can be measured. Measurement results are shown in Fig 3. By least-squares fitting, the radius of the circle is determined to be 20.3 arc-sec. The form of the circle reflects the tilt errors of a full rotation.

Eccentric error measurement. To the best adjustment of the corner cube reflector, the measurement result are shown in Fig. 4. The errors of X and Y directions are in the range of ±5 μm and ±7 μm, respectively.

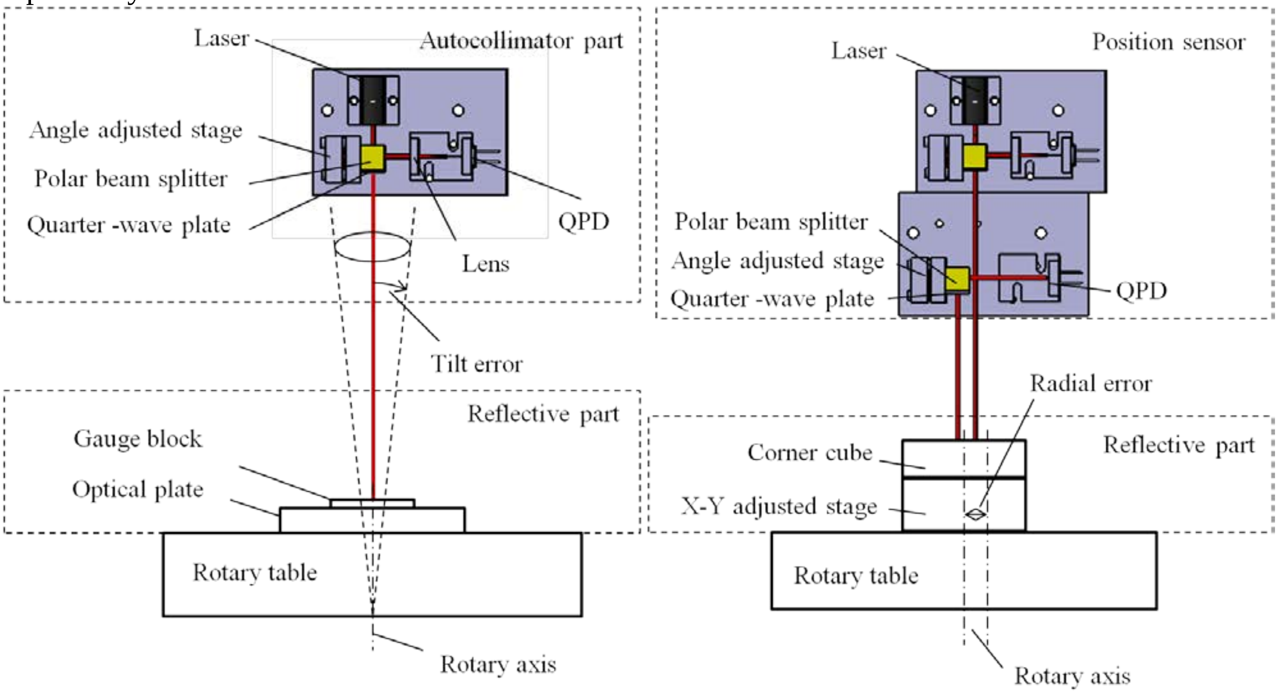

Fig. 2 (left) Tilt measurement system in rotary axis; (right) Eccentric error measurement system

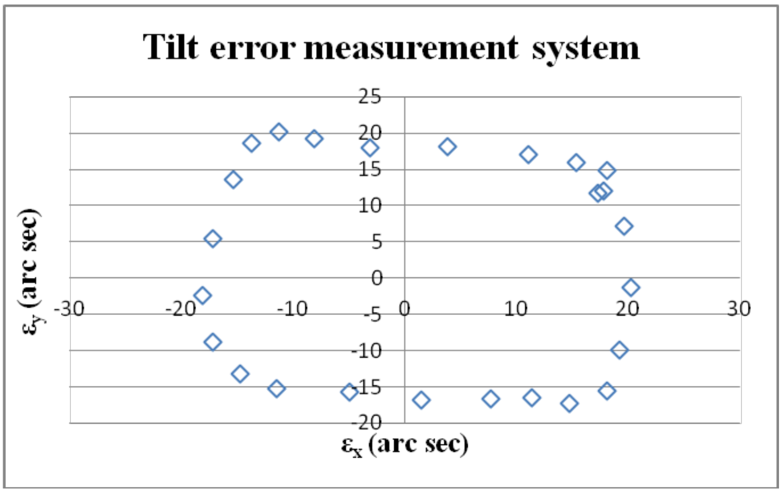

Fig. 3 Measurement results of tilt errors (X 及Y間距要一致才會像一圓)

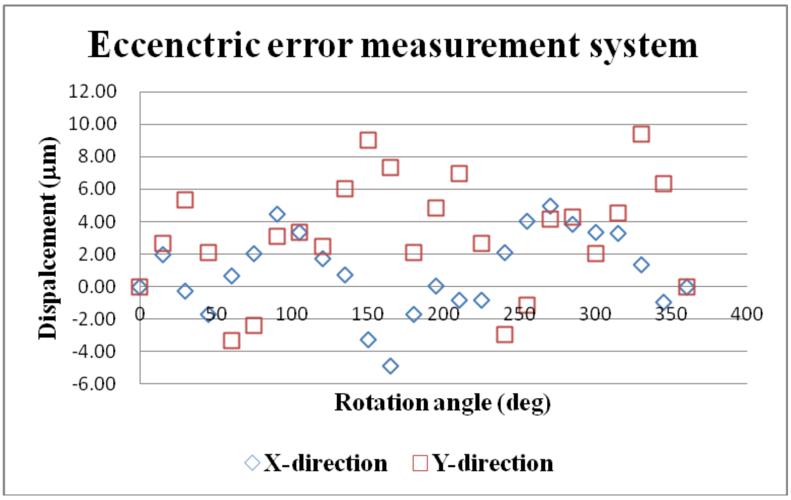

Fig. 4 Measurement results of eccentric errors

Error analysis

As shown in Fig. 5, it is seen that the tilt error will cause the eccentric error. Point O is the original center of the rotary axis. When tilt error occurs, O will be moved to O_t. Therefore, the eccentric error can be determined by tilt error, as given in Eq. 1 and Eq. 2, where L denotes the height of rotary table. In our system, L is approximately 37mm.. The measured tilt error is about 20.3 arc-sec, as given in Fig. 3. Therefore, the calculated eccentric error is in the range of ±4 μm, which is slightly deviated from the measured results given in Fig. 4. The main reason is that, it is difficult to completely eliminate radial motion error of the corner cube reflector, so the residual eccentric errors are inevitably included. The difference could be the actual eccentric error of the stage itself.

$$\delta_Y = L\varepsilon_X \quad (1)$$

$$\delta_X = L\varepsilon_Y \quad (2)$$

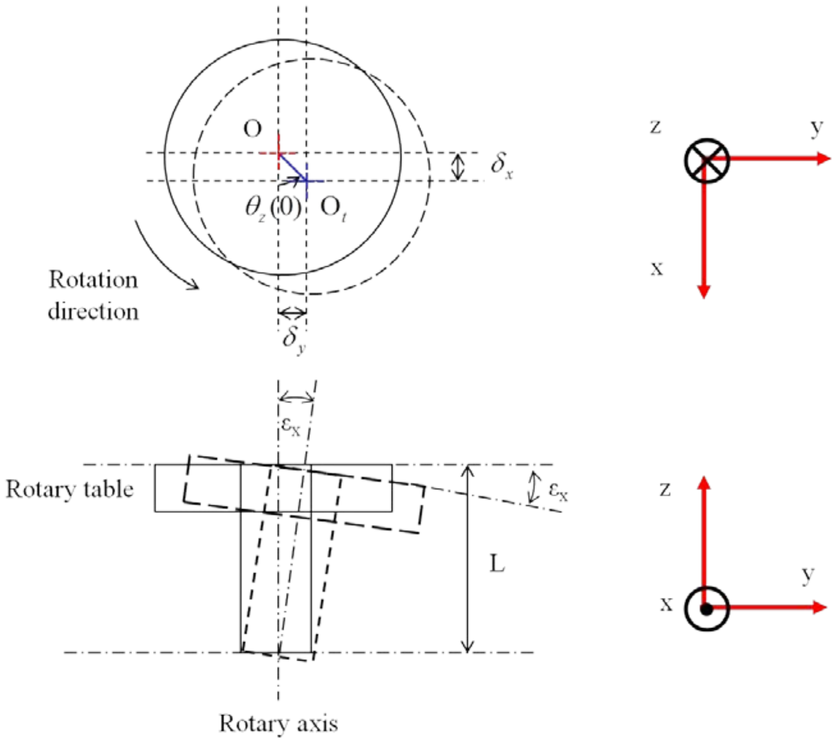

Fig. 5 the relationship between tilt error and eccentric error

Conclusion

Measurement systems for tilt error and eccentric error are developed in this study. From experimental results, tilt error was fitted by least-squares method and the center offset was compensated. However, revolution error cannot be totally excluded. Besides, eccentric error was obtained by analyzing tilt error. Based on the assumption that the tilt error will induce eccentric error at the measuring height, actual eccentric error can be separated.

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