The Measurement and Correction of the Spindle Squareness Error on Five-Axis Machine Tools

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Research Article

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The measurement and correction of the spindle squareness error on five-axis machine tools

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Abstract: The present study aims to establish a measurement method for the squareness error between the machine spindle and the machine table plane. The contact-type touch trigger probe is installed on the spindle of machine tool. When the probe ball touches the rectangle box, a signal is sent to the CNC system to record the space position of the spindle in the machine coordinate system. What this design is to pass to adopt three views of the spindle to determine its spatial location. In the light of the front view and the side view of the spindle, the tilt angle can be identified. According to the projection data, the perpendicularity of the spindle to the horizontal plane is adjusted until the tilt angle error decrease to zero. To verify this method, the corresponding tests are performed on five-axis CNC machine tool. The experimental results show that vertical error of the spindle is reduced by about 60 percent after the tilt angle is adjusted. Therefore, the proposed measurement and calibration method is effective

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in NC machine tool.

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1. Introduction

Along with the development of the numerical control technology, the requirement on processing accuracy of NC machine tool is becomes higher and higher. There are many factors making low machining accuracy, and the squareness error between the machine spindle and the machine table plane is a typical performance. In five-axis machine tool the existing spindle is equipped with a single synchronous hydraulic cylinder and servo motor, which will generate sidelong moment on the sliding slipcover. To control error margin is an important step to resolve problem of accuracy.

There are two basic methods to improve the precision of the spindle, error compensation and error prevention. Masaomi Tsutsumi [1] describes the enhancement of geometric accuracy of five-axis machining centers based on identification and compensation of geometric deviations. Zhang et al. [2] used double ballbar to diagnose the geometric error for the rotary table of five-axis machine tool. Some researchers have demonstrated numerical compensation of the location errors [3-5]. The aim of machine tool error compensation is ‘to counteract’ the terminal error of the tool and to eliminate or to reduce the process errors. Error prevention refers to reduce error source through taking a series of technological measures. It is important to develop a method to improve installation accuracy. ISO/DIS 10791-1 [6] standards give quasi-static tests to calibrate static position and orientation errors of the axis average line of rotary axes. There have been number of researchers focused on the measurement method of machine tool errors. A laser tracker is adopted for the geometric error identification of NC machine tool [7]. Kwang-II Lee et al. [8] proposed parallelism error measurement for the spindle axis of machine tools by two circular tests with different tool lengths. The geometric error is usually measured by using capacitive sensors and precision balls [9-10] , and a laser diode and position sensitive sensors for the spindle axis [11-12]. The individual errors are obtained by direct measurement which need different instruments [13]. Laser interferometer has been widely adopted in machine error detection [14]. The dynamic tracking measurement is widely used in the large workpiece assembly [15-16]. The imprecision of the rotary axes resulted from the position independent geometric errors is considered for a tilting rotary type five axis machine tool using a double ball bar [17].

However, there is a lack of simple and accurate measurement method for correcting squareness error of machine tool spindle. This paper evaluates the assembling errors of the spindle by using touch sensors. Angular error is created from the measured data. By adjusting the lateral bolts of the spindle, the squareness error between the machine spindle and the intersection of two plane will be controlled within an acceptable range. At the end, the squareness of machine tool spindle is verified by using laser interferometer.

2. Squareness error measurement

The structure of the five-axis machine tool is shown in Fig. 1.

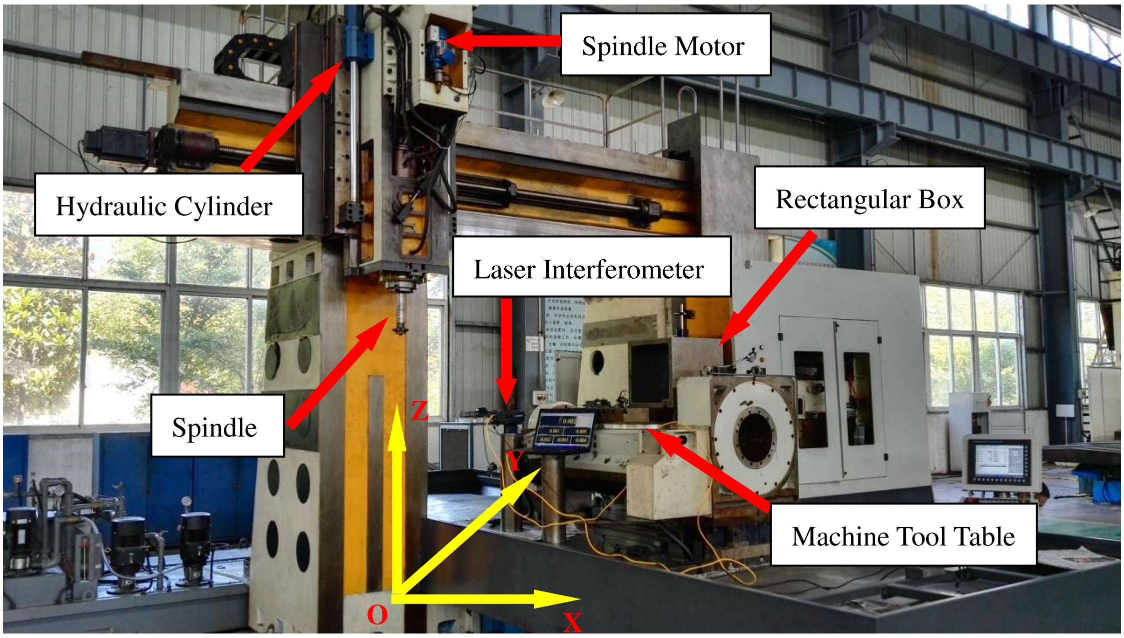

Fig. 1 The structure of the five-axis machine tool

The spindle is equipped with the motor, the hydraulic cylinder, and so on. The overturning moment and the shear deflections have been produced because lateral forces are much larger. This leads to the conclusion that the spindle is not always perpendicular to a horizontal plane. It is generally known that the position relation of line and plane in three dimensional space has three basic types: crossing, parallel and coincidence. If a straight line is perpendicular to two intersecting lines in a plane the line is perpendicular to the plane, which is a special case of the crossing. If a straight line is perpendicular to the projection of the oblique line in the plane, the straight line is perpendicular to the oblique line according to the principle of space vector. For a five-axis machine tool the spindle produce tilt in the space because of having assembling error and adjusting error.

According to the structure of NC machine tool, setting the Z direction is the feed direction of the spindle, a horizontal plane is made up of X-axis and Y-axis. The contact-type touch trigger probe is fixed on the end of the spindle. As the standard measuring equipment, the rectangular box is placed on the level worktable. In order to be measured, the spindle will need to be moved so that the probe keep close to one of the side of rectangular box, the contact point A' is found, as shown in Fig. 2(a). When the contact of a probe ball with the object is detected, a signal is sent to the NC system which record its position in the machine coordinate system and the movement track of the spindle. The position coordinate of the contact point can be analyzed from the probe ball radius and machine position. The spindle moves along the Z direction until another side of rectangular box, the contact point B' is found, as shown in Fig. 2(b). The movement path of the spindle is shown in Fig. 2(a). By the same reason, the spindle can be moved to the front of the rectangular box. The contact point A'' and B'' are recorded in NC system respectively, as shown in Fig. 2(c)-(d). According to the geometric characteristic of contact point trace in the plane, the space location of the spindle can be identified.

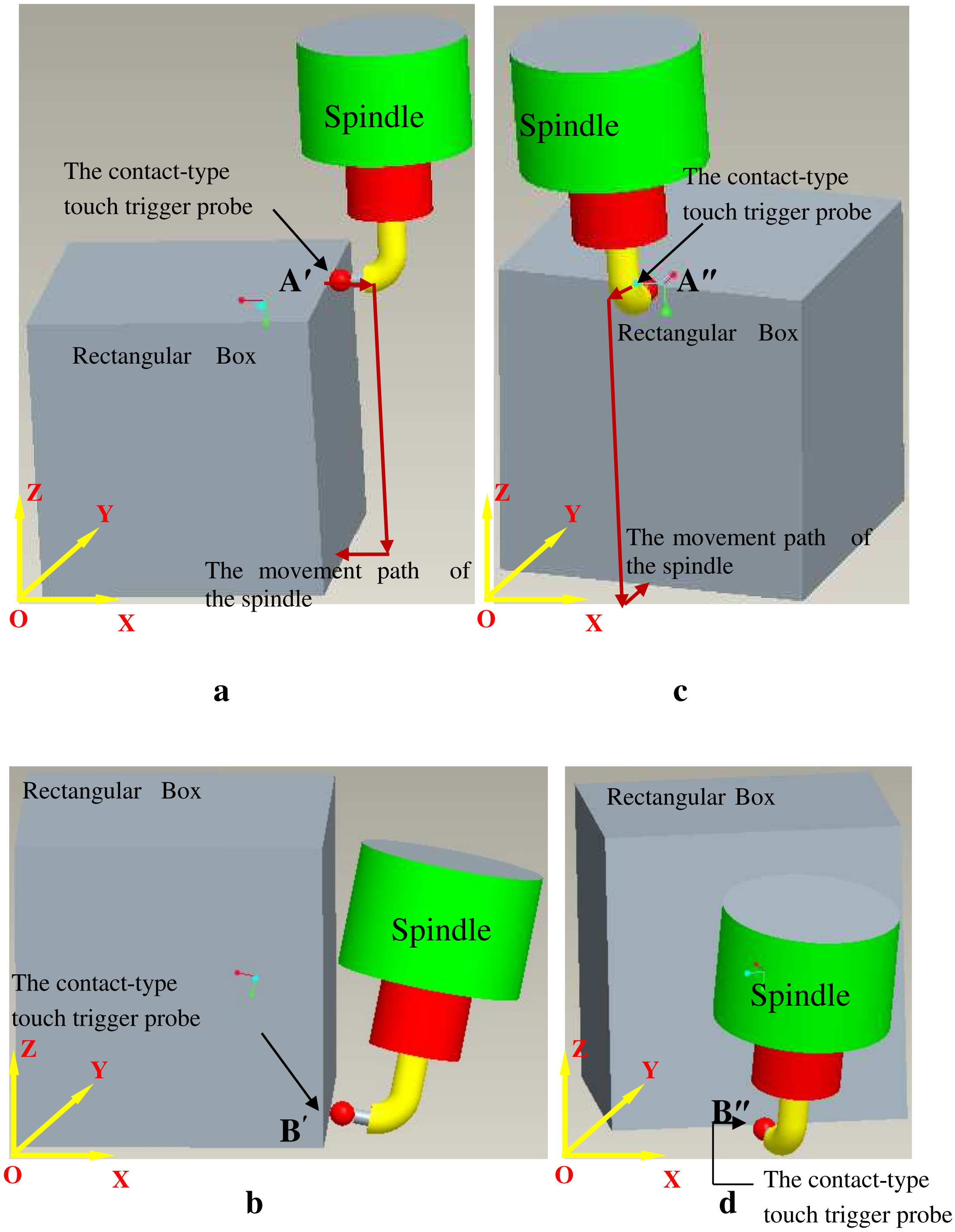

Fig. 2 The measure method (a)-(d)

3. Identification of the squareness error of the spindle

The deviation angle of the spindle is determined from the projection of the central axial AB on the π' and π'' plane, as shown in Fig. 3.

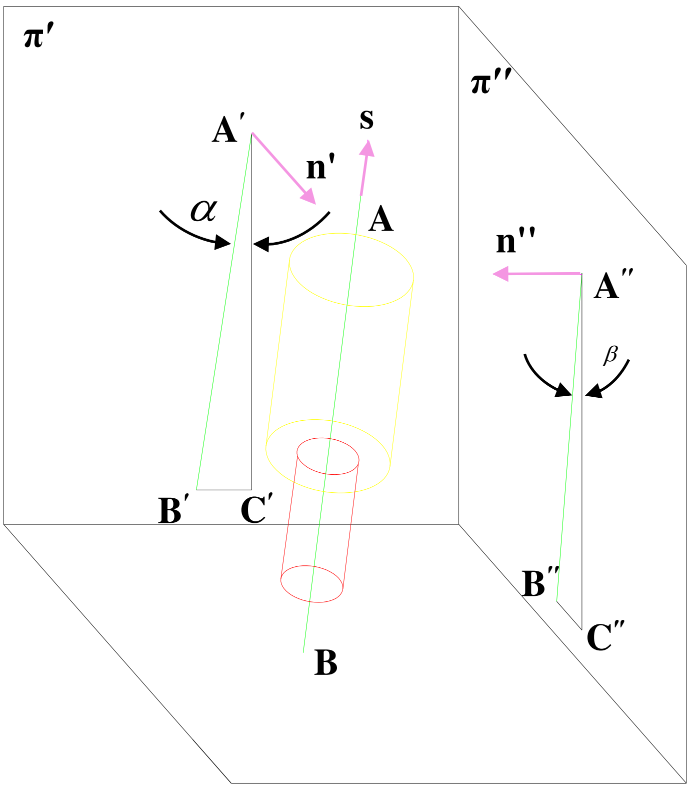

Fig. 3 The projection of the spindle from probed points

Supposing the center line of the spindle intersect plane π', $A'B'$ is the projection of AB on the plane π', the acute angle β between the oblique line AB and the projective $A'B'$ is denoted by the angle of straight line and plane, that is $\angle(AB,\pi')=\angle(AB,A'B')$. Similarly, the center line of the spindle intersect plane π'', $A''B''$ is the projection of AB on the plane π'', the acute angle α between the oblique line AB and the projective $A''B''$ is denoted by the angle of straight line and plane, that is $\angle(AB,\pi'')=\angle(AB,A''B'')$.

The angle α formed by the projections of the intersection line of the central axial AB and plane π'' on the plane π'. Suppose the direction vector of the spindle is $s=\{l,m,n\}$ and the normal vector to the plane π' is $n'=\{U,V,W\}$, the angle between central axis of the spindle and a plane is denoted by

$$\beta=\frac{\pi}{2}-(s,n') \text{ or } \beta=(s,n')-\frac{\pi}{2} \tag{1}$$

Therefore, $\sin\beta=\left|\cos(s,n')\right|$, (2)

$$\sin\beta=\frac{|s\cdot n'|}{|s||n'|}=\frac{|Ul+Vm+Wn|}{\sqrt{l^2+m^2+n^2}\sqrt{U^2+V^2+W^2}} \tag{3}$$

Suppose the normal vector to the plane π'' is $n''=\{U',V',W'\}$, the angle between central axis of the spindle and a plane is denoted by

$$\alpha=\frac{\pi}{2}-(s,n'') \text{ or } \alpha=(s,n'')-\frac{\pi}{2} \tag{4}$$

Therefore, $\sin\alpha=\left|\cos(s,n'')\right|$, (5)

$$\sin\alpha=\frac{|s\cdot n''|}{|s||n''|}=\frac{|U'l+V'm+W'n|}{\sqrt{l^2+m^2+n^2}\sqrt{U'^2+V'^2+W'^2}} \tag{6}$$

If the spindle is not perpendicular the plane of machine tool table, the inclination angle of the spindle has great effect on processing accuracy. The small angular error causes large deviation from the desired position of the tool tip depend upon the distance between the spindle pivot and the length of tool shank. The attitude of the spindle in the three-dimensional space can be satisfied to realize calibration efficiently by minimizing the angle α and β. After minor adjustments, the displacement of the spindle relative to the machine tool table could be considerably greater, which can be transformed to the problem of the positioning accuracy. The spatial position and attitude of the spindle is different before and after the calibration. In the light of the projection of the spindle in horizontal plane the relative displacement can be computed. The positioning error has arisen based on the theory. It is an common method to reduce position errors of machine tool by using the compensation function of CNC systems.

4. Experiment

In order to demonstrate the feasibility of this method, an experiment was conducted on a five-axis machine tool. Obtaining the squareness error is a prerequisite to adjust the tilt angle of the spindle. In this study, a RMP-60 touch-trigger probe was mounted directly onto the end face of the spindle. The diameter of the ruby sphere is 6 mm, the contact is detected by the spring loaded kinematic arrangement of rods and balls. The side length of the square box placed on the machine tool table is 300 mm. Of course, the square box and the machine tool table must be horizontal. To reduce the influence of environmental temperature, the spindle need 0.5 hours for warm-up after turning on. From the NC display system can be seen that the acute angle α and β are 0.0048 degrees and 0.0031 degrees before the inclination angle of the spindle adjusted, respectively.

In order to validate this method, the corresponding tests was performed. The straightness of the X-axis and the perpendicularity of Z-axis to X-axis were measured by using an API laser interferometer. The straightness error of each axis was a key factor affecting the squareness between axes. The 7 sample points on the X-axes were recorded respectively. By the same reason, the sample points on the Y and Z axes were no exception.

It is shown from the test results that the straightness error for X-axis and Z-axis are 0.0157 mm and 0.04027 mm respectively, the vertical deviation of X-axis relative to Z-axis is 0.005 degrees, as shown in Fig. 4. The deviation angle of the spindle in the X direction is adjusted so that the spindle is parallel to the YZ plane. The measured results after the calibration show that the vertical deviation of X-axis relative to Z-axis is 0.002 degrees, the straightness error of Z-axis is 0.03652 mm and the straightness error of X-axis remain unchanged, as shown in Fig. 5.

Similarly, the results of measurement show that the straightness error for Y-axis and Z-axis are 0.0413 mm and 0.0426 mm respectively, the vertical deviation of Y-axis relative to Z-axis is 0.003 degrees before the adjustment, as shown in Fig. 6. The deviation angle of the spindle in the Y direction is adjusted so that the spindle is parallel to the XZ plane. After the calibration the measured results show that the vertical deviation of Y-axis relative to Z-axis is 0.001 degrees, the straightness error of Z-axis is 0.03569 mm and the straightness error of Y-axis remain unchanged, as shown in Fig. 7. At this moment the graphics display in NC system showed that the acute angle α and β are 0.0017 degrees and 0.0012 degrees, respectively. The vertical error can be reduced to 0.002 degrees from 0.005 degrees by analyzing the squareness of the spindle to X-axis from Figs. 4 and 5. The NC system displays that the acute angle α can be reduced to 0.0017 degrees after the adjustment from 0.0048 degrees before the adjustment. In the same way, the vertical error can be reduced to 0.001 degrees from 0.003 degrees by analyzing the squareness of the spindle to Y-axis from Figs. 6 and 7. The NC system displays that the acute angle β can be reduced to 0.0012 degrees after the adjustment from 0.0031 degrees before the adjustment.

From the above analysis, it is shown that installation accuracy of the machine tool is improved by about 60%. There is consistency to a certain extent between the display values of the NC system and the results measured by using the laser interferometer.

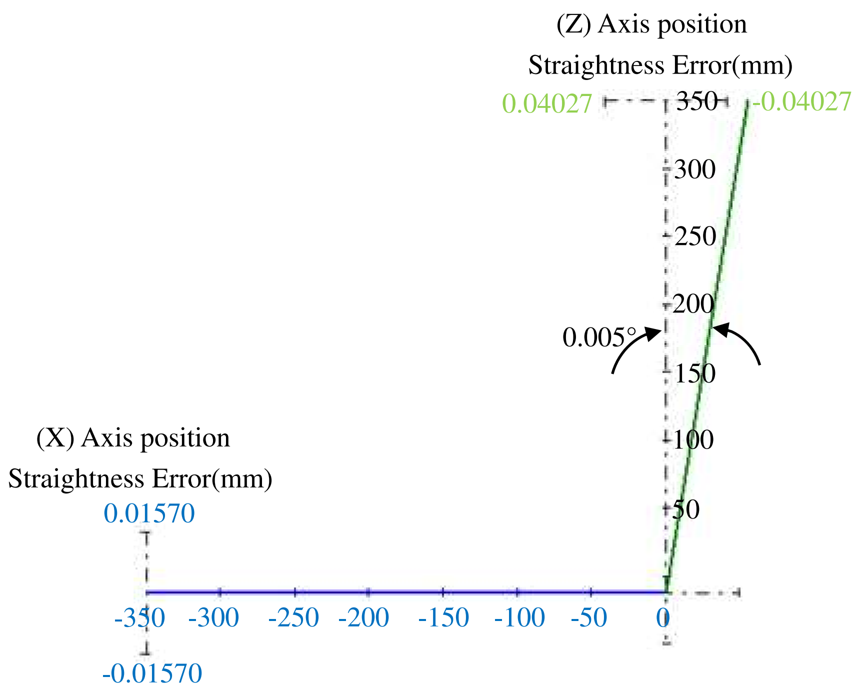

Fig. 4 The vertical deviation of X-axis relative to Z-axis before the adjustment

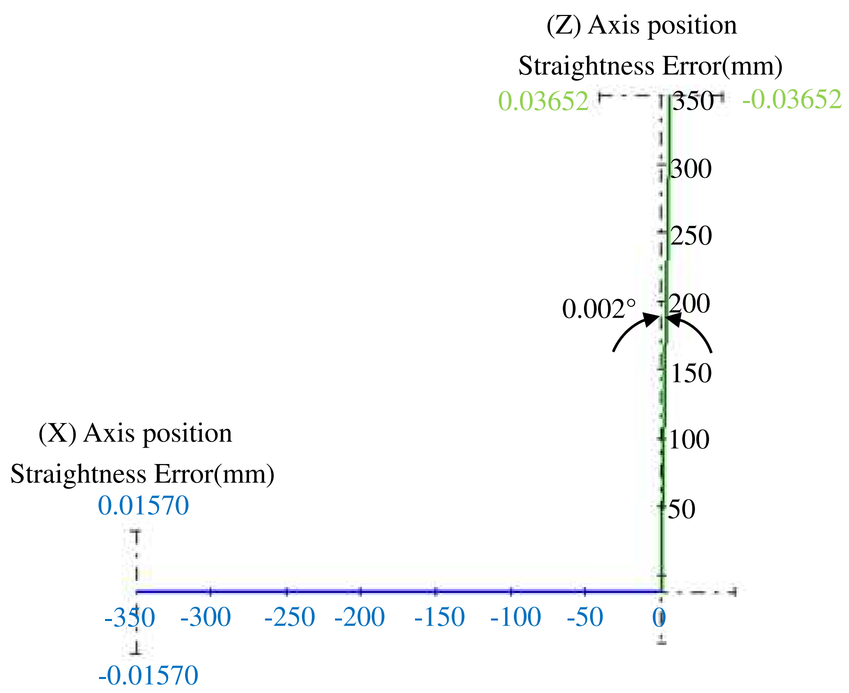

Fig. 5 The vertical deviation of X-axis relative to Z-axis after the adjustment

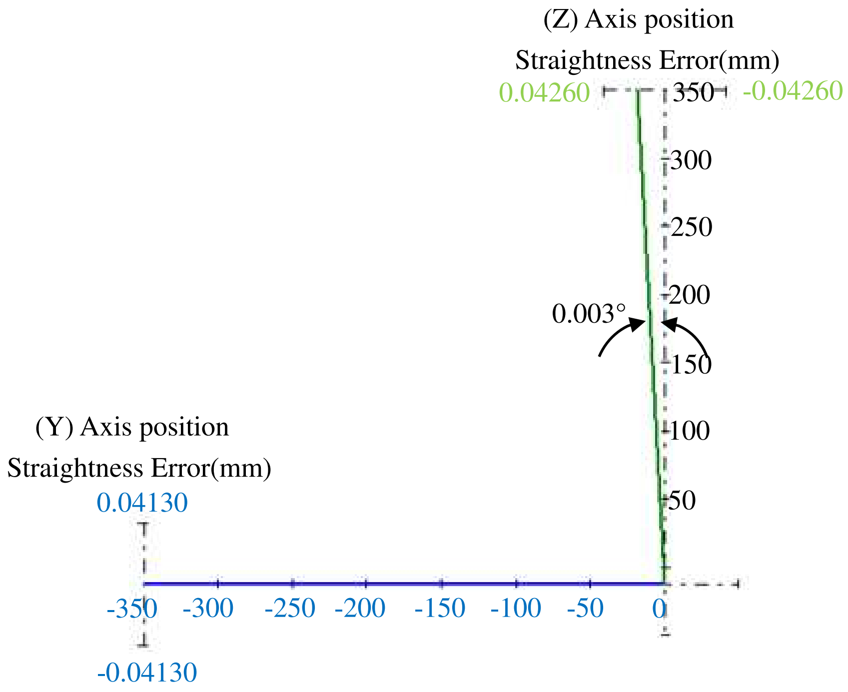

Fig. 6 The vertical deviation of Y-axis relative to Z-axis before the adjustment

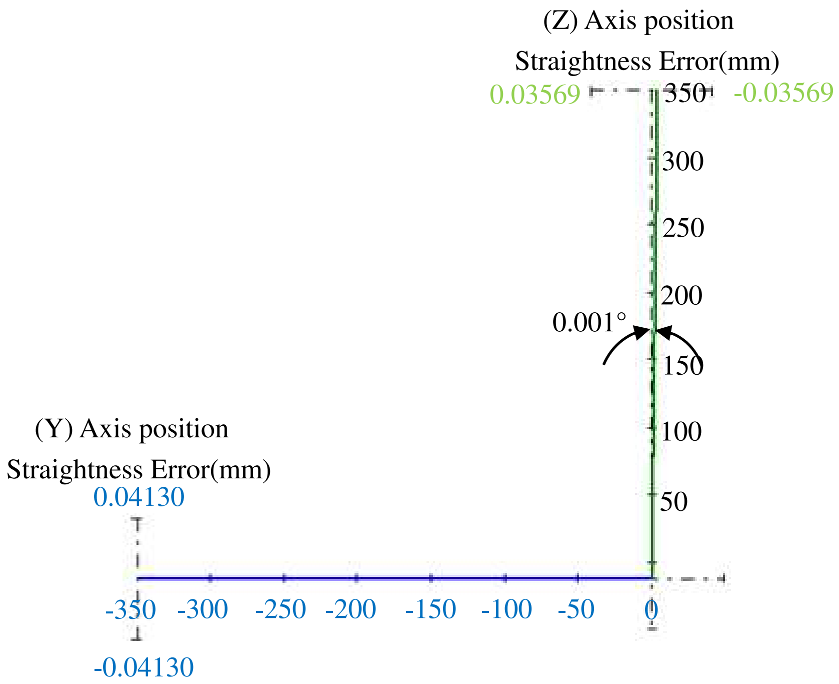

Fig. 7 The vertical deviation of Y-axis relative to Z-axis after the adjustment

5. Conclusion

This paper presents a new method for measuring the squareness error between the machine spindle and the machine table plane by using the contact-type touch trigger probe. After the traditional methods of straightness measurement are analyzed and compared, the measurement based on the precision sphere and rectangular box is adopted. The measuring precision and sensitivity by this way is very high. In accordance with the projection principle of descriptive geometry, front view and left view of the spindle are considered and top view is ignored because the adjusting error of the spindle on the horizontal plane can be restricted by error compensation technology.

Compared with the previous methods, this method has several advantages: (1) no a additional measurement is required to the squareness error of the spindle in machine tool, (2) the method of measurement is developed for any multi-axis machine tools, (3) this method can restrain the integrated error and improve the precision of machine tool.

Moreover, stress concentrations can lead to the spindle fatigue. How to effectively decrease the stress concentrative factor and improve fatigue life of the spindle become to the most important problem. A related research will be followed by more discussions and concerns in the future.

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The reference section:

-Ethical Approval

-Consent to Participate

-Consent to Publish

-Authors Contributions

-Funding

-Competing Interests

-Availability of data and materials

The above part has nothing to do with the manuscript. 'Not applicable' for that specific section.

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Figures

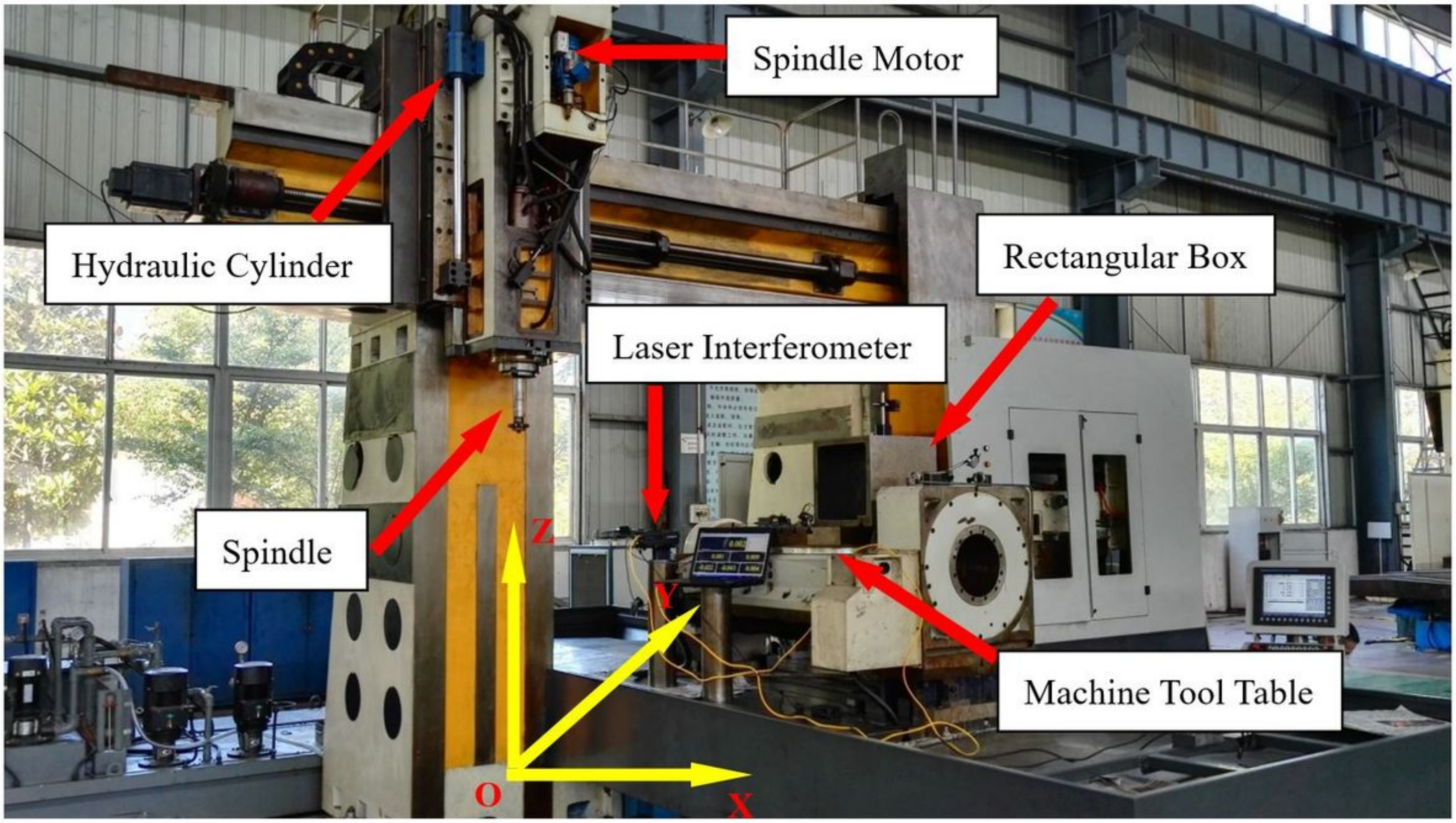

Figure 1

The structure of the five-axis machine tool

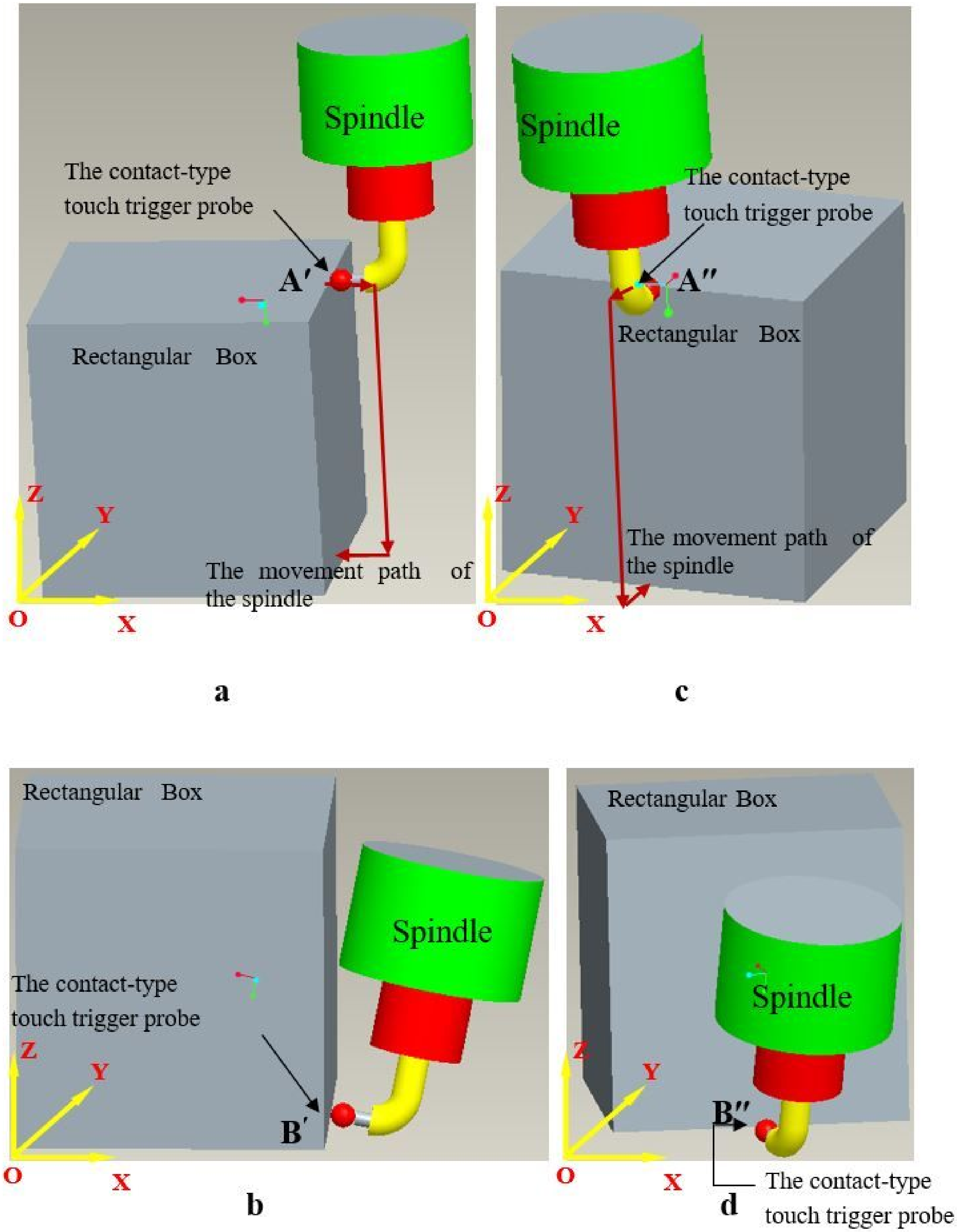

Figure 2

The measure method (a)-(d)

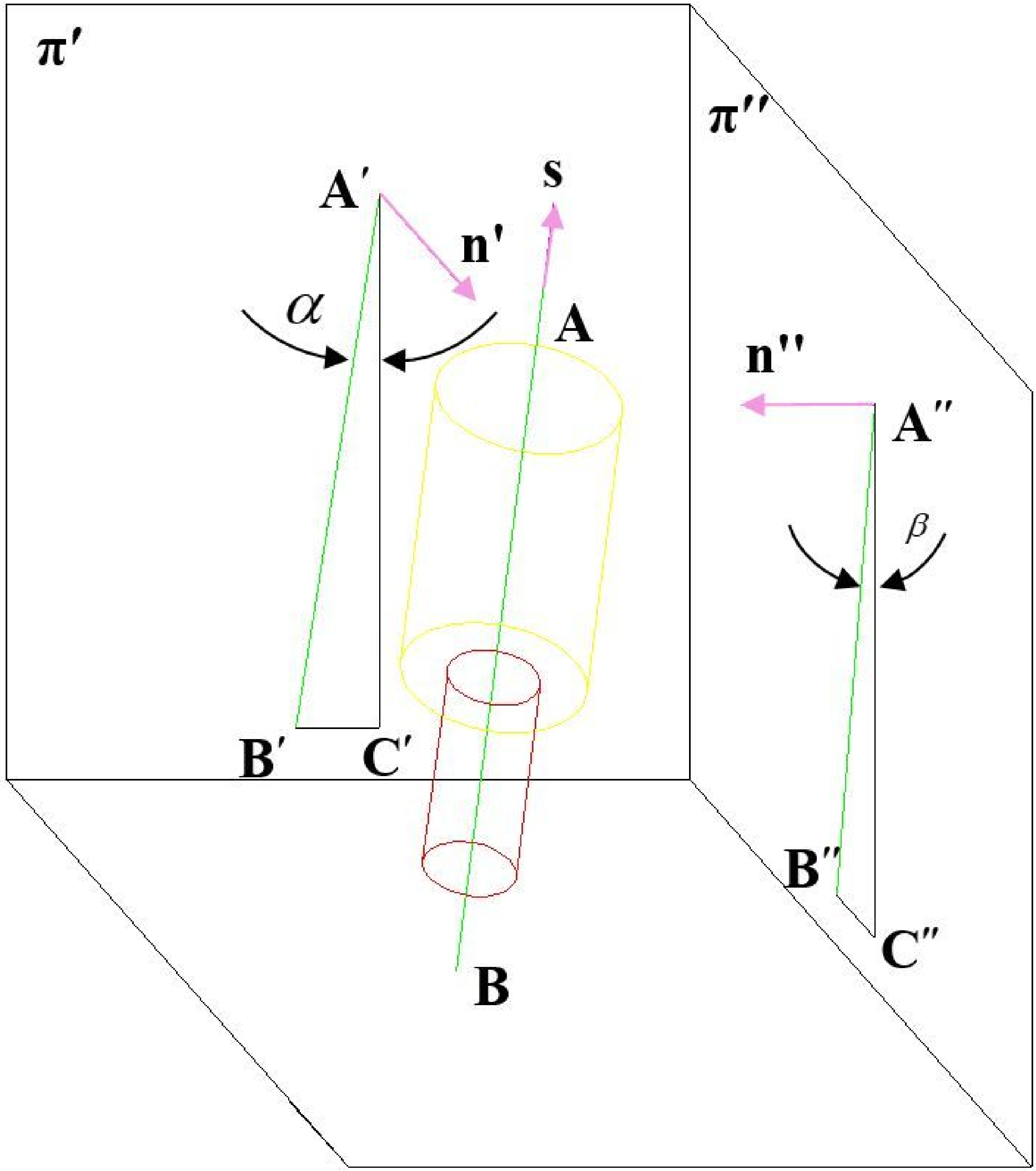

Figure 3

The projection of the spindle from probed points

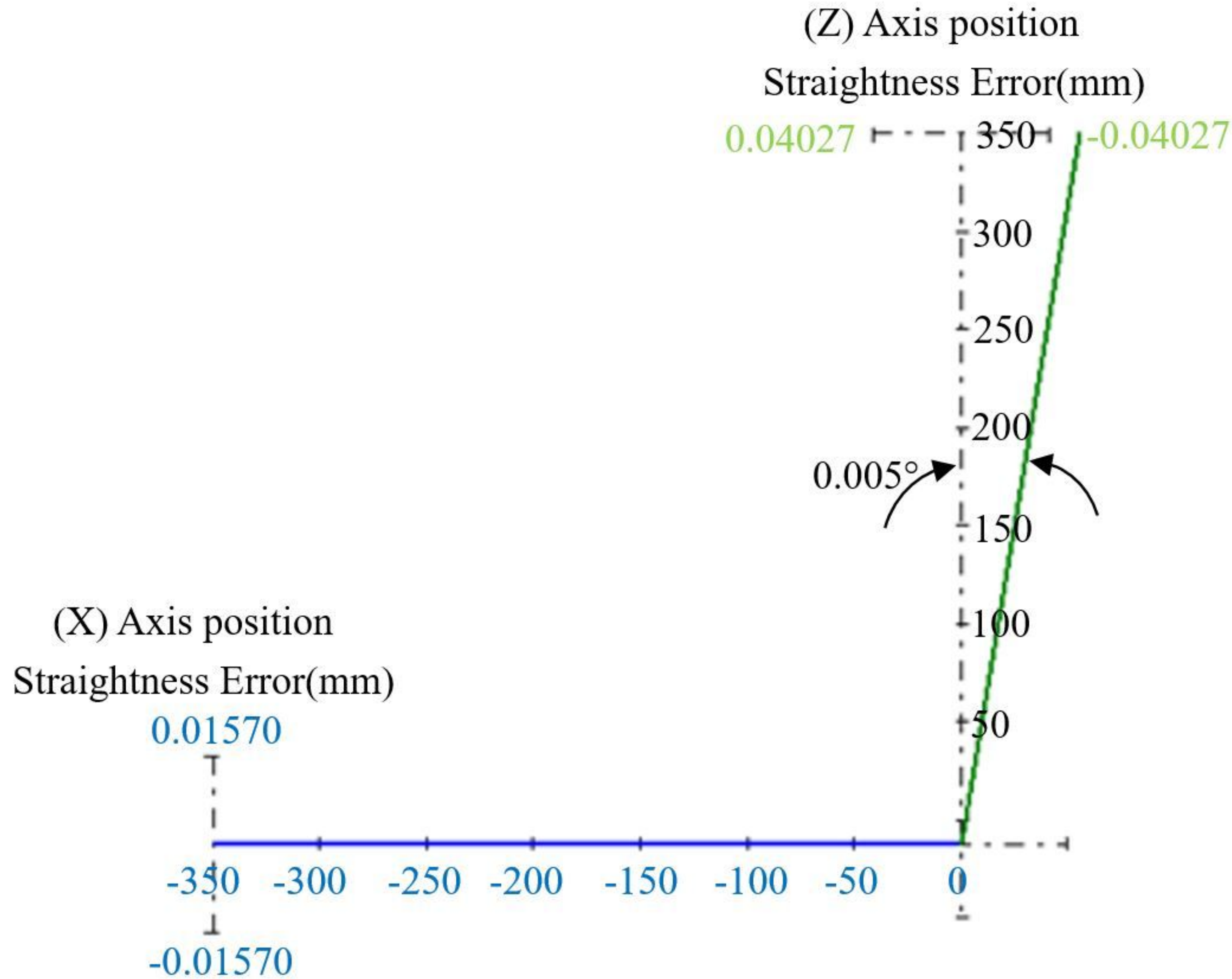

Figure 4

The vertical deviation of X-axis relative to Z-axis before the adjustment

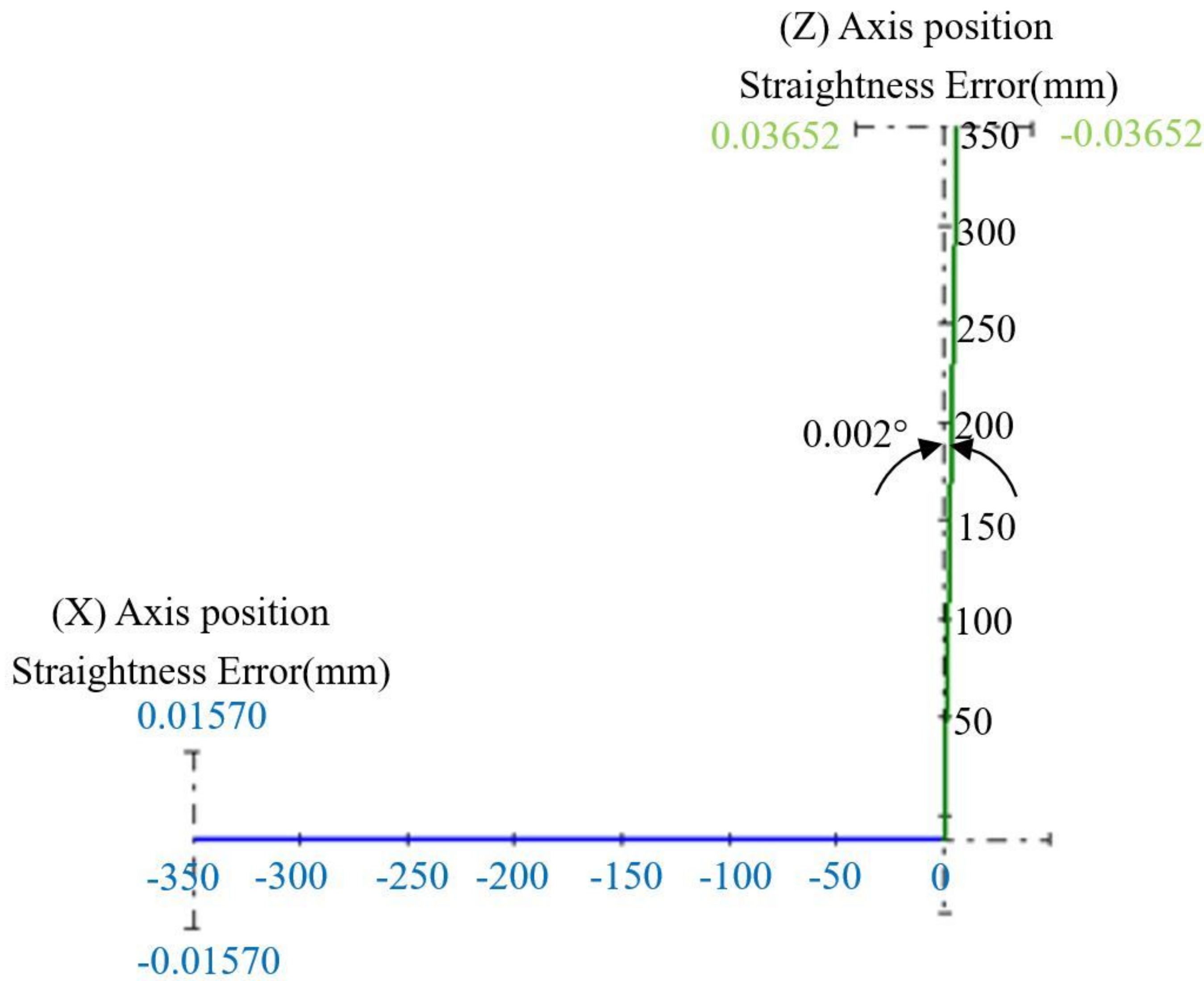

Figure 5

The vertical deviation of X-axis relative to Z-axis after the adjustment

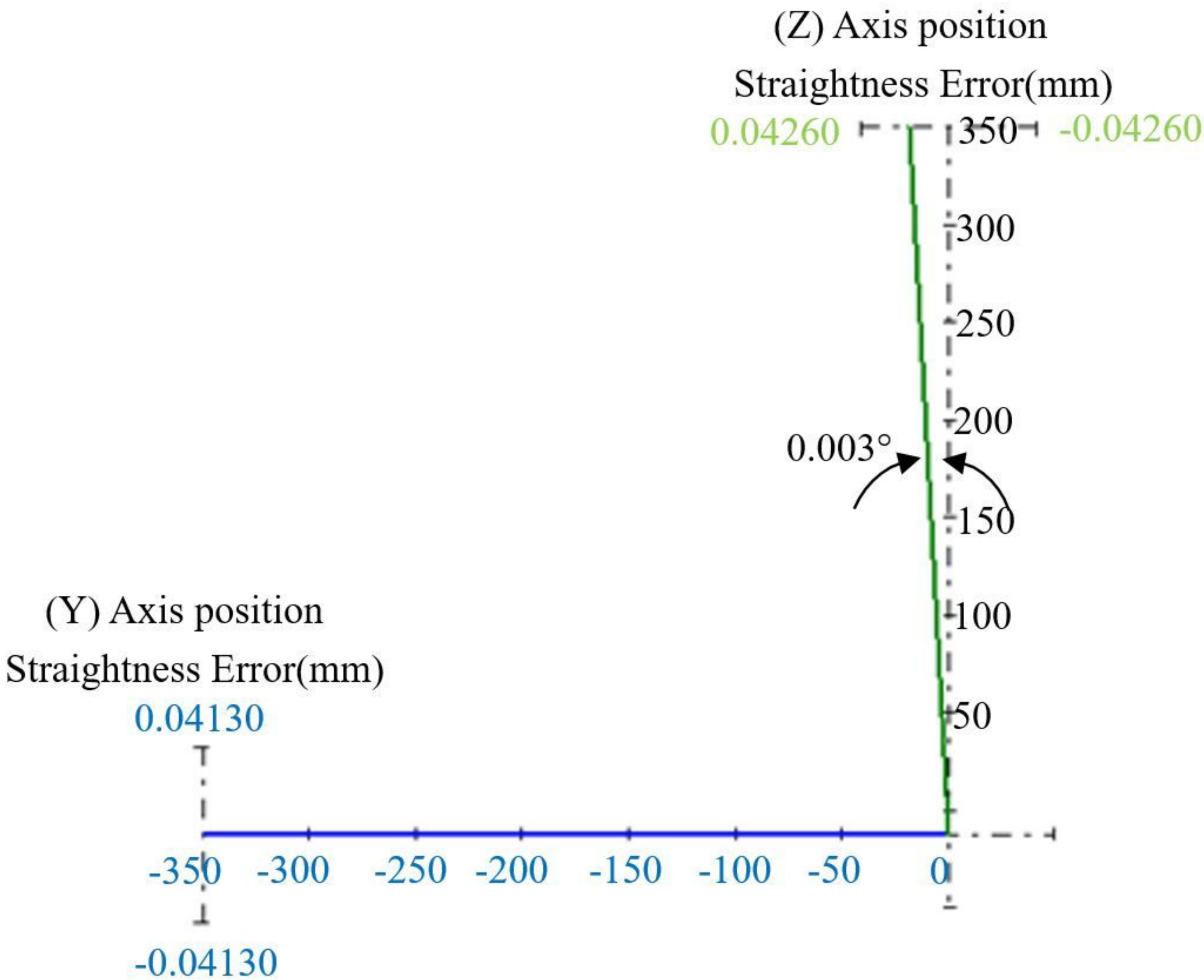

Figure 6

The vertical deviation of Y-axis relative to Z-axis before the adjustment

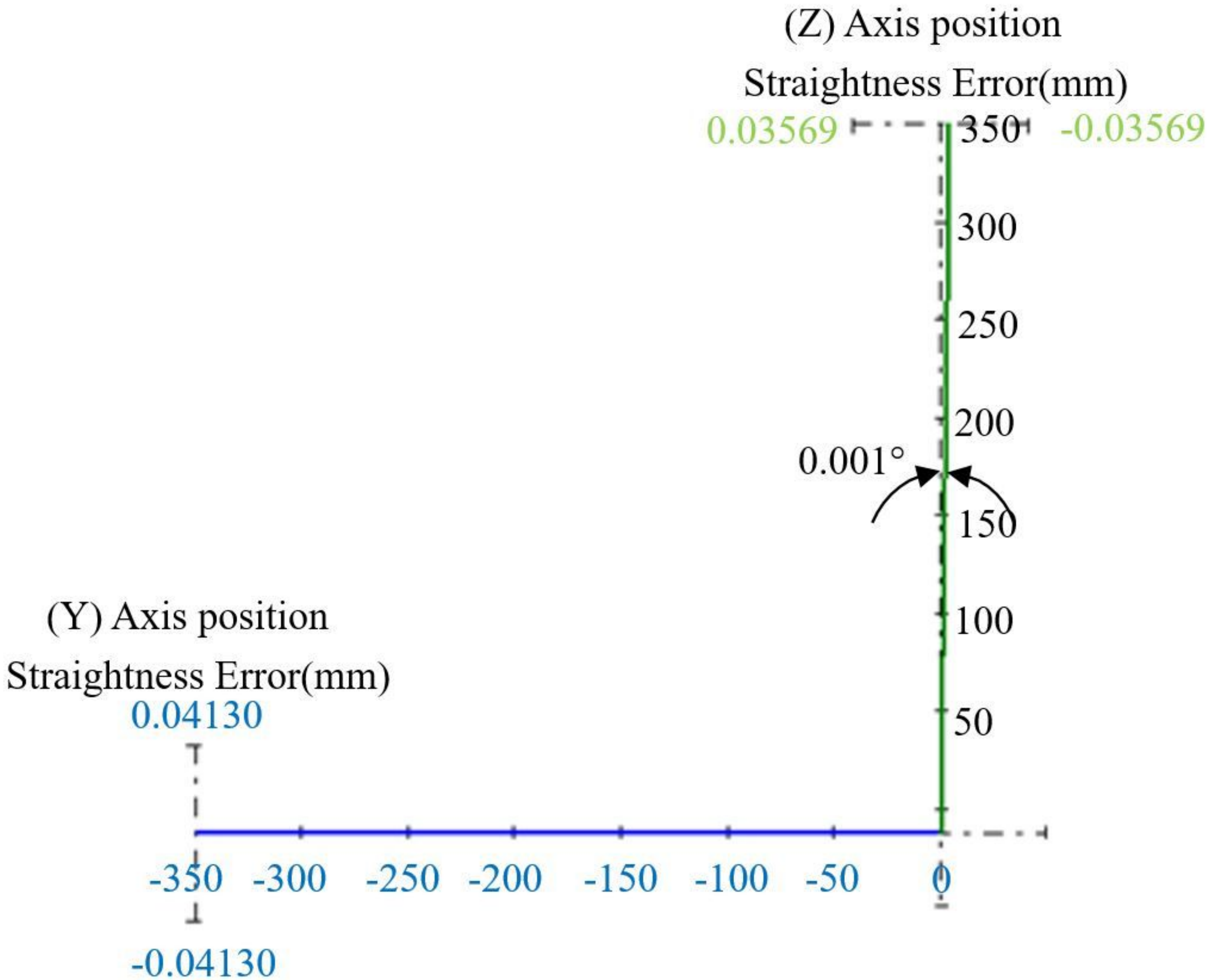

Figure 7

The vertical deviation of Y-axis relative to Z-axis after the adjustment