Int J Adv Manuf Technol (2013) 65:275–281
DOI 10.1007/s00170-012-4166-4

ORIGINAL ARTICLE

Geometric error measurement and compensation for the rotary table of five-axis machine tool with double ballbar

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Received: 6 September 2011 / Accepted: 10 April 2012 / Published online: 5 May 2012

Abstract This paper proposes a novel measuring method for geometric error identification of the rotary table on five-axis machine tools by using double ballbar (DBB) as the measuring instrument. This measuring method greatly simplifies the measurement setup, for only a DBB system and a height-adjustable fixture are needed to evaluate simultaneously five errors including one axial error, two radial errors, and two tilt errors caused by the rotary table. Two DBB-measuring paths are designed in different horizontal planes so as to decouple the linear and angular errors. The theoretical measuring patterns caused by different errors are simulated on the basis of the error model. Finally, the proposed method is applied to a vertical five-axis machining center for error measurement and compensation. The experimental results show that this measuring method is quite convenient and effective to identify geometric errors caused by the rotary table on five-axis machine tools.

Keywords Geometric errors · Rotary table · Double ballbar · Error measurement · Error compensation · Five-axis machine tool

1 Introduction

Five-axis machine tools are becoming increasingly popular and can be found in a large number of manufacturing applications: from automotive to aerospace, from large mechanical parts to miniature medical equipment, and from daily repair tools to scientific research instruments, for they can provide better tool orientation ability, higher material removal rate, less fixture and tool adjusting time, and lower production cost. However, five-axis machine tools are usually more complicated and less rigid in structure compared with traditional three-axis machine tools, which leads to lower machining accuracy [1]. The rotary axes are the dominant sources of machining errors, so if there is an effective measuring method to identify the geometric errors of the rotary axes and then implement proper error compensation technique, the machining performance of five-axis machine tools will be improved significantly.

Many researchers have investigated the machining errors of five-axis machine tools and presented some error identification methods based on various kinds of measuring instruments. Bryan [2, 3] firstly introduced the double ballbar (DBB) method in 1982 to evaluate the machine performance, including thermal error expansion of linear axis, squareness, backlash, servo mismatch, etc. Tsutsumi et al. [4] focused on the deviations inherent to the rotary axes and proposed a DBB method to inspect angular and linear deviations. Lei et al. [5] used DBB to evaluate dynamic performance of the rotary axes, including the following parameters: feed rate, position loop gains, natural frequency, and damping factor. Lai et al. [6] introduced a method, using DBB, to diagnose the nonlinear error sources in the guideway system. Zargarbashi et al. [7] designed five DBB-measuring tests to assess the trunnion axis (A-axis) motion errors. Dassanayake et al. [8] used DBB to identify the ten inherent deviations to double pivot head-type five-axis machines. In addition to the above DBB-measuring methods, some other instruments were also utilized for the performance evaluation. Lei et al. [9, 10] developed a new measurement device, namely 3D probe ball, and

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corresponding methods for accuracy evaluation of five-axis machine tools. Weikert [11] used a measuring device which was called R test to calibrate errors like backlash, positioning error, squareness, parallelism, etc. Hong et al. [12] also demonstrated an application of R test to measure the enlargement of a periodic radial error motion of C-axis with B-axis rotation. Jywe [13] developed a planar encoder measuring system for the performance tests of machine tools.

Although a considerable amount of research work has been conducted to identify the linear axes errors and certain errors caused by the rotary axes [14–16] of specified machine tool structure, there is still a need for a convenient and effective method to measure the errors of rotary axes systematically. In this paper, a novel methodology is developed to measure five errors out of six degrees of freedom (DOF) geometric errors caused by the rotary table. A special fixture is designed to assist the DBB-measuring tests. After two DBB tests conducted in different horizontal measuring planes, three linear and two angular errors can be identified by using the measuring model.

2 Geometric error model of the rotary table

Five-axis machine tools with a tilting rotary table are most common in manufacturing industry. As shown in Fig. 1, the research and experiments were both conducted on this type of machining center. The vertical spindle is mounted with three linear axes, while the workpiece is located on the rotary table controlled by two rotary axes.

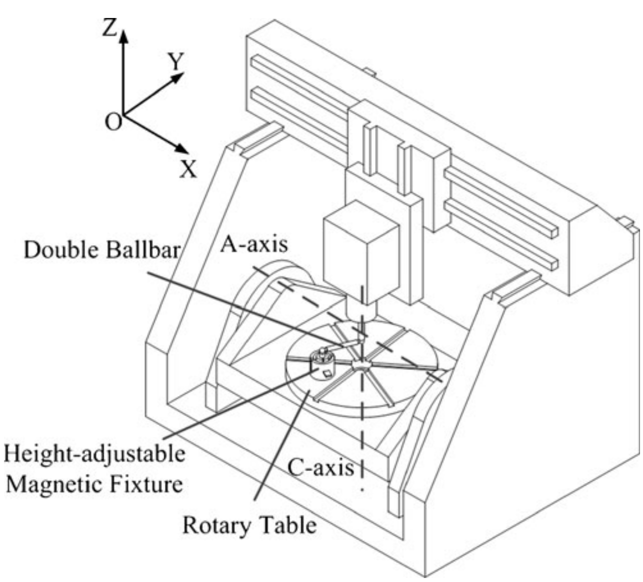


Fig. 1 Five-axis machine tool with a tilting rotary table

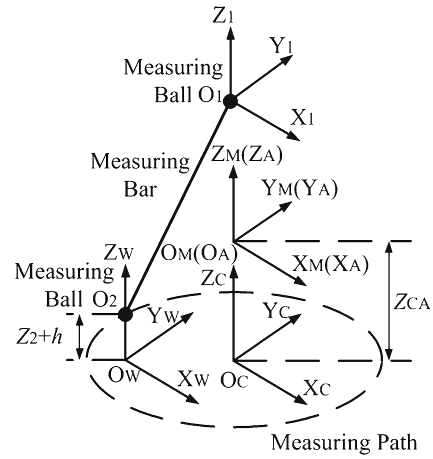


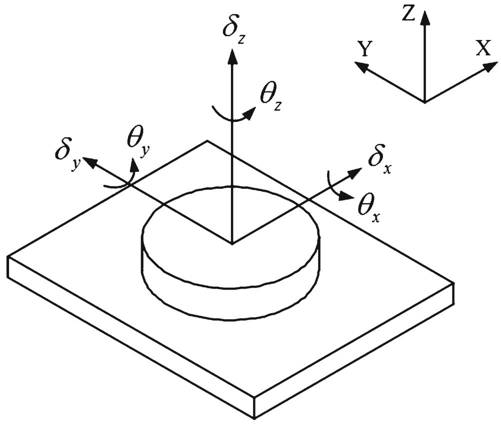
Fig. 2 Coordinate systems definition for DBB-measuring test

Some coordinate systems should be defined to establish the geometric error model. In Fig. 2, the machine coordinate system, namely MCS $\{O_M–X_MY_MZ_M\}$, is defined as the reference system whose origin is located at the intersection of A- and C-axis. The initial position of the A-axis coordinate system $\{O_A–X_AY_AZ_A\}$ overlaps with MCS. The C-axis coordinate system $\{O_C–X_CY_CZ_C\}$ is defined on the rotary table. The workpiece coordinate system, namely WCS $\{O_W–X_WY_WZ_W\}$, is defined on certain position of the rotary table. All the linear axes coordinate systems are defined co-axial to MCS and with the same origin when the machine tool is at its machine zero position.

During the measuring test, only C-axis moves, while the other four axes are kept stationary. To simplify the error model, the X-, Y-, Z-, and A-axes are considered perfect in their position and motion. Therefore, only the errors caused by C-axis influence the DBB-measuring results. For a rotary axis, six DOF geometric errors can be found during the nominal movement, including one axial error, two radial errors, one angular position error, and two tilt errors. Figure 3 shows these error components of the rotary table. However, the measuring method proposed in this paper can just identify all the error components except θ_z. According to the above analysis and the symbol definition, the homogenous transformation matrices (HTM) can be deduced as follows:

${}^{C}_{W}\mathbf{T}$ denotes a HTM from WCS to the C-axis coordinate system

$$ {}^{C}_{W}\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & x_W \\ 0 & 1 & 0 & y_W \\ 0 & 0 & 1 & z_W \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$



δ_x: Radial error in X-axis direction

δ_y: Radial error in Y-axis direction

δ_z: Axial error in Z-axis direction

θ_x: Tilt error around X-axis

θ_y: Tilt error around Y-axis

θ_z: Angular position error around Z-axis

Fig. 3 Six geometric errors of the rotary table

${}^{A}_{C}\mathbf{T}$ is the rotation matrix which describes the motion of C-axis nominal rotation by angle c:

$$ {}^{A}_{C}\mathbf{T} = \begin{bmatrix} \cos c & -\sin c & 0 & 0 \\ \sin c & \cos c & 0 & 0 \\ 0 & 0 & 1 & -z_{CA} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

where, z_{CA} is the distance between O_C and O_A in Z-axis direction, as shown in Fig. 2.

If the geometric errors caused by C-axis exist, the error matrix $\mathbf{E}$ is defined by Eq. (3).

$$ \mathbf{E} = \begin{bmatrix} 1 & -\theta_z & \theta_y & \delta_x \\ \theta_z & 1 & -\theta_x & \delta_y \\ -\theta_y & \theta_x & 1 & \delta_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

If A-axis moves by a nominal angle a, HTM from A-axis to MCS can be defined by Eq. (4).

$$ {}^{M}_{A}\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos a & -\sin a & 0 \\ 0 & \sin a & \cos a & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4} $$

As depicted above, the A-axis is stationary during the measuring tests, that is a=0 in Eq. (4). Therefore, ${}^{M}_{A}\mathbf{T}$ becomes an identity matrix.

See Fig. 2, suppose the position of the measuring ball O_2 in WCS is ${}^{W}\mathbf{P}_{O_2}$ (given in Eq. (5)), we can obtain the position of O_2 in MCS by Eq. (6).

$$ {}^{W}\mathbf{P}_{O_2} = [0 \quad 0 \quad z_2 + h \quad 1]^{T} \tag{5} $$

$$ {}^{M}\mathbf{P}_{O_2} = {}^{M}_{A}\mathbf{T} \cdot \mathbf{E} \cdot {}^{A}_{C}\mathbf{T} \cdot {}^{C}_{W}\mathbf{T} \cdot {}^{W}\mathbf{P}_{O_2} \tag{6} $$

where z_2 is the height of the ball cup associated with the ball O_2 and h indicates the height of the magnetic fixture.

Now consider the position of the measuring ball O_1 which is located at the spindle nose.

$$ {}^{M}\mathbf{P}_{O_1} = {}^{M}_{Y}\mathbf{T} \cdot {}^{Y}_{X}\mathbf{T} \cdot {}^{X}_{Z}\mathbf{T} \cdot {}^{Z}\mathbf{P}_{O_1} = [x,y,z,1]^{T} \tag{7} $$

where x, y, and z are the machine tool linear axes nominal displacement.

The DBB reading corresponds to the length of the measuring bar. And the length of the bar is determined by the actual relative position of the measuring ball O_1 and O_2 through Eqs. (6) and (7). Suppose the length of the bar is L, we can get its value through Eq. (8).

$$ L = \left| \overrightarrow{O_1O_2} \right| = \left| {}^{M}\mathbf{P}_{O_2} - {}^{M}\mathbf{P}_{O_1} \right| \tag{8} $$

From Fig. 2 and Eq. (1), it can be seen that the initial position of WCS in the C-axis coordinate system does not exert any influence on the DBB-measuring pattern, so we can put the origin of WCS at the abscissa axis of $\{O_C–X_CY_CZ_C\}$ to simplify the calculation. That is to say y_W=z_W=0. The explicit form of Eq. (8) is given in Eq. (9), once the products of small error terms have been neglected.

$$ \begin{aligned} L(c)^2 = {} & 2 \cdot (z_2 + h - z - z_{CA}) \cdot \delta_z + 2 \cdot x_W \cdot \cos(c) \cdot (\delta_x + z \cdot \theta_y) \\ & +2 \cdot x_W \cdot \sin(c) \cdot (\delta_y - z \cdot \theta_x) + (z - h)^2 \\ & +(z_2 - z_{CA})^2 - 2 \cdot (z - h) \cdot (z_2 - z_{CA}) + x_W^2 \end{aligned} \tag{9} $$

From Eq. (9), some key conclusions about the measuring pattern caused by different geometric errors can be drawn as follows:

1. The coefficient of axial error δ_z is independent of the position of C-axis, but just related to the initial coordinate positions;
2. The coefficient of radial error δ_x and tilt error θ_y is proportional to cos(c), while that of radial error δ_y and tilt error θ_x is proportional to sin(c). In addition, δ_x and θ_y are mutually coupled, so are δ_y and θ_x;
3. The angular position error θ_z does not appear in Eq. (9) because of the neglect of small error terms in calculation. This indicates that the length change due to θ_z cannot be observed in the DBB-measuring pattern though it does exist. So this proposed method is not feasible to measure

the angular position error θ_z, which is the only limitation of this method. However, other measuring instruments could be used as a supplementary method to measure θ_z, such as laser interferometer, autocollimator associated with multi-facet polygon prism, etc. [17].

In Eq. (9) there are five unknowns, i.e., five geometric errors, thus five independent equations are necessary for the full solution. Some unknowns are mutually coupled as explained above, so at least two different values of z, which stands for the position of Z-axis, should be set during the measuring tests. Meanwhile, the value of h should also be changed correspondingly so as to keep the nominal length of measuring bar unchanged. Consequently, Eq. (9) can be replaced by Eq. (10), where i=1, 2 indicates different measuring tests.

$$\begin{aligned}L_i(c)^2 = {} & 2\cdot(z_2+h_i-z_i-z_{\mathrm{CA}})\cdot\delta_z+2\cdot x_{\mathrm{W}}\cdot\cos(c)\cdot(\delta_x+z_i\cdot\theta_y)\\ & +2\cdot x_{\mathrm{W}}\cdot\sin(c)\cdot(\delta_y-z_i\cdot\theta_x)+(z_i-h_i)^2+(z_2-z_{\mathrm{CA}})^2\\ & -2\cdot(z_i-h_i)\cdot(z_2-z_{\mathrm{CA}})+x_{\mathrm{W}}^2\end{aligned} \tag{10}$$

In either test, four key positions of the measuring path are chosen to solve the equations, that is c=0°, 90°, 180°, and 270°. So eight equations can be obtained to calculate the square values of bar length: $L_i(0)^2$, $L_i(90)^2$, $L_i(180)^2$, and $L_i(270)^2$.

These equations can be expressed in matrix form as $\mathbf{L}=\mathbf{P}\cdot\mathbf{E}$, where **L** is a column vector of the square values of bar length, **E** is the column vector of the geometric errors, and **P** is the coefficient matrix which is determined by the coordinate positions. The analysis result shows that the coefficient matrix **P** is not of full rank. No matter what coordinates are assigned to h, z, or x_{W}, the rank of **P** identically equals to five. That means there are just five independent equations which can be obtained from two measuring tests conducted in different horizontal planes. And thus, this set of equations is adequate to solve the five geometric errors.

The data processing software is developed in MATLAB language to separate the geometric errors and draw the measuring patterns. During the tests, a specific fixture is employed to adjust the height of the magnetic ball cup, as shown in Fig. 1. The usage of this fixture can help reduce the mounting errors between the two measuring tests, because it just moves the measuring ball O_2 in the direction of Z-axis but keeps it stationary in the direction of the X- and Y-axis.

3 Measuring test procedure

Some preparations should be made before the measuring tests. A height-adjustable fixture should be mounted with the ball cup of DBB, and the distance between the center of measuring ball O_1 and the spindle nose should be determined. In addition, the ambient temperature should be set at around 20°C, so the thermal error could be neglected during the measurement. The test procedure for error identification of C-axis is as follows:

1. Move the rotary table to the initial position where c=0 and a=0;
2. Clamp the measuring ball O_1 to the spindle nose, and move the center of O_1 to the initial position (0, 0, 140) in MCS;
3. Mount the fixture which is connected with the magnetic ball cup on the rotary table and adjust the center of the measuring ball O_2 to the initial position (150, 0, –120) in MCS;
4. Install the ballbar and conduct the first measuring test. Data should be collected by the DBB sensor, and the first four equations deduced from Eq. (10) are obtained;
5. Uninstall the ballbar and move Z-axis to make the center of O_1 exactly located at (0, 0, 200). Also, the center of O_2 should be moved to (150, 0, −60) by adjusting the height of the fixture;
6. Install the ballbar again and conduct the second measuring test. Consequently, the last four equations can be obtained;
7. All the data collected by DBB are processed by the software so as to identify the error components and draw the measuring pattern.

4 Geometric error simulation of the DBB-measuring pattern

Simulation was conducted to establish the relationship between the measuring patterns and error components so as to demonstrate the geometric error's influence on the measuring patterns. Some key dimensions of the machine tool structure and the DBB setup as well as the assumption values of the errors are shown in Table 1.

Table 1 Key dimensions and error assumptions

Dimension	Value
Measuring bar length	250 mm
(x_{W}, y_{W}, z_{W})	(150, 0, 0)
z_{CA}	120 mm
z_2	60 mm
h	h_1=0, h_2=60 mm
Angular errors	θ_x, θ_y=±0.005°, θ_z=0°
Linear errors	δ_x, δ_y, δ_z=±0.01 mm

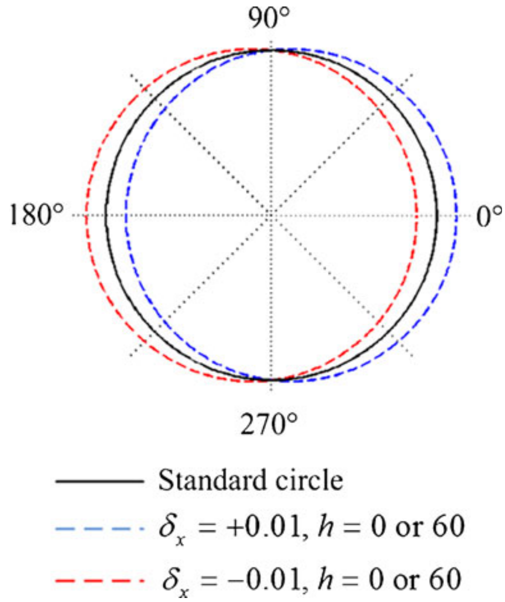


Fig. 4 DBB simulation pattern caused by δ_x

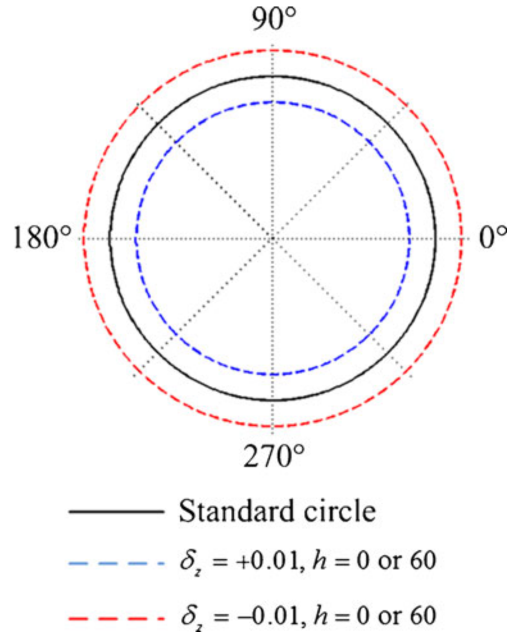


Fig. 6 DBB simulation pattern caused by δ_z

The simulation results caused by different geometric errors are shown in Figs. 4, 5, 6, 7 and 8, respectively. Compared with the standard circle, the measuring patterns are eccentric circles except for the influence of δ_z whose circles are concentric. It is also observed that the measuring patterns caused by the linear errors in the first test (h=0) coincide with those in the second test (h=60 mm). However, all the patterns caused by angular errors are different from each other in both tests. So this characteristic can be taken to decouple the relationship between δ_x and θ_y, also between δ_y and θ_x.

The method for identifying the errors on the basis of the simulation results is discussed as follows. At the first step,

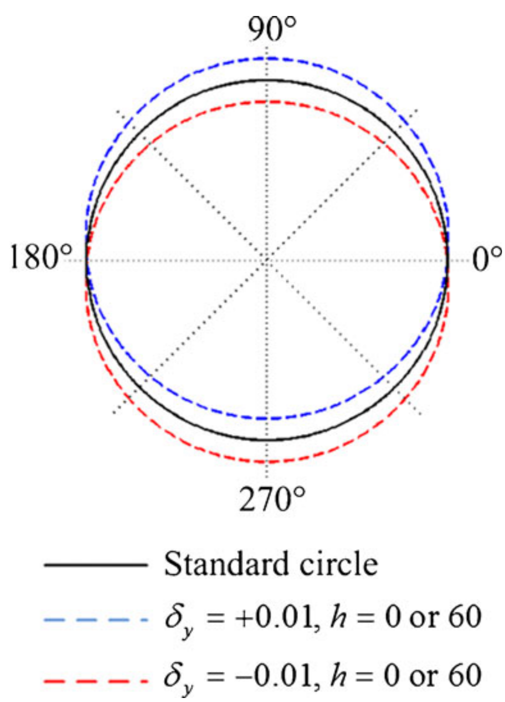


Fig. 5 DBB simulation pattern caused by δ_y

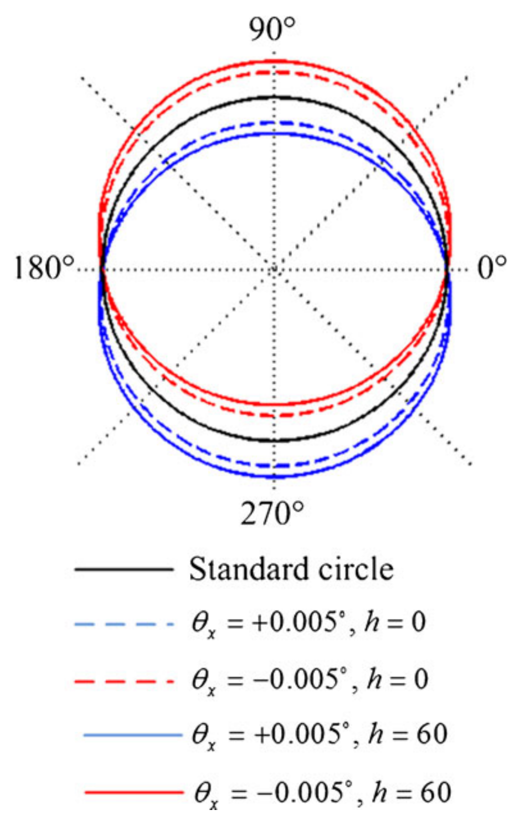


Fig. 7 DBB simulation pattern caused by θ_x

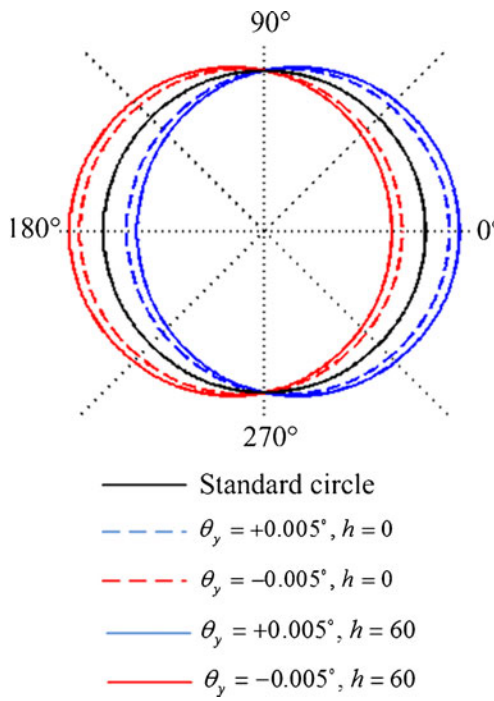


Fig. 8 DBB simulation pattern caused by θ_y

the axial error in Z-axis direction δ_z can be identified if it is possible to take the change of the radius. Then at the second step, we may conduct two measuring tests to obtain eight equations to solve all the errors except θ_z.

5 Experimental verification and compensation

To validate the effectiveness of the proposed method, some experiments were conducted on a high-speed five-axis machining center (model: VMC0656 by Shenyang Machine

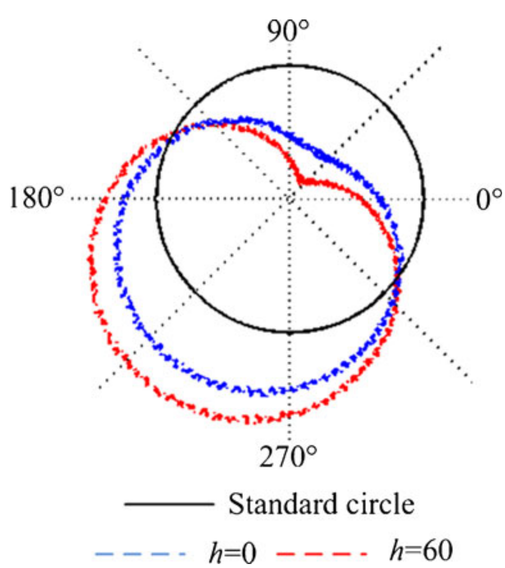


Fig. 9 DBB-measuring pattern before error compensation

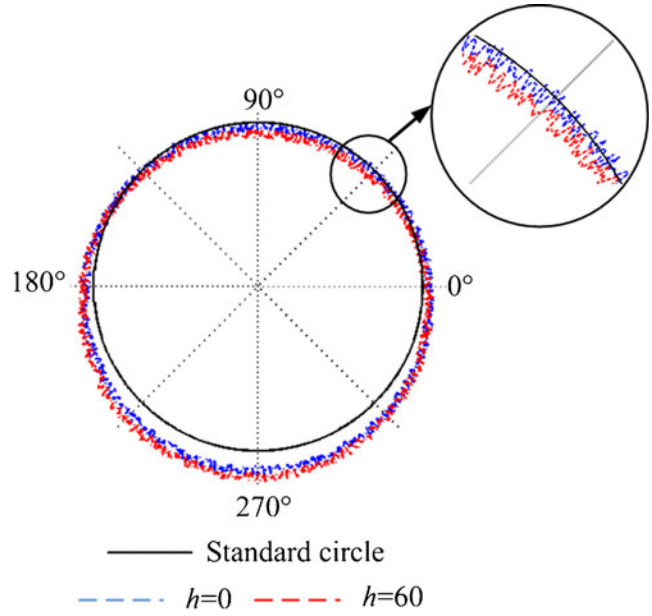


Fig. 10 DBB-measuring pattern after error compensation

Tool Corporation Ltd.) to identify the geometric errors caused by C-axis. The overall experimental procedure is listed as follows:

1. The geometric errors existing before error compensation are measured with the proposed method;
2. Solve the error components with the developed data processing software, and draw the measuring pattern;
3. Five identified geometric errors are corrected by computer-aided manufacturing software, and the compensation values are sent to the control system;
4. Conduct the measuring test after error compensation to confirm whether the measuring method and compensation technique are effective.

What needs special attention is that the total angular displacement of C-axis is from −90° to 450° during the test, while data are only collected in the period between 0–360° to avoid instability at the start and the end of the motion. The measuring patterns before and after error compensation are shown in Figs. 9 and 10, respectively. The comparison results between the two tests are listed in Table 2. It can be

Table 2 Geometric errors of the rotary table before and after error compensation

Geometric errors	Values before compensation	Values after compensation
δ_x	6 μm	2 μm
δ_y	−4 μm	1 μm
δ_z	5 μm	−1 μm
θ_x	5.4″	1.1″
θ_y	−4.4″	0.6″

seen from Fig. 10 and Table 2 that the measuring patterns after error compensation agree well with the standard circle; all the errors are reduced by 66 % at least.

6 Conclusions

In this paper, a DBB-measuring method is proposed to identify the geometric errors of the rotary table on five-axis machine tools. The most important characteristic of this method is that the measuring procedure consists of two circular tests conducted in two horizontal planes so as to decouple the linear and angular errors. Five geometric errors, i.e., two angular errors and three linear errors, can be identified in the measurement. The developed mathematical model is simulated to demonstrate unwanted geometric errors' influence on measuring patterns. In order to validate the proposed method, some experiments are conducted on a high-speed five-axis machining center. Measurements are carried out both before and after the error compensation. Experimental results show that the proposed DBB method is effective and convenient for identifying the geometric errors caused by the rotary table.

Acknowledgment This research was sponsored by Chinese National Science and Technology Key Special Projects [No. 2011ZX04015-031] and the National Science Foundation Project of P.R. China [No. 51175343].

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