Measurement of Error motions on Five-axis Machine Tools by Ball Bar Tests

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Abstract
The inclusion of the application of the double ball bar (DBB) measurement to the accuracy calibration of five-axis machine tools into the revision of ISO standards is currently under the discussion. This paper presents the modified DBB measurement device, referred to as "DBB5" in our study, where master balls are supported from the 45° direction to the spindle axis. It can perform all the circular tests on XY, YZ, and ZX planes without changing the setup. This paper first presents the parameterization of alignment errors and error motions of rotary axes in the five-axis kinematics. Experimental application of the DBB5 to the calibration of rotary axes error motions is then presented.

Keywords: Five-axis machine tool, Measurement, Ball bar, Component error, Location error

1 INTRODUCTION

For many machine tool builders in Japan, five-axis controlled machining centers, or multi-task turning centers (mill-turn centers), have been among their main products in the world-wide market. Since a five-axis machining center has linear and rotary axes that are stacked over each other, motion errors of each axis, as well as its assembly errors, are accumulated as an error in the TCP (tool center position) relative to the workpiece. It is, therefore, naturally more difficult for five-axis machine tools to ensure higher motion accuracies. However, with an increasing need for machined components with geometric complexity in a high efficiency, there are more cases where five-axis machine tools are used in machining applications requiring higher machining accuracy. The improvement of their motion accuracies is a crucial demand in the market.

As a basis to improve the motion accuracy of five-axis machines, it is important to develop its measurement scheme in an accurate and efficient manner. ISO technical sub-committee ISO TC39/SC2 has been working on standardizing test codes for five-axis machine tools [1]. In current ISO standards, ISO 10791-1[2] to -3 describe measurement methods for five-axis machines with a universal spindle (i.e. two rotary axes in the spindle side). The tests described there focus on evaluating static position and orientation of rotary axis average lines. The *axis average line*, defined in ISO 230-1 [3] and 230-7 [4], represents the *mean* location and orientation of the axis of rotation over its full rotation.

Such errors are collectively called *location errors* in [4] (see Section 2). Clearly, location errors are among the most fundamental error sources in the five-axis kinematics. Their calibration schemes have been studied by many researchers lately. Typical ones include the application of the telescoping double ball bar (DBB) [5,6] to the calibration of rotary axis location errors [7-10]. Its inclusion in the revision of ISO 10791-6 is currently under the discussion in ISO TC39/SC2 [11]. While the literatures [7-10] mainly considers the application to five-axis machines with a tilting rotary table (i.e. two rotary axes in the work table side), the application to various other configurations has been reported, e.g., five-axis machines with a universal spindle [12] and mill-turn centers [13]. Its application is not limited to the calibration of static errors; the calibration of dynamic errors has been also reported, e.g. dynamic errors of a swiveling axis in a mill-turn center [14]. synchronization error of a linear and a rotary axis [15], or the contouring error in the cone frustum machining test [16]. Various other measurement schemes, e.g. the R-test, probing-based schemes, or machining tests, have been also reported, as is reviewed in [17].

Many calibration schemes for five-axis machines, including ball bar tests in ISO/DIS 10791-6 [11], aim to identify location errors of rotary axes. On the latest small-sized five-axis machining centers, from our experiences, it is often the case that location errors are tuned sufficiently small in the machine assembly. In such a case, more complex error motions can be a dominant error factor in the machining accuracy. For example, in the cone frustum machining test described in NAS (National Aerospace Standard) 979 [18], the reference [19] showed that complex error motions of rotary axes can be a dominant error factor in the test piece's contour error.

The final objective of this study is to develop a methodology to separately measure each error motion of rotary axes, and to diagnose its error cause. As the first step, this paper reviews the parameterization of alignment errors and error motions of rotary axes in the five-axis kinematics. Then, the modified DBB device, called "DBB5" in our study, will be presented. When the conventional commercial DBB device is applied to a five-axis machine tool, an operator often has to change its setup for each test, to avoid the interference between the device and the machine. The modified DBB device can significantly reduce the number of such setup changes.

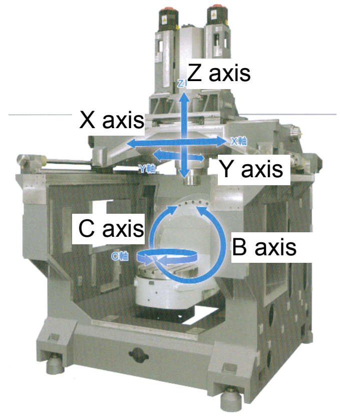
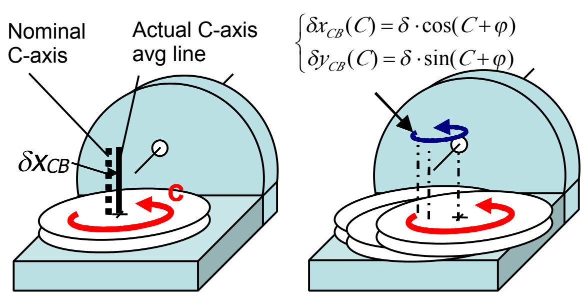


Figure 1: Configuration of experimental five-axis machining center [21]

Table 1 Location errors for machine configuration in Fig.1

Symbol [20]	Symbol [3]	Description
Location errorsof rotary axis		
a_{BY}	E_{A0B}	Squareness error of B- to Z-axis
b_{BY}	E_{B0B}	Initial angular error of B-axis
g_{BY}	E_{C0B}	Squareness error of B- to X-axis
a_{CB}	E_{A0C}- E_{A0B}	Squareness error of C- to B-axis
$d\ x_{BY}$	E_{X0B}	Position error of B-axis avg. line in X
$d\ y_{BY}$	E_{Y0B}	Position error of C-axis avg. line in Y
$d\ z_{BY}$	E_{Z0B}	Position error of B-axis avg. line in Z
$d\ x_{CB}$	E_{X0C}- E_{X0B}	Position error of C- to B-axis avg. line
Location errors of linear axis		
g_{YX}	E_{C0Y}	Squareness error of Y- to X-axis
a_{ZY}	E_{A0Z}	Squareness error of Z- to Y-axis
b_{ZX}	E_{B0Z}	Squareness error of Z- to X-axis



(a) Position error of C-axis avg. line, $d\ x_{CB}$.

(b) Radial error motion ("run-out") of C-axis, parameterized by $d\ x_{CB}(C)$ and $d\ y_{CB}(C)$

Figure 2: An example of location and component errors

2 PARAMETERIZATION OF ROTARY AXIS ERROR MOTIONS

Motion error of a five-axis machine tool can be categorized into: 1) error motions of a linear axis, 2) error motions of a rotary axis, 3) alignment errors of linear and rotary axes, and 4) synchronization errors of linear and rotary axes. Location errors parameterize mainly the item 3). This section mainly presents the parameterization of error motions 1) and 2) [19].

This paper considers a five-axis machine tool with a tilting rotary table shown in Fig. 1. This machine's kinematics

Figure 3: Configuration of conventional DBB device [11]

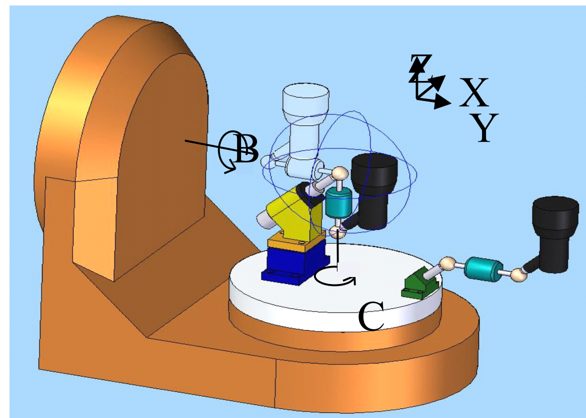


Figure 4: Configuration of the modified DBB device, DBB5

can be described by using total 11 location errors shown in Table. 1 [20]. For example, as shown in Fig. 2(a), the location error, $d\ x_{CB}$, representing the X-position error of the C-axis average line, is defined constant, independent on the C-axis angular position. This is because the axis average line represents the *mean* location and orientation of the axis of rotation.

On the other hand, for example, the pure radial error motion [4] (or "run-out") of C-axis, depicted in Fig. 2(b), can be described by $d\ x_{CB}(C)$ and $d\ y_{CB}(C)$, parameterized as a function of C-angle. Similarly, when the table is displaced in the Z-direction with its B-axis tilting due to the gravity-induced deformation, it may be modeled by $d\ x_{BY}(B)$.

A larger class of error motions can be modeled as location errors that vary depending on the angular position of a rotary axis. Table 2 shows the correspondence of each position-dependent geometric error parameter to general error causes. For the simplicity, Table 2 only shows error motions of B-axis. Such position-dependent geometric errors are referred to as "component errors" in ISO 230-7 [4].

For machine tool manufacturers, it is important not only to measure error motions, but also to reduce them. The main focus of this paper is in the measurement of each error motion. However, as illustrated in Table 2, the measurement of error motions is the basis for the diagnosis of mechanical causes.

3 MODIFIED DBB DEVICE (DBB5)

Figure 3 depicts the configuration of the typical conventional DBB measurement device [11]. In the conventional DBB device, master balls are supported in the direction parallel to the spindle. As a result, it enables the 360° circular test only in the XY plane. In YZ and ZX planes, the setup of ball sockets must be changed by an operator to avoid the interference between the DBB bar and ball sockets [6].

Table 2: Component errors of B-axis and their possible causes

Symbol	Symbol[17]	Description
Component errors of rotary axis		
$\alpha_{BY}(B)$	E_{AB}	Orientation changes of B-axis with B rotation
$\beta_{BY}(B)$	E_{BB}	Angular error of B-axis rotation
$\gamma_{BY}(B)$	E_{CB}	Orientation changes of B-axis with B rotation
$\alpha_{CB}(C, B)$	E_{AC}-E_{AB}	Orientation changes of C-axis with C, B rotation
$\beta_{CB}(C, B)$	E_{BC}-E_{BB}	Orientation changes of C-axis with C, B rotation
$\gamma_{CB}(C, B)$	E_{CC}-E_{CB}	Angular error of C-axis rotation
$\delta x_{BY}(B)$	E_{XB}	Location changes of B-axis center with B rotation
$\delta y_{BY}(B)$	E_{YB}	Location changes of B-axis center with B rotation
$\delta z_{BY}(B)$	E_{ZB}	Location changes of B-axis center with B rotation
$\delta x_{CB}(C, B)$	E_{XC}-E_{XB}	Location changes of C-axis center with C, B rotation
$\delta y_{CB}(C, B)$	E_{YC}-E_{YB}	Location changes of C-axis center with C, B rotation
$\delta z_{CB}(C, B)$	E_{ZC}-E_{ZB}	Location changes of C-axis center with C, B rotation
Component errors of linear axis		
$\gamma_{YX}(Y)$	E_{CY}	Yaw changes of Y-axis with Y motion
$\alpha_{YX}(Y)$	E_{AY}	Pitch changes of Y-axis with Y motion
$\beta_{YX}(Y)$	E_{BY}	Roll changes of Y-axis with Y motion
$\delta x_{YX}(Y)$	E_{XY}	Straightness of Y-axis
$\delta y_{YX}(Y)$	E_{YY}	Linear positioning error of Y-axis
$\delta z_{YX}(Y)$	E_{ZY}	Straightness of Y-axis
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Possible major error causes
Errors in positioning mechanism
Errors in rotary encoder
Pitch error in transmission mechanism (e.g. worm gear)
Inaccurate pitch error compensation
Errors associated with bearings
Run-out
"Angular motion" of rotation centerline
Profile error caused by geometric error of rings
Profile error caused by variation in roller size
Gravity influence
Deformation of rotating unit
Angular positioning error caused by gravity influence

Figure 4 depicts the modified DBB device, called "DBB5," developed in our study. Master balls (both on the spindle side and on the table side) are supported from the 45° direction to the spindle axis. By this setup, the 360° rotation is possible on all XY, YZ, and ZX planes.

The following section shows its application to the calibration of motion errors of a five-axis machine. This paper mainly presents its application to the identification of location errors of rotary axes. A part of component errors of rotary axes will be also observed.

4 MEASUREMENTS FOR 5-AXIS MACHINES

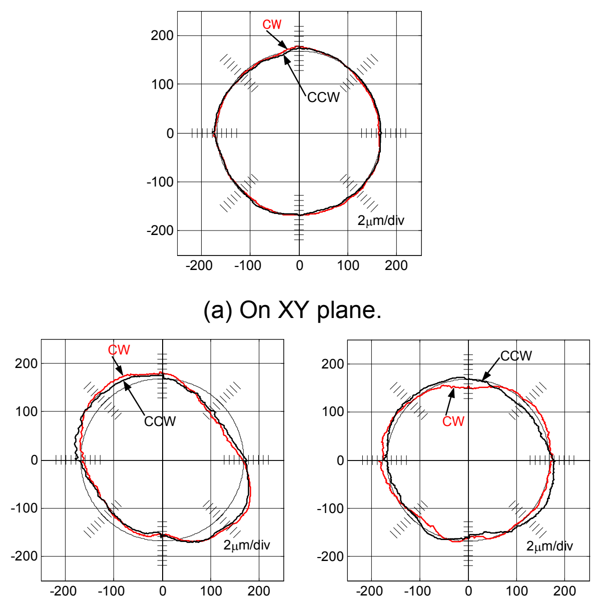
A vertical-type five-axis machining center with a tilting rotary table, NMV5000DCG [21] by Mori Seiki Co., Ltd., is used in the experiments. Its machine configuration is shown in Fig. 1. It has a rotary table (C-axis) tilted by a swiveling axis (B-axis). Both B and C axes are driven by a direct drive (DD) motor. Y and Z axes are driven by synchronously controlled two ball screws and servo motors. X axis is driven by a single ball screw and servo motor.

The modified DBB device, DBB5, is made by re-assembling the commercial conventional DBB device, DBB110, Heidenhain, by the authors. The reference bar length is 168 mm.

4.1 Circular Tests on XY, YZ, and ZX Planes

First, 360° circular tests were conducted on XY, YZ, and ZX planes by using DBB5. Figure 5 shows measured contouring error profiles. The feedrate was 600 mm/min.

From test results, the squareness error of Z- to Y-axis is estimated a_{ZY} =10.2 μm/168 mm, and that of Z- to X-axis is b_{ZX} = -3.0 μm/168 mm. Since the diagnosis methodology for circular tests has been well developed [5], we would not discuss these test results in further details.



(a) On XY plane.

(b) On YZ plane.

(c) On XZ plane.

Figure 5: Circular test error profiles measured by DBB5.

Figure 6: Experimental setup (Meas. C-X (+Z))

4.2 Measurement of C-axis Error Motions

4.2.1 Measurement of location errors

Four measurements shown in Figs. 7(a-1) to (d-1) were conducted to evaluate an error in the position and orientation of C-axis as it rotates for 360°. Figure 7 (a-1) depicts the schematics of "Measurement C-X (-Z)." The master ball is placed approximately on the C-axis average line and the bar direction is fixed in X-direction. Only the C-axis rotates by 360°, while all the linear axes stay unmoved.

Similarly, in "Measurement C-Y (-Z)" illustrated in Fig. 7(b-1), the DBB bar direction is fixed in the Y-direction as the C-axis rotates. In "Measurement C-X (+Z)" (Fig. 7(c-1)) and "Measurement C-Y (+Z)" (Fig. 7(d-1)), the location of the master ball is changed to higher Z-level by using a chuck by EROWA AG. In our tests, the height of the master ball was higher by d_z=100 mm. The rotational speed of C-axis was 720°/min in all tests. Figure 6 shows the experimental setup for Measurement C-X (+Z).

Figures 7(a-2)(b-2)(c-2) and (d-2) show measured error profiles. Note that the center shift of the measured trajectory is numerically removed in these plots for easier observation. The circularity error (the difference of the maximum and the minimum error), and the mean error (the difference between the mean of the error and the reference length) are summarized in Table 3.

1) *Orientation of C-axis average line*

The mean error of each error trajectory indicates the position of C-axis rotation center with respect to the location of the spindle-side ball. Suppose that the mean error of Measurement C-X (-Z), C-Y (-Z), C-X (+Z), and C-Y (+Z), are respectively given by r_{x1}, r_{y1}, r_{x2}, and r_{y2} (see Table 3) Then, the orientation error of the C-axis axis average line can be estimated as follows:

$$\beta_{CZ} = (r_{x2} - r_{x1})/d_z = -4.2\ \mu m/100mm \quad (1)$$

$$\alpha_{CZ} = -(r_{y2} - r_{y1})/d_z = +5.5\ \mu m/100mm \quad (2)$$

where α_{CZ} and β_{CZ} denote the orientation error of the C-axis average line around Y-and X-axes, respectively, with respect to the Z-axis reference line.

2) *Position error of C-axis average line*

The position error of C-axis average line can be computed similarly:

$$\delta x_{CY} = \delta x_{BY} + \delta x_{CB} = r_{x1} - \beta_{CZ} Z_1 \quad (3)$$

$$\delta y_{CY} = \delta y_{BY} = r_{y1} - \alpha_{CZ} Z_1 \quad (4)$$

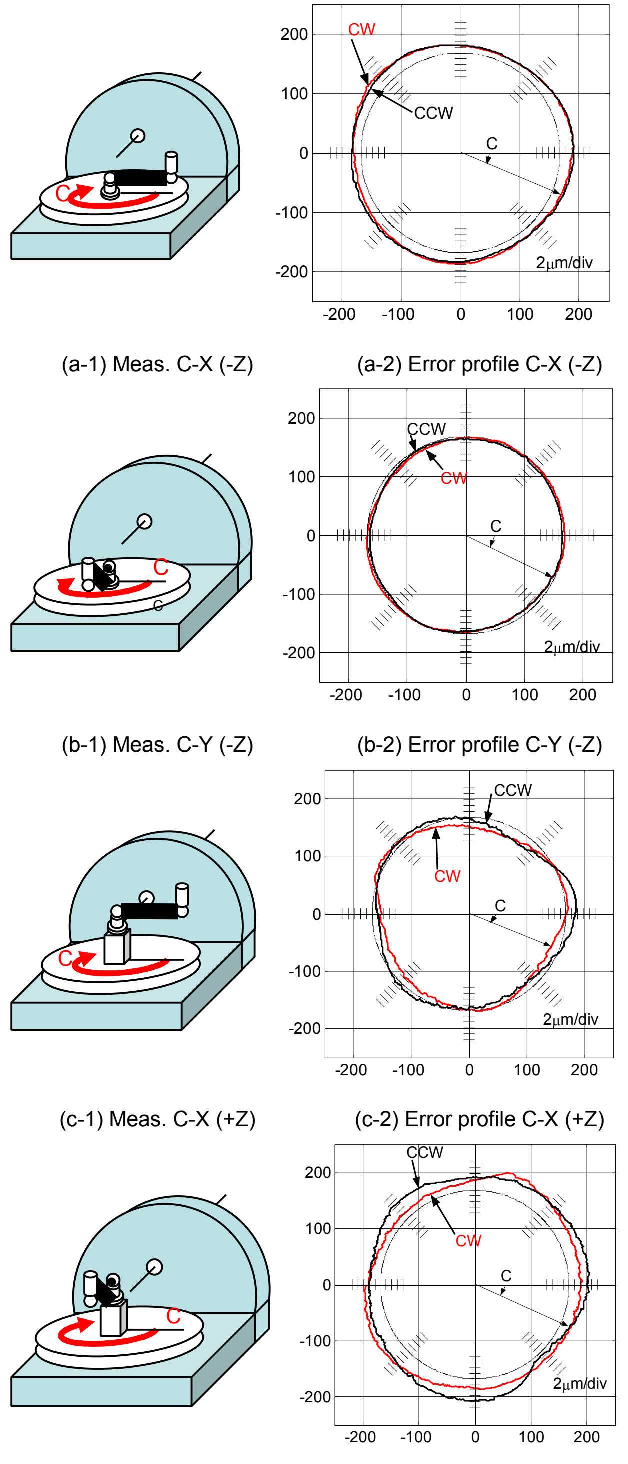
where δx_{CY} and δy_{CY} respectively denote the position error of the C-axis average line in X- and Y-directions with respect to the origin of the machine coordinate system. Z_1 is the (approximate) Z location of the master ball in Measurements C-X/Y (-Z).

4.2.2 Observation of component errors

The radial error motion [4], parameterized by $\delta x_{CA}(C)$ and $\delta y_{CY}(C)$, can be observed from four plots in Fig. 7.

In Figs. 7(c-2) and (d-2), the measured error is larger than in Figs. 7(a-2) and (b-2). This suggests the tilt error motion [4] of C-axis, i.e. the orientation of C-axis changes with its rotation ($\alpha_{CZ}(C)$ and $\beta_{CZ}(C)$).

Furthermore, the axial error motion [4] of C-axis ($\delta z_{CA}(C)$) can be observed from Measurement C-Z shown in Fig. 8(a-1).



(a-1) Meas. C-X (-Z) (a-2) Error profile C-X (-Z)

(b-1) Meas. C-Y (-Z) (b-2) Error profile C-Y (-Z)

(c-1) Meas. C-X (+Z) (c-2) Error profile C-X (+Z)

(d-1) Meas. C-Y (+Z) (d-2) Error profile C-Y (+Z)

Figure 7: Measurement C-X and C-Y.

Table 3 Circularity error and mean error in C-axis tests.

	C-X (-Z)	C-Y (-Z)	C-X (+Z)	C-Y (+Z)
Circularity error μm	3,0	2.2	7.3	6.8

Mean error m m	r_{x1}=+3.2	r_{y1}=-0.6	r_{x2}=-1.0	r_{y2}=+4.9

4.2.3 Comparison with ball bar tests in ISO/DIS 10791-6

ISO/DIS 10791-6 [11] describes the ball bar test in Fig. 8(b-1) to observe the orientations of the C-axis average line, a_{cz} and b_{cz} (Annex B, BK2). In this test, C-axis rotation is synchronized with X-Y circular interpolation.

Fig. 8(b-2) shows the measured error profile. The average center of measured error trajectories in CW and CCW rotations is (C_x, C_y)=(-0.4, +0.7) m m.

Then, the orientation of C-axis average line (squareness of C-axis to X- and Y-axes) can be computed as follows:

$$\beta_{CY} = C_x / R = -0.3 \text{ m m/100mm} \quad (4)$$

$$\alpha_{CY} = -C_y / R = -0.5 \text{ m m/100mm} \quad (5)$$

where R=135 mm is the distance of the table-side sphere to the C-axis average line. The estimates above are different from those in Eqs. (1)(2) by about 4 to 5 m m/100mm. This is because Meas. C-XY (Fig. 8(b-1)) measures the squareness of C- to X- (or Y-) axis, while Meas. C-X and C-Y (Fig. 7) measures the parallelism of C- to Z-axes. For example, when there exists the squareness error of Z- to X- (or Y-) axis, both results would naturally differ.

Furthermore, in Meas. C-X and C-Y (Fig. 7), only the C-axis rotates without moving X- and Y-axes. It is an advantage that X- and Y-axis error motions do not influence the test result at all. On the other hand, its disadvantages are: 1) total four tests are required, and 2) they cannot be done when a sphere cannot be placed on a rotary axis centerline.

Note that ISO/DIS 10791-6 describes ball bar tests for not only the axial direction (Fig. 8(b-1)), but also radial and tangential directions of a rotary axis.

4.3 Measurement of B-axis Error Motions

Similar tests were conducted for B-axis. As shown in Figs. 9(a-1) to (d-1), the table-side sphere is located approximately on the B-axis average line. The B-axis rotates with the ball bar fixed to X- or Z-directions. Table 4 summarizes the circularity error and the mean error in the four tests. When the mean error in Meas. B-X (-Y), B-Z (-Y), B-X (+Y), and B-Z (+Y) is respectively given by r_{x1}, r_{z1}, r_{x2}, and r_{z2} (see Table 4), orientation errors of the B-axis average line around Z- and X-axes are respectively given by:

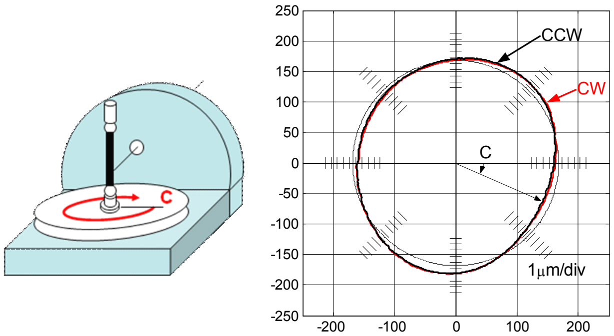
$$\gamma_{BY} = (r_{x2} - r_{x1}) / d_y = +2.7 \text{ m m/271 mm} \quad (6)$$

$$\alpha_{BY} = -(r_{x2} - r_{x1}) / d_y = +1.4 \text{ m m/271 mm} \quad (6)$$

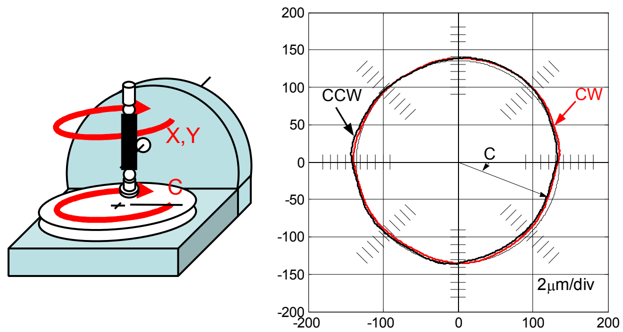
They are smaller than C-axis. The difference in -Y side tests (Fig. 9(a)(b)) and +Y side tests (Fig. 9(c)(d)) is also smaller, which suggests that the axial error motion and the tilt error motion of B-axis is smaller. It should be noted that the rotation angle of B-axis was 190° in Fig.9 (b)(d) and 145° in (a)(c) to avoid the interference of the ball bar and the spindle or the table.

5 CONCLUSION

This paper presented the modified DBB device, "DBB5," where master balls are supported from the 45° direction to the spindle axis. It performs all the circular tests on XY, YZ, and ZX planes without changing the setup.

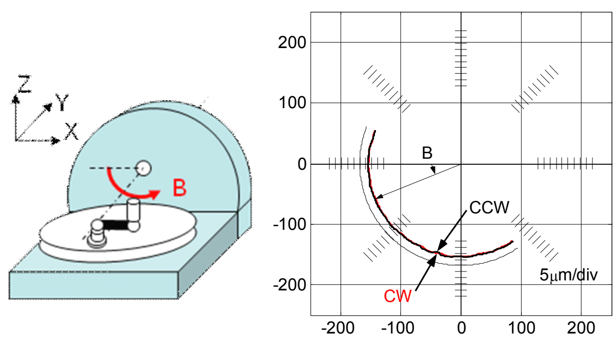


(a-1) Meas. C-Z (a-2) Error profile C-Z

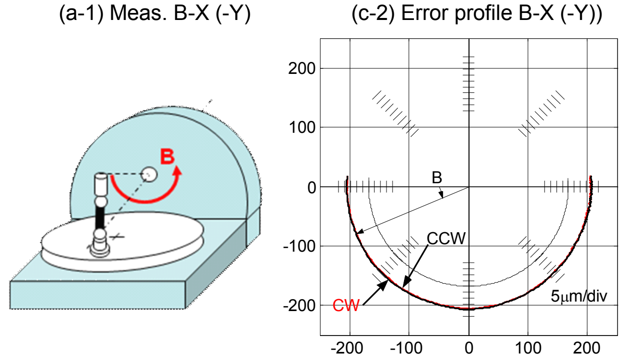


(b-1) Meas. C-XY (b-2) Error profile C-XY

Figure 8: Measurement C-Z and C-XY.



(a-1) Meas. B-X (-Y) (c-2) Error profile B-X (-Y))



(b-1) Meas. B-Z (-Y) (b-2) Error profile B-Z (-Y))

Figure 9: Measurement B-X and B-Z.

Its application to the calibration of motion errors associated with rotary axes on a five-axis machining center with a tilting rotary table is presented. The table-sided sphere is located on the rotary axis centerline, and the rotary axis is rotated without moving linear axes. Axial, radial and tilt error motions of a rotary axis can be observed.

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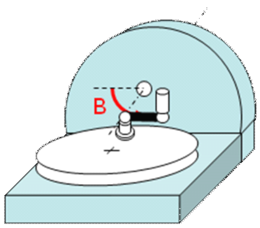
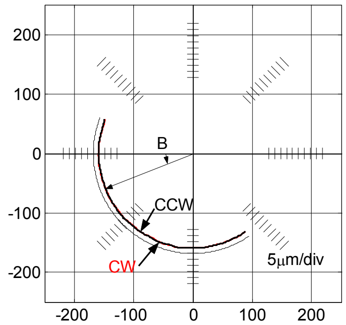
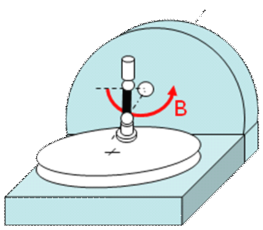
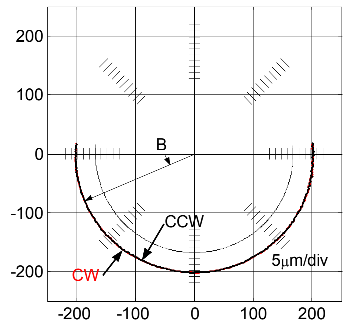




(c-1) Meas. B-X (+Y) (c-2) Error profile B-X (+Y))





(d-1) Meas. B-Z (+Y) (d-2) Error profile B-Z (+Y))

Figure 9: Measurement B-X and B-Z (continued).

Table 4 Circularity error and mean error in B-axis tests.

	B-X (-Y)	B-Z (-Y)	B-X (+Y)	B-Z (+Y)
Circularity error m m	1.9	2.7	1.3	2.2
Mean error m m	r_{x1}=-7.3	r_{z1}=+18.6	r_{x2}=-4.6	r_{z2}=+17.2

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