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MEASUREMENT OF MOTION ACCURACIES OF FIVE-AXIS MACHINE TOOLS BY USING THE DOUBLE BALL BAR METHOD DBB5

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ABSTRACT

The inclusion of the application of the double ball bar (DBB) method to the accuracy calibration of five-axis machine tools into the revision of the 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, such that the interference between the bar and ball sockets can be avoided. It can perform all the circular tests on XY, YZ, and ZX planes without changing the setup. It can be also applied to the calibration of static and dynamic errors in the position and the orientation of rotary axes on a five-axis machine tool. Experimental application examples of the DBB5 to the error calibration of a commercial five-axis machining center with a tilting rotary table are presented.

Key words: Machining center, Five axes control, Double ball bar method, Motion accuracy, Error compensation.

1 Introduction

A significant number of five-axis controlled machining centers have been recently used in the manufacturing industries in Japan. Since a five-axis machining center has linear and rotary axes that are stacked over each other, motion errors of each axis and its assembly error are accumulated in the tool position. At this stage, there is a common recognition in the manufacturing industry that it is generally difficult to apply a five-axis machining center to manufacture high-precision dies/molds due to its limited motion accuracies compared to conventional three-axis machining centers. However, with the recent popularization of five-axis machining centers, there are more cases where five-axis machining centers are used in such a high-precision machining application. The improvement of their motion accuracies to similar level as conventional three-axis machines is a crucial demand in the market.

As a basis to improve the motion accuracy of five-axis machines, it is important to develop a measurement scheme to evaluate their motion errors in an accurate, and efficient manner. The current ISO standards describe measurement methods to evaluate static errors of the position and the orientation of rotary axes (such errors are collectively called kinematic errors), with a main focus on five-axis machines with a universal spindle (ISO 10791-1∼3). For five-axis machines with a tilting rotary table, which are more widely manufactured by Japanese machine tool builders, there are fewer description in the current version of ISO standards. However, the revision of the ISO standards are currently under the discussion in the ISO technical committee TC39/SC2/WG3 such that the standards cover more variety of five-axis machines.

To measure motion errors of conventional three-axis machining centers, the Double Ball Bar (DBB) method has been widely accepted in the industry of machine tool builders [1]. The application of the DBB measurement to identify kinematic errors of a five-axis machine tool has been studied [2; 3], and

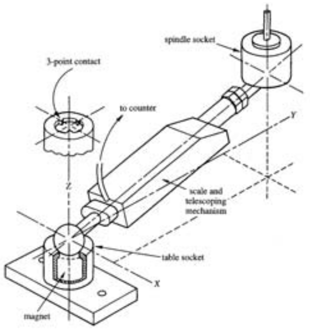


Figure 1. Configuration of the conventional DBB device [1]

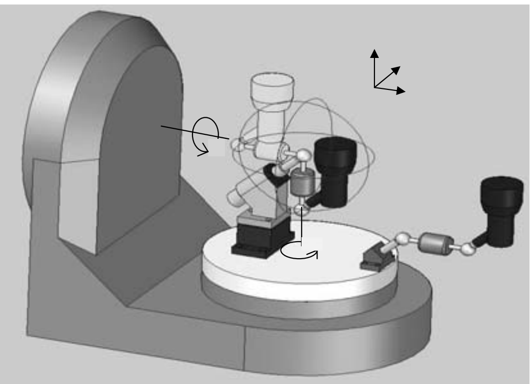


Figure 2. Configuration of the modified DBB device, DBB5

its inclusion in the revision of the ISO standards is currently under discussion in TC39/SC2/WG3. However, when the conventional commercial DBB device is applied to the accuracy calibration of a 5-axis machine tool, it often causes the interference between the device and the machine, which requires an operator to change the setup every time. This paper presents the modified DBB measurement device, referred to as "DBB5" in our study, such that it can be applied to the accuracy calibration of a five-axis machine tool in a more efficient manner with requiring less setup changes.

2 Configuration of DBB5

Figure 1 depicts the configuration of the typical conventional DBB measurement device [1]. In the conventional DBB device, master balls (both on the spindle side and on the table side) are supported in the direction parallel to the spindle. As a result, the setup shown in Fig. 1 allows the 360° circular test only in the XY plane; in the YZ and ZX planes, only 180° rotation is possible due to the interference between the DBB bar and ball sockets. Therefore, in order to perform 360° rotation in the YZ and ZX planes, the setup of ball sockets must be changed by an operator for every measurement.

Figure 2 depicts the modified DBB device developed in our study. In this configuration, master balls (both on the spindle side and on the table side) are supported from the 45° direction to the spindle axis. By supporting master balls from the 45° direction, the 360 °rotation is possible on all of XY, YZ, and ZX planes with the same setup, avoiding the interference between the DBB bar and ball sockets.

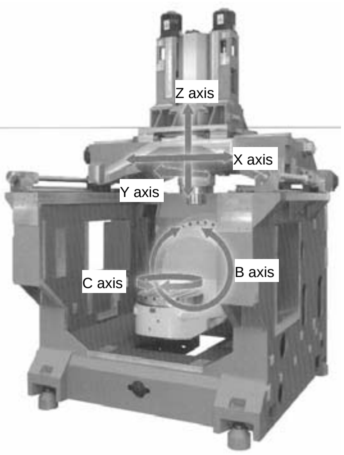


Figure 3. Configuration of the experimental five-axis machining center

The modified DBB device, "DBB5," can be applied to the accuracy calibration of a five-axis machine tool. The following section shows its application examples to the calibration of motion errors of a five-axis machine.

3 Application Examples

The present DBB5 device is applied to the experimental calibration of motion errors on a commercial five-axis machine. A vertical-type five-axis machining center with a tilting rotary table, NMV5000DCG[4] by Mori Seiki Co., Ltd., is used in the experiments. Its machine configuration is illustrated in Fig. 3. It has a rotary table that is supported by one side by the B-axis, for better accessibility by a machine operator. Both B and C axes are driven by a direct drive (DD) motor. Y and Z axes are driven by a set of two ball screws and servo motors. X axis is driven by a single ball screw and servo motor.

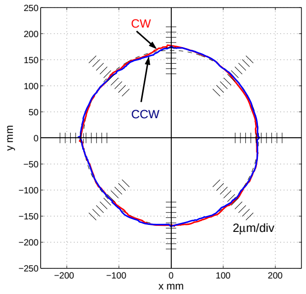
The modified DBB device, DBB5, is made by re-assembling the commercial conventional DBB device, DBB110 by Heidenhain, by the authors. The reference bar length is 168 mm.

3.1 Circular tests on XY, YZ, and ZX planes

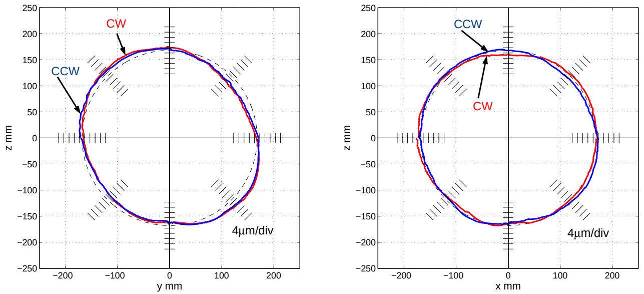
First, 360° circular tests were conducted on the XY, YZ, and ZX planes by using DBB5, as illustrated in Fig. 2. Figure 4 shows measured contouring error profiles of a circular test on XY, YZ, and ZX planes. The radius of the reference trajectory is 168 mm, and the feedrate is 600 mm/min.

3.2 Measurement of motion errors associated with the C axis

Four measurements shown in Fig. 5 were conducted to evaluate an error in the position and the orientation of the cen-



(a) XY plane.



(b) YZ plane. (c) XZ plane.

Figure 4. Error profiles of circular test on XY, YZ, and XZ planes.

ter axis of C-axis as it rotates by 360°. Figure 5(a-1) depicts the schematics of "Measurement C-X (Low)," where only the C-axis is rotated by 360°, while all the linear axes stay unmoved. The master ball is placed approximately on the center of the C-axis, and thus the bar direction is fixed in the X direction during the rotation. Similarly, in "Measurement C-Y (Low)" illustrated in Fig. 5(b-1), the DBB bar direction is fixed in the Y direction as the C-axis rotates. In "Measurement C-X (High)" and "Measurement C-Y (High)," depicted respectively in Figs. 5(c-1) and (d-1), the location of the master ball is changed to higher Z-level by using a chuck by EROWA AG. In these setups, the height of the master ball was higher by 100 mm than that in Measurement C-X/Y (Low). The rotational speed was 720 deg/min in all the measurements. Figure 6 shows a photograph of the experiment performing Measurement C-X (High).

Figures 5(a-2)(b-2)(c-2) and (d-2) show measured DBB error profiles in respective measurements. Note that the center shift and the average radial error are compensated (removed) in these plots. The center shift (the location of the center of the measured profile computed by using the least square method), the circularity error (the difference of the maximum and the minimum error), and the average radial error (the difference between the mean of the error and the reference length) are summarized in Table 1.

From the measured profiles, the following observation can be made:

1) *Orientation of C-axis center line*:

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

$$\beta_{CZ} = -\left(r_{x2} - r_{x1}\right)/Z \tag{1}$$

$$\alpha_{CZ} = -\left(r_{y2} - r_{y1}\right)/Z \tag{2}$$

where β_{CZ} and α_{CZ} denote the orientation error of the C axis around Y and X axes, respectively, with respect to the Z axis. Z denotes the difference in the Z-height in Measurements C-X/Y (low) and (high). These errors are among the most fundamental errors in a five-axis machine, and are included in kinematic errors defined in [3]. In this experiment, they are identified as: β_{CZ}=-5.5 μm/100 mm, α_{CZ}=+4.2 μm/100 mm,

2) *Linear shift of C-axis*:

Defining the Z origin at the position where the tool tip is located at the center of the B axis, the linear shift of the center of the C axis at $Z = 0$ can be computed similarly:

$$\delta_{x,CY} = r_{x1} - \beta_{CZ} \cdot Z_1 \tag{3}$$

$$\delta_{y,CY} = r_{y1} + \alpha_{CZ} \cdot Z_1 \tag{4}$$

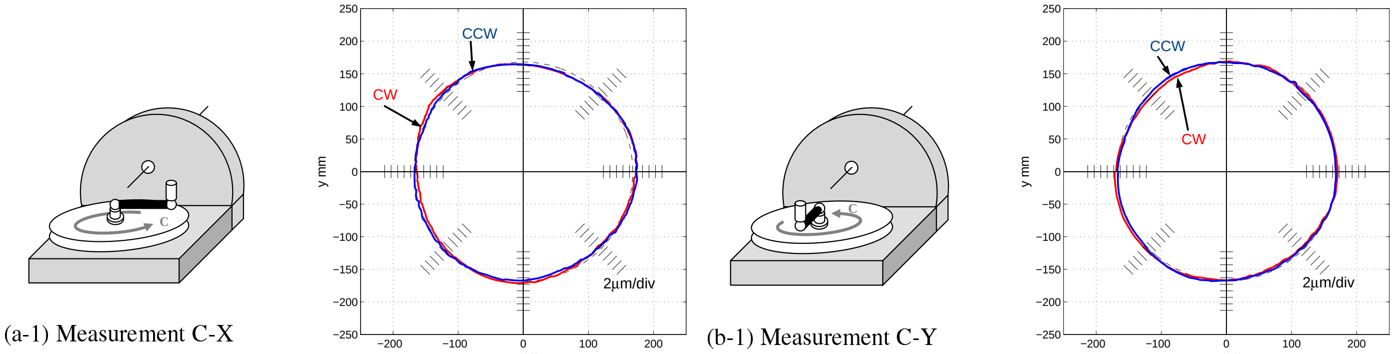
where $\delta_{x,CY}$ and $\delta_{y,CY}$ denote the linear shift of the center of the C axis at $Z = 0$ in X and Y directions, respectively, with respect to the origin of XY coordinates. Z_1 is the (approximate) Z location of the master ball in Measurements C-X/Y (low). They are also included in kinematic errors defined in [3].

3) *Dynamic error of the location and the orientation of C-axis*:

Dynamic change of the location and the orientation of the center axis of C axis during its 360° rotation can be also observed from four plots in Fig. 5. In particular, the difference between error profiles in Fig.5 (a-2)(b-2) and those in Fig.5 (c-2)(d-2) indicate that the orientation of the center line of C-axis is subject to dynamic change during the rotation of C-axis.

4 Conclusion

This paper presented the modified DBB device, referred to as "DBB5" in our study, where master balls (both on the spindle side and on the table side) are supported from the 45° direction to the spindle axis, such that the interference between the bar and ball sockets can be avoided. Its one clear advantage is that all the circular tests on XY, YZ, and ZX planes can be done without changing the setup. This paper presented its application to the calibration of motion errors associated with rotary axes on a five-axis machining center with a tilting rotary table. In particular, the measurement of position and orientation errors of the center line of the C axis during its 360° rotation is presented. The accuracy calibration of the B axis was also conducted in an analogous manner, which is omitted in this paper due to the page limit.

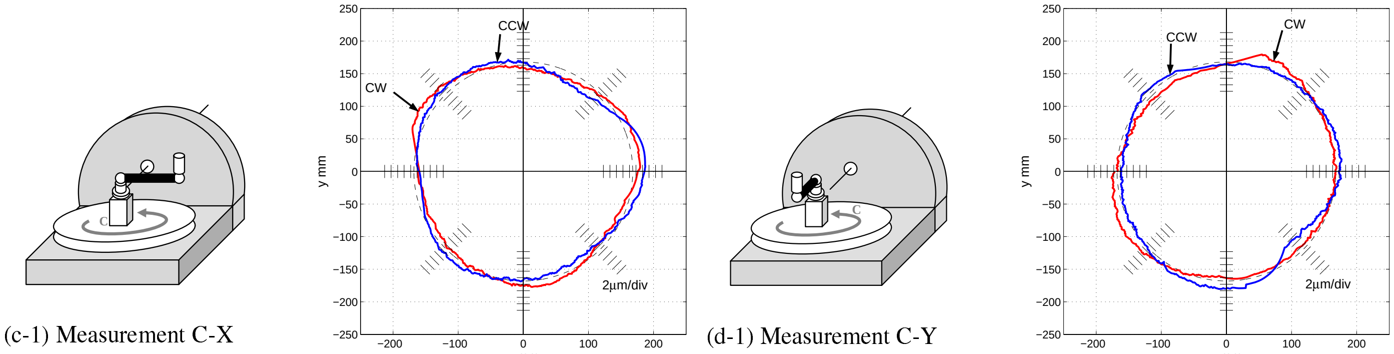


(a-1) Measurement C-X (Low).

(a-2) Error profiles (C-X (Low)).

(b-1) Measurement C-Y (Low).

(b-2) Error profiles (C-Y (Low)).



(c-1) Measurement C-X (High).

(c-2) Error profiles (C-X (High)).

(d-1) Measurement C-Y (High).

(d-2) Error profiles (C-Y (High)).

Figure 5. DBB Error profiles to evaluate kinematic errors associated with the C axis.

Table 1. Center shifts and circularity errors of Measurement C-X (low), C-Y (High), C-X (Low), and C-Y(High).

	Center Shift		Circularity	Average
	X (μm)	Y (μm)	(μm)	(μm)
Measurement C-X (low)	+2.6	+12.3	3.0	+3.2
Measurement C-Y (low)	+8.4	+2.0	2.2	-0.6
Measurement C-X (high)	-57.3	-5.3	7.3	-1.0
Measurement C-Y (high)	-10.4	+62.4	6.8	+4.9

Figure 6. A photograph of experiments using DBB5.

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