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Study on Improvement of Motion Accuracy of 5-Axis Control Machining Center (Influence of the rotary axis traveling range on the alignment error)

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The demand for 5-axis control machining centers is rapidly increasing to achieve process integration and high machining accuracy. This paper proposes the development of a 5-axis control machining center with the Table-on-Table structure to achieve high accuracy with a large rotary axis traveling range. The Table-on-Table type structure can easily achieve a wide traveling range, especially for the first rotary axis. Achievement of high accuracy with a large traveling range has been verified by simulating a method similar to the double ball bar (DBB) measurement. When the magnitude of an alignment error is estimated using the data measured by the DBB measurement including motion errors of the rotary axis, it is shown by the simulation analysis that the magnitude of the estimated alignment error depends on the traveling range.

Key Words : Accuracy, Generation Motion, Machine Tool, 5-Axis Control Machining Center, Alignment Error of Rotary Axis, Motion Error, DBB

1. Preface

Needs for 5-axis control machining centers have been rapidly growing in the recent years for the purposes of “process integration” and “improvement of machining accuracy.” However, 5-axis control machining centers have additional two rotary axes compared to 3-axis control machining centers, which generally makes it difficult to achieve the machine accuracy equivalent to that of 3-axis control machining centers or higher. A variety of 5-axis machining centers have been developed so far. Above all, machines with the structure shown in Fig. 1 (b), so-called the trunnion type, are widely developed because they are relatively easy to be designed and the accuracy is stable. Yet, whether the trunnion type 5-axis control machining center is superior in accuracy to the ones with other structures has not been verified.

As the structure of 5-axis control machining center, a variety of types other than the trunnion type are designed as shown in Figure 1: the Table-on-Table type, the single-axis tilt spindle type, the 2-axis rotary and tilt spindle type, and the fixed table type.

This research examines which structure enables to meet the required accuracy easily from the view point of motion accuracy. Among the 5-axis control machining centers shown in Figure 1, the traveling range of the first rotary axis is significantly different. That is, the Table-on-Table type machines can have the traveling range of the first rotary axis of almost 360°, whereas the trunnion type machines can have the traveling range of the first rotary axis of only close to 180°, and many of the machines with the single-axis tilt spindle type, the 2-axis rotary and tilt spindle type, and the fixed table type can have the traveling range of the first rotary axis of only around 90°.

We examine how the traveling range of the first rotary axis influences on the machine accuracy through simulations. That is, we assumed the rotation center could be easily determined by using machines with a wide range of the first rotary axis of close to 360°. We presume that once the center axis position is defined, the standards for measurement of motion accuracy and assembly operation can be defined clearly.

If the center of the rotary axis cannot be clearly defined, the alignment error including offset error and angle error easily becomes large as shown in Figure 2. It is already confirmed by actual measurement that the Table-on-Table type 5-axis control machining centers are superior in motion accuracy to the ones with the trunnion type [2].

The purpose of this study is to support a theory that the larger the rotating angle is, the more accurate the rotating center of the rotary axis is, and the alignment error becomes smaller through simulation analysis using a method similar to the DBB measurement [3]. Moreover, the same simulation analysis is conducted using the path of motion error actually measured by the DBB method.

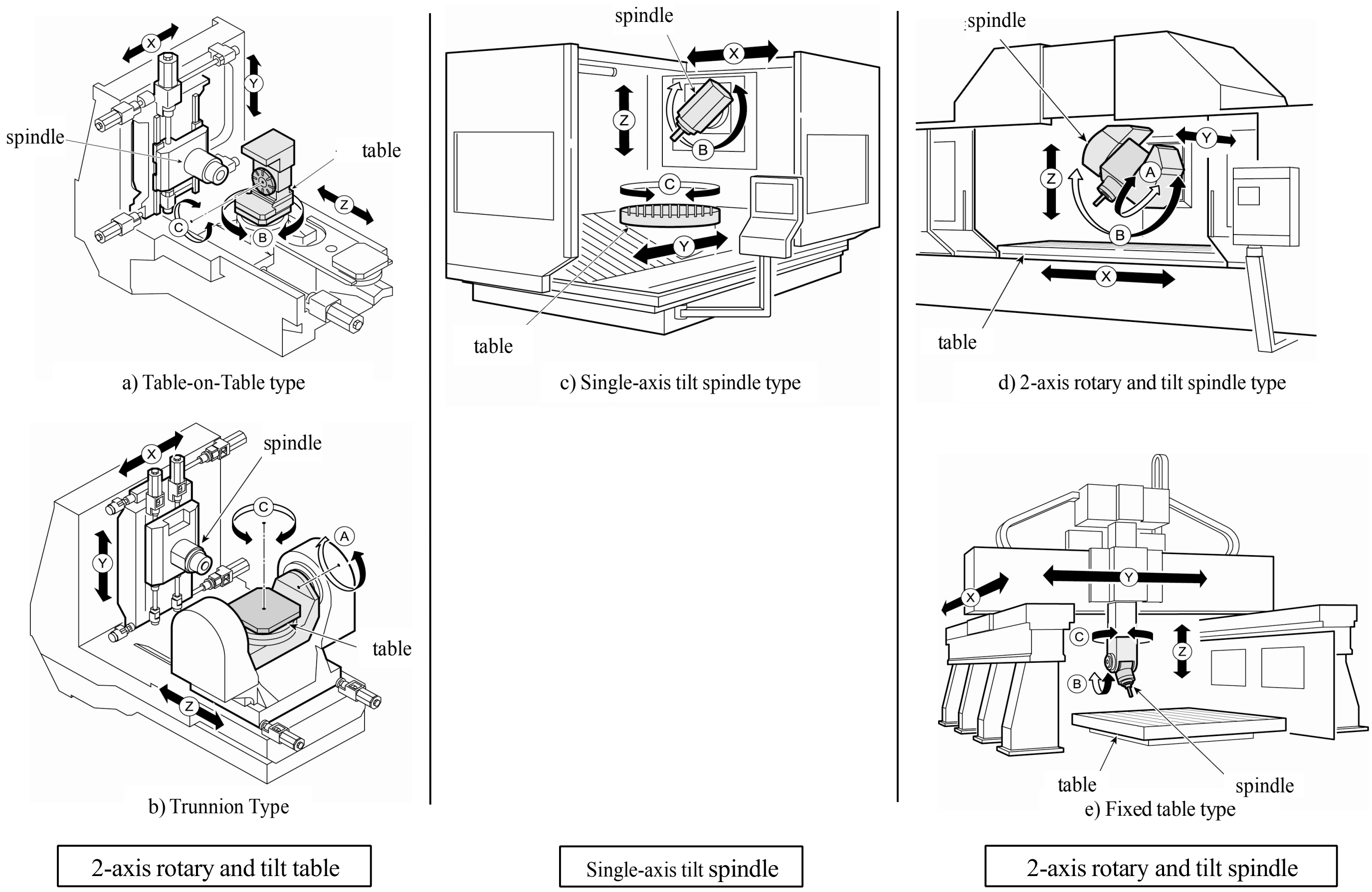
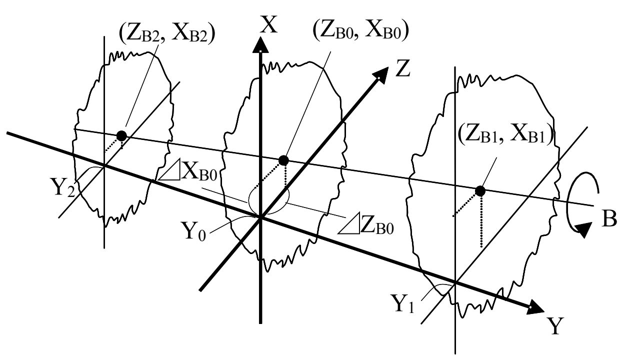


Fig. 1 The types in each pattern of 5-axis control machining centers



Center position of offset error : (Z_{B0}, X_{B0})

Offset error : $\angle Z_{B0} = Z_{B0}$, $\angle X_{B0} = X_{B0}$

Angle error : $\angle Bz = (Z_{B1} - Z_{B2}) / (Y_1 - Y_2)$

$\angle Bx = (X_{B1} - X_{B2}) / (Y_1 - Y_2)$

Fig. 2 Definition of offset error and angle error in rotary axis B

2. Method of Simulation Analysis

2・1 When an only offset error exists

In this simulation, the alignment error is assumed to be composed of an offset error and an angle error as shown in Figure 2. That is, we assume there are no bending components of second component or higher at the rotation center. First of all, we consider the case that there is only an offset error of the alignment error. In the simulation analysis, we examine the influence of the traveling range of the rotary axis on the estimated offset error which is assumed from the measurement data by the DBB method for the case that only a motion error of lower order components, the tenth component or lower, exists. We set aside the motion error components of tenth component or higher because the influence is assumed to be small. We call a motion error component with n-cycle component during one rotation (360°) as n order component. The overview of the program to be used in simulations is described in Figure 3. The main procedures are as follows:

(1) Calculate the distance r between the center coordinate (Z_{B0}, X_{B0}) at the Y_0 section of the rotary axis including an offset error and the rotation center on the spherical coordinate, which is set on the table described in Figure 5.

(2) Apply amplitude and phase slightly smaller than the offset amount of the axis center as a motion error generated by rotation of the target rotary axis to noise component.

(3) Calculate the locus generated in (1) and (2) for 360°. An example of the calculation result of the locus of a motion error is described in Figure 4 (a).

(4) Create the locus of motion errors using the one generated in (3) of which just the traveling angle component is cut off. Figure 4 (b) shows the locus of motion errors when the traveling range is 180° (from -90° to 90°), and (c) in the same figure shows the one when the traveling range is 90° (from -45° to 45°).

(5) Calculate a coordinate of the presumed rotation center (Z'_{B0}, X'_{B0}) using the method of least squares from the locus of motion errors determined in (4).

(6) Compare the coordinate of the estimated rotation center calculated in (5) with the assumed coordinate of the rotation center in (1) to calculate estimated offset errors, $\Delta Z'_{B0} = Z'_{B0} - Z_{B0}$ and $\Delta X'_{B0} = X'_{B0} - X_{B0}$.

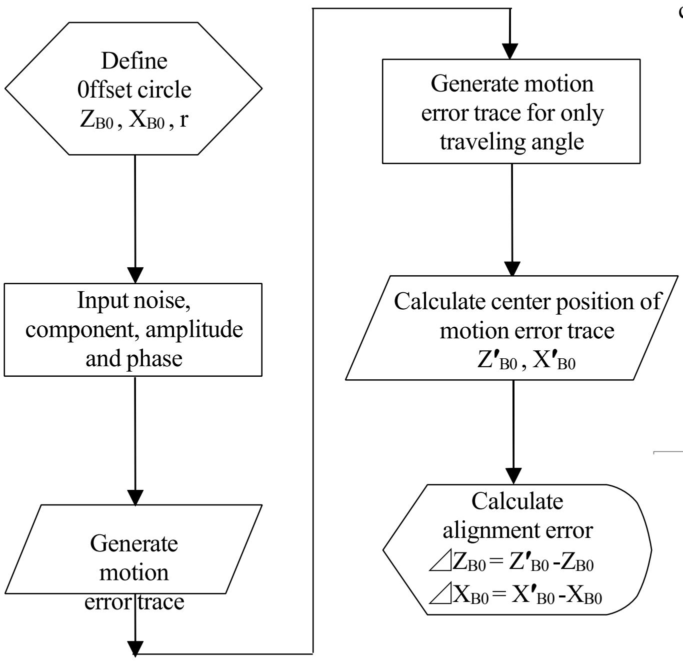


Fig. 3 Flow chart for simulation

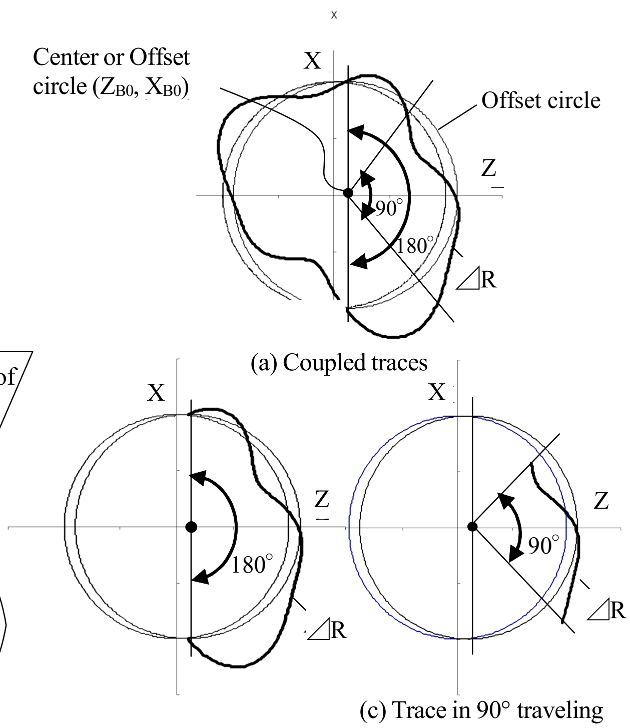


Fig. 4 Examples of measured motion error traces depending on rotating angle

2 ・ 2 When an angle error exists as well

In this paragraph, the influence of the traveling range of the rotary axis on the estimated angle error is examined by simulation analysis on the condition that an angle error exists as well as an alignment offset error of the rotary axis. The procedure of the simulation analysis is as follows:

(1) The predetermined offset is given to Y_0, Y_1, Y_2, respectively, to define the center coordinate of the rotary axis on each plane: (Z_{B0}, X_{B0}), (Z_{B1}, X_{B1}) and (Z_{B2}, X_{B2}).

(2) The center coordinate (Z'_{B0}, X'_{B0}) of each position is calculated for every rotation angle. The simulation analysis is conducted in the same way as described in 2.1.

(3) The angle errors in the Z- and X- axis directions are calculated using the simulation result obtained from (2). The estimated angle errors, $\varDelta B_{z12}$ and $\varDelta B_{x12}$, are calculated according to $\varDelta B_z = (Z_{B1} - Z_{B2}) / (Y_1 - Y_2)$, $\varDelta B_x = (X_{B1} - X_{B2}) / (Y_1 - Y_2)$, using the offset error estimated from the two positions.

(4) The result obtained from (3) is compared to the setting condition to calculate the estimated angle errors of alignment: $\varDelta B'_Z$ and $\varDelta B'_X$.

3. Contents and Conditions of Simulation Analysis

3 ・ 1 When only an offset error exists

3 ・ 1 ・ 1 Setting of component, rotary axis traveling ranges and offset errors

The estimated error of center position is examined for each of the second to tenth, fifteenth and twentieth order component by simulation analysis on the condition that the rotary axis traveling range is 180°. The center coordinate of offset error (Z_{B0}, X_{B0}) is set to be at (0 μm, 10 μm), and amplitude for each order component to be 5 μm.

The simulation analysis is conducted in such a way that the estimated error is calculated every 30° from 90° to 360°. The center coordinate of offset error (Z_{B0}, X_{B0}) is set in two patterns: (0 μm, 0 μm) and (0 μm, 10 μm). The second component with amplitude of 5 μm, the third component with amplitude of 3 μm, and the fifth component with amplitude of 2.5 μm are given as the motion error component.

The estimated error of the center position is examined by simulation analysis on the conditions that the center coordinate of offset error (Z_{B0}, X_{B0}) is at (0 μm, 0 μm), (0 μm, 10 μm), (10 μm, 0 μm) or (10 μm, 10 μm). The second component with amplitude of 5 μm, the third component with amplitude of 3 μm, and the fifth component with amplitude of 2.5 μm are given as the motion error component.

3 ・ 1 ・ 2 Simulation using measured motion error traces

The above-mentioned simulation analysis is conducted on the B-axis which is the first rotary axis of a newly developed Table-on-Table type 5-axis machining center, using the motion error traces of the rotating axis measured according to the DBB5[(4),(5)] method. The motion error trace is calculated as follows [(6)*]:

(1) One of the balls of the DBB device is allocated on the center of the B-axis, and the bar is set in the X-axis direction as shown in Figure 5.

(2) The error $\varDelta X_B$ is measured when the linear axis is stopped and only the B-axis is rotated from -100° to 180°.

(3) The bar is set in the Y-axis direction to measure the error $\varDelta Z_B$ in the same way.

(4) The motion error of the rotary axis B, $\varDelta R$, is calculated from vector composition of $\varDelta R_{ZB}$ and $\varDelta R_{XB}$ calculated in the preceding item.

In the simulation analysis, a full 360 degree is divided by 1,000.

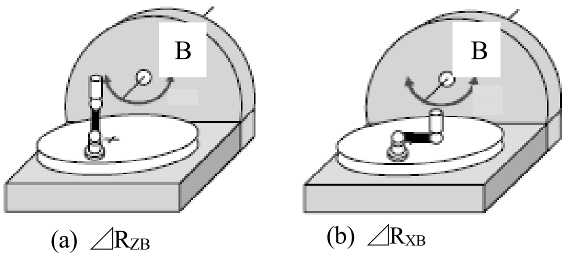


Fig. 5 Measurement of radial motion for rotary axis B

Table 1 Alignment error given at Y0, Y1, Y2

Y Position mm	Offset error		Angle error	
	⊿Z_B µm	⊿X_B µm	⊿B_Z µm / 350 mm	⊿B_X µm / 350 mm
Y_1:350	10	10	10	0
Y_0:0	0	10		
Y_2:-350	-10	10		

3・2 When an angle error exists as well

The offset errors and angle errors set for Y_0, Y_1, and Y_2 are shown in Table 1. In the simulation, it is assumed that an angle error of 10 µm/350 mm exists as well as an offset error of 10 µm in the Z-axis direction. The offset error and angle error in the X-axis direction are assumed to be very small.

4. Results of Simulation Analysis and Consideration

4・1 When only an offset error exists

4・1・1 Influence of component

The estimated error of the center position is calculated and shown in Figure 6 on the condition that the center coordinate of the B-axis (Z_{B0}, X_{B0}) is at (0 µm, 10 µm), and any of the second to tenth, fifteenth or twentieth component with amplitude of 5 µm exists alone.

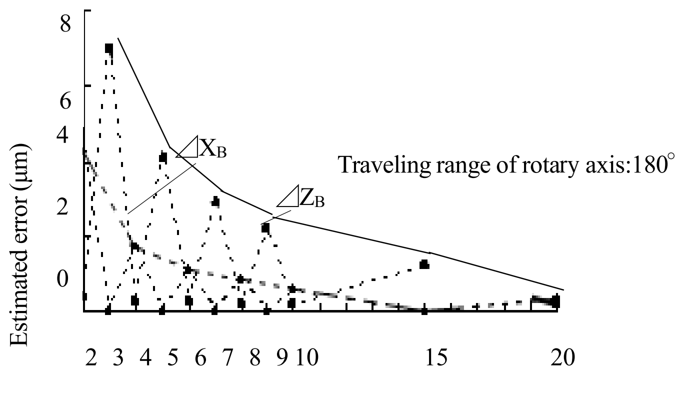


Fig. 6 Influence of noise component

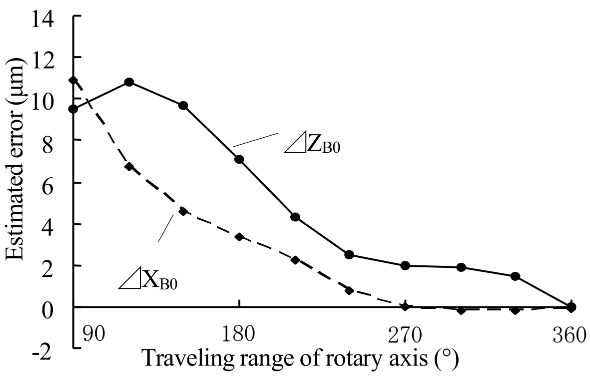
The higher the component is, the smaller the influence of the center position on the estimated error becomes. It was found that the tenth component had only one quarter of influence of the second component. The reason that small errors occur at the even order's components is that all phases are assumed to be 0° in the calculation.

4・1・2 Influence of traveling range of rotary axis

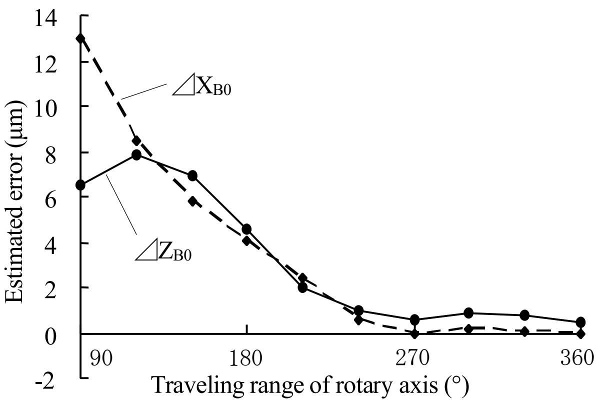
The Estimated error of the center position is calculated and shown in Figure 7 on the condition that the center coordinate of the B-axis (Z_{B0}, X_{B0}) is at (0 μm, 0 μm) or (0 μm, 10 μm) (cases without an offset error and with an offset error of 10μm in the X-axis direction are studied), and the traveling range of the rotary axis is changed by 30°.

Naturally, when the traveling range of the rotary axis is 360°, the estimated error of the center position is very small at 1 μm or less in both cases. However, when the center coordinate of the B-axis (Z_{B0}, X_{B0}) is at (0 μm, 10 μm) with a rotary axis traveling range of 180°, the estimated error is 3.5 μm in the X-axis direction and 7.2 μm in the Z-axis direction. With a rotary axis traveling range of 90°, the estimated error is 10.9 μm in the X-axis direction, and 9.5μm in the Z-axis direction, which are considered to be estimated huge error values. On the other hand, when the traveling range of the rotary axis is about 270 °, the estimated error becomes very small at 2 μm or less in both cases.

From the result mentioned above, it was found that the offset error could be easily reduced with the Table-on-Table type structure which can achieve a rotary axis traveling range of almost 360° than with the Trunnion type which can only achieve a rotary axis traveling range of less than 180°.



(a) (Z_{B0}, X_{B0}) = (0 μm, 10 μm)



(b) (Z_{B0}, X_{B0}) = (0 μm, 0 μm)

Fig. 7 Influence of the traveling range of rotary axis on the offset error

4・1・3 Influence of position of offset error

When the center position of the B-axis (Z_{B0}, X_{B0}) is at (0 μm, 0 μm), (0 μm, 10 μm), (10 μm, 0 μm) or (10 μm, 10 μm), the estimated errors, $\triangle Z'_{B0}$ and $\triangle X'_{B0}$, are calculated for each offset circle position by simulation analysis. Then estimated radial error $\triangle r'_{B0}$ is calculated from vector composition of $\triangle Z'_{B0}$ and $\triangle X'_{B0}$ to examine the influence of the offset error position. The influence of the offset circle position on the estimated radial error $\triangle r'_{B0}$ for different rotary axis traveling ranges (90°, 180°, 270° and 360°) is shown in Figure 8.

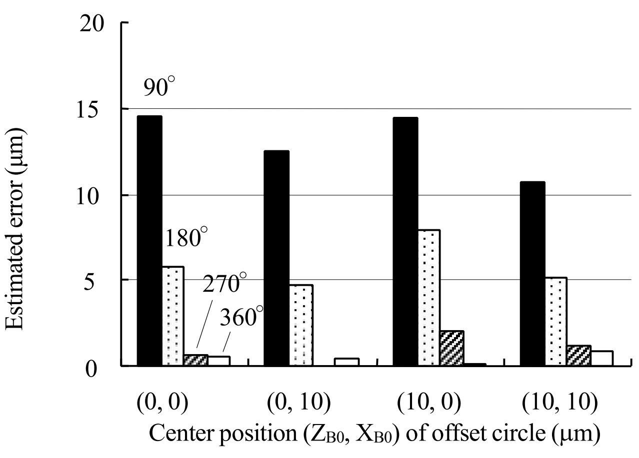
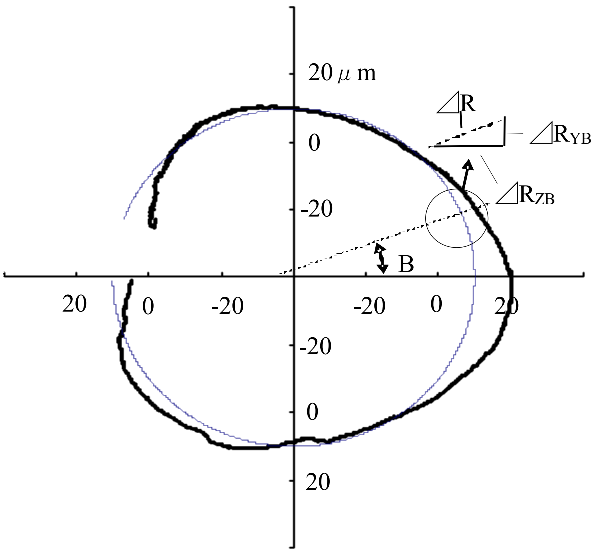


Fig. 8 Influence of the offset circle position on the offset error

As shown in Figure 8, each estimated radial error, $\triangle r'_{B0}$, of different offset circle positions calculated for every rotary axis traveling range resulted in similar value. As with the case of the influence of rotary axis traveling ranges described in 4.1.2, the estimated error is very small at 2 μm with any offset circle positions, if the rotary axis traveling range is 270° or more.

4・1・4 Simulation Analysis using measured values

The motion error trace of the B-axis which is the first rotary axis of a newly developed 5-axis control machining center was measured by the DBB5 method on the condition that only the B-axis is in motion and that Y=0, and it is



developed machining center measured by
DBB5 method

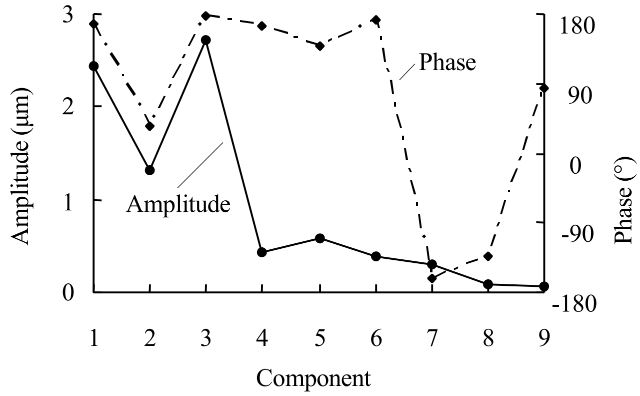


Fig. 10 Fourier analysis of motion error trace

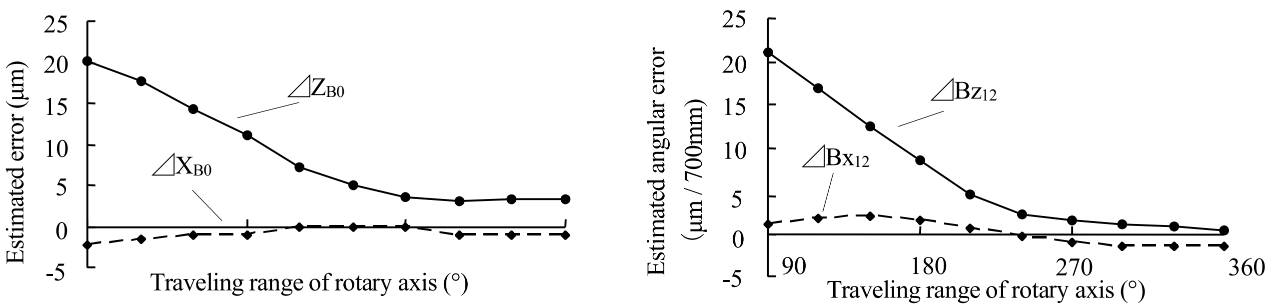
In this case, the motion error of maximum circle area radius is 10 μm. The amplitude and phase of each order component obtained from the motion error trace by Fourier analysis is shown in Figure 10.

As shown in the figure, the amplitude of the second component is 1.3 μm, and that of the third component is large at 2.7 μm.

The influence of traveling range of rotary axis on the estimated offset error is examined by simulation analysis using measured amplitude and phase of up to the tenth component.
The eleventh or higher components are ignored because no component with large amplitude exists, and the analysis result shown in Figure 6 indicates that they have no significant influence on the simulation result.

As shown in Figure 11, the result similar to Figure 8 was obtained from the analysis. Namely, when the traveling range of the rotary axis is 180°, the estimated offset error was about 11 μm, and when the traveling range of the rotary axis is 90°, the estimated offset error is very large at about 20 μm.

Practically, in many cases a Trunnion type 5-axis control machining center can only achieve a traveling range of the rotary axis B of 150°, and in that case the estimated error is assumed to be about 15 μm.



90 180 270 360

Fig. 11 Influence of traveling range of rotary axis on the estimated offset error based on motion error trace by DBB5 on newly developed machining center

Fig. 12 Influence of the traveling range of rotary axis on the estimated angle error

4・2 When an angle error exists as well

The influence of the traveling range of the rotary axis B on the estimated angle error is shown in Figure 12 on the condition that the motion error shown in Figure 4 exists on the B-axis as well as the angle error set in Table 1. Under this condition, the estimated error in the X-axis direction whose angle error does not exist is very small at 2 μm/700 mm regardless of traveling range of the rotary axis. However, the estimated error in the Z-axis direction which was given an angle error is very large at 21 μm/700 mm when the traveling range of the rotary axis Z is 90°.

The estimated error becomes smaller as the traveling range of the rotary axis is wider: when the range is 210°, the error is 4.5 μm/700 mm, and when the range is 270°, the error is 1.8 μm/700 mm. The estimated error gradually decreases as the traveling range of the rotary axis becomes wider, and when the traveling range is 360°, the estimated error is down to 0.2 μm/700 mm.

5. Conclusion

The influence of the traveling range of the rotary axis with a motion error on the alignment error of an assumed the rotary axis center was examined on the 5-axis control machining center by simulation analysis for the purpose of studying how a machine structure influences motion accuracy of the machine. The conclusions led by the analysis results are mainly as follows:

(1) The estimated alignment error of the Table-on-Table type structure that can achieve a traveling area of almost 360° for the first rotary axis was very small.

(2) The estimated alignment error of the Trunnion type structure whose traveling area for the first rotary axis is 180° was almost the same as the amplitude of the motion error component.

(3) The estimated alignment error of the universal head spindle whose traveling area for the first rotary axis is 90° was about three to five times as much as the amplitude of the motion error component.

(4) With a rotary axis traveling area of 270°, the estimated alignment error was 2 μm or less; therefore, the alignment can be assumed almost accurately.

(5) The similar results were obtained for (1) - (3) from the simulation analysis using motion error traces measured by the DBB method.

From the examination and analysis results, it was found desirable that a rotary axis traveling range of more than 270° should be achieved in order to reduce the estimated angle error of the rotary axis. It was also verified that the Table-on-Table type structure that can achieve a rotary axis traveling range of almost 360° was more likely to reduce a possibility of the estimated alignment error than the Trunnion type structure that can barely achieve a rotary axis traveling range of almost 180°.

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