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Geometric Error Estimation and Compensation of Rotation Axis for Five-Axis Machining Centers Using a Common Measuring Tool

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In precision machining, it is important to minimize the geometric error of the rotation axis in five-axis machining centers. The double ball bar and R-test methods are used to evaluate and understand rotation axis errors in five-axis machining centers. However, expensive equipment is necessary to implement these methods. Moreover, there are many cases in which, even if the error of the rotation axis is identified, users cannot correct these errors. Therefore, an evaluation method is proposed for understanding the error of the rotation axis in five-axis machining centers using a simple mathematical model and a dial gauge. Furthermore, a method for compensating for the geometric error of the rotation axis is suggested, and its effectiveness was demonstrated through real machining.

1. Introduction

Problems are caused by the rotating axis in a five-axis machining center (5-axis MC), which is indispensable for reducing the lead time and for machining complicated shapes. Researchers have conducted numerous studies on the accuracy measurement of 5-axis MCs — for example, a method using a ball bar [1] or sphere [2] and a displacement meter [3] has been developed. In the relatively new 5-axis MC, machine tool makers and numerical control (NC) equipment makers provide software to set the parameters related to the rotating axis using a reference ball and touch sensor. These methods make accurate measurements possible without the need for cutting. However, expensive measuring instruments are required. Therefore, there are many 5-axis MC users in an environment where the latest measurements, as described above, cannot be performed easily. Even if the geometric error can be measured, it is often difficult for the user to correct the angle error of the rotation axis. However, the geometrical error of 5-axis MCs is often studied based on the shape creation theory of machine tools, similar to the forward kinematics of robots. However, this theory is difficult to understand intuitively for users working in this field. Therefore, a method was developed for expressing the centerline of the rotation axis of a 5-axis MC as a single line. In this study, a method was developed to estimate the geometrical error of the rotation axis using only the measuring instruments generally prepared in the field of machining and using the proposed mathematical representation of the centerline of the rotation axis. After confirming that the thermal displacement and tool shape error are likely to affect the machining result in actual machining, a previously proposed fine groove cutting test [4] was performed. Furthermore, the fine-groove cutting test was performed again using the program that was used to correct the error, that the improvement of the machining result was verified, and the effectiveness and problems of the proposed estimation method were examined.

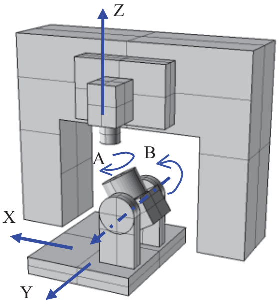


Fig. 1 Five-axis machining center

2. Machine tool and rotation axis centerline

2.1 Five-axis MC

There are three types of 5-axis MC structure: spindle swivel, table swivel, and mixed. Of these, the table swivel 5-axis MC, which is shipped in the largest number, was addressed in this study. The machine used in the experiment is a table swivel 5-axis MC with the A- and B-axes as the rotating axes, as shown in Fig. 1. In this article, the positioning state of the rotating axis, such as the 0° A-axis and 0°

B-axis, is simply described as A0B0. Here, of the rotation axes of the 5-axis MC used in the experiment, the axis that can rotate 360° or more is defined as the A-axis, not the C-axis, as shown in Fig. 1.

2.2 Rotation axis centerline and coordinate system

In this study, the centerline of the axis of rotation was considered a straight line, and the centerline of the axis of rotation was estimated. In the case of the rotation axis centerline of the unit direction vector (a, b, c) and rotation center (Xc, Yc, Zc), the rotation axis centerline parameters are expressed as (a, b, c, Xc, Yc, Zc). In the coordinate system, the XY origin is the center of rotation of the A-axis at 0° on the B-axis set by the manufacturer when the 5-axis MC was delivered. Similarly, the Z origin is the position of the B-axis rotation center set at the time of delivery.

3. Geometric error estimation of the rotation axis by a general measuring instrument

3.1 Estimating the A-axis centerline direction vector

At A0 and A180, the displacements of the three points in the Z-direction were measured from the reference plane using a displacement meter. Specifically, at A0, the displacement meter was applied to the upper surface of the reference plane from the positive Z-direction, the indicated value of the displacement meter was set to zero, and the work origin was (0, 0, 0) mm. Subsequently, the XY-coordinate values of the remaining two points and the numerical values indicated by the displacement meter were used as the measured values, and the same measurement was performed at A180 to obtain the measured values. Then, the normal vector of the reference plane composed of three points measured at A0 was (a1, b1, c1), and the normal vector of the reference plane composed of three points measured at A180 was (a2, b2, c2). Assuming that the A-axis centerline direction vector is (Aa, Ab, Ac), the A-axis centerline direction vector can be calculated using Eqs. (1)–(3). In this study, a dial gauge (Mitutoyo No. 2109S-10) was used as the displacement meter.

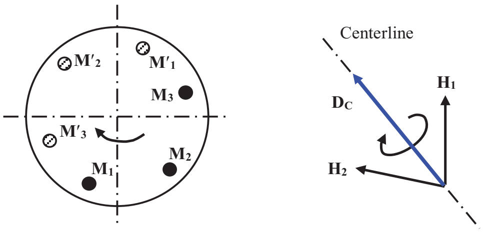
$$A_a = \frac{1}{\sqrt{1+\left(\frac{b_1+b_2}{a_1+a_2}\right)^2+\left(\frac{c_1+c_2}{a_1+a_2}\right)^2}} \tag{1}$$

$$A_b = \left(\frac{a_1+a_2}{b_1+b_2}\right) A_a \tag{2}$$

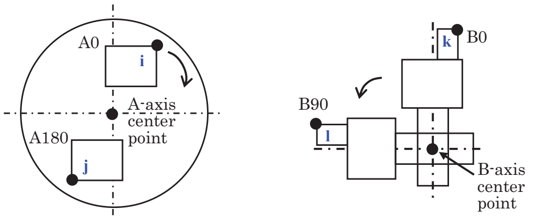
$$A_c = \left(\frac{a_1+a_2}{c_1+c_2}\right) A_a \tag{3}$$

3.2 Estimating the A-axis center point

The side surface of the rectangular parallelepiped reference device was attached such that it was parallel to the X- and Y-axes of the 5-axis MC, and the apex position of the reference device — point i shown in Fig. 3(a) — was measured at A0B0. Using a reference tool and reference block, the coordinates near the vertices were read and set as (X_{A1}, Y_{A1}). Next, the A-axis was rotated by 180°, and the vertex position of the reference block — point j shown in Fig. 3(a) — was measured. Assuming that this point is (X_{A2}, Y_{A2}), the center point of the A-axis (X_{A0}, Y_{A0}) can be obtained from Eq. (4).



(a) A-axis (b) B-axis
Fig. 2 Center point measurement method



(a) A-axis (b) B-axis
Fig. 3 Center point measurement method

$$\begin{pmatrix} X_{A0} \\ Y_{A0} \end{pmatrix} = \frac{1}{2}\begin{pmatrix} X_{A1} + X_{A2} \\ Y_{A1} + X_{A2} \end{pmatrix} \tag{4}$$

3.3 Estimating the B-axis centerline direction vector

The normal vector of the reference plane at B0 and B90 is used for the B-axis, where the stroke of the rotation axis is limited. When the normal vector of the reference plane composed of three points measured at B0 is set to (a3, b3, c3) and the normal vector of the reference plane composed of three points measured at B90 is set to (a4, b4, c4), Eqs. (5)–(7) are established. Here, (Ba, Bb, Bc) is the B-axis centerline direction vector.

$$B_a = \frac{-2(b_3c_3-b_4c_4)}{(a_3+a_4)^2+(b_3+b_4)^2+(c_3+c_4)^2} \tag{5}$$

$$B_b = \frac{B_a(b_3+b_4)-c_3+c_4}{c_3+c_4} \tag{6}$$

$$B_c = \frac{B_a(c_3+c_4)+b_3-b_4}{a_3+a_4} \tag{7}$$

3.4 Estimating the center point of B-axis

The center point of the B-axis is calculated using the method shown in Fig. 3(b). In other words, when the B-axis is 0°, the vertex positions (X_{B1}, Z_{B1}) of the reference device in the machine coordinate system are measured — point k in Fig. 3(b). Next, the B-axis is rotated by 90°, and the vertex positions (X_{B2}, Z_{B2}) of the reference block are measured — point l in Fig. 3(b). Assuming that the B-axis rotation center is (X_{B0}, Z_{B0}), the B-axis rotation center can be calculated using Eq. (8).

$$\begin{pmatrix} X_{B0} \\ Z_{B0} \end{pmatrix} = \frac{1}{2}\begin{pmatrix} X_{B1} + X_{B2} + Z_{B1} - Z_{B2} \\ -X_{B1}+X_{B2} + Z_{B1} + Z_{B2} \end{pmatrix} \tag{8}$$

3.5 Estimated result of rotation axis geometric error obtained by displacement meter

To confirm the validity of the numerical values obtained by the proposed measurement method, the measurement was performed with the B axis rotated by 0.1°. Table 1 shows the estimation results of the rotation axis centerline direction vectors of the A- and B-axes, and Table 2 shows the estimation results of the rotation centers of the

Table 1 Estimated directional vector results of rotation axis

Axis name	Directional vector		
	X (mm)	Y (mm)	Z (mm)
A-axis	−0.0016486	−0.0000389	0.9999986
B-axis	−0.0000778	1.0000000	0.0001250

Table 2 Estimated center point results of rotation axis

Axis name	Center point		
	X (mm)	Y (mm)	Z (mm)
A-axis	0.081	0.006	—
B-axis	0.03	—	0.012

A- and B-axes. Here, the angle between the X and Z values of the A-axis centerline direction vector in Table 1 and the vector (0, 0, 1) in the XZ-plane is 0.094458°. This value is close to the angle at which the B-axis is tilted in advance. In other words, it suggests that the accuracy of the 5-axis MC can be controlled by using the proposed measurement method, even in a field without an expensive measuring machine.

4. Machining error confirmation by fine groove cutting and geometric error compensation

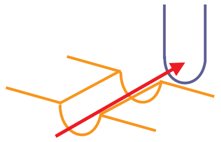
4.1 Error factors that occur during actual machining

A machining accuracy test performed by cutting fine grooves was developed previously. In this study, this test was used to confirm whether the geometrical error estimated as described in the previous section is valid. During actual processing, the error factors increase and become complicated. Therefore, after confirming the amount of error that may occur in actual machining, a fine-groove cutting test was performed.

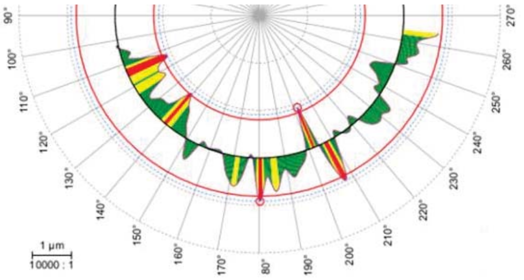
4.1.1 Machining error caused by tool shape error

In the fine-groove cutting test, a ball end mill with a radius of 5 mm was used to minimize the effects of tool deflection and other factors. However, the distance from the center of the theoretical tool to the cutting edge is not always constant because of the sphericity of the tool and runout of the spindle. Therefore, the tool shape error was confirmed in advance using the following procedure.

As shown in Fig. 4(a), a semicylinder with a radius of 5 mm was machined using a ball end mill with a radius of 3 mm, leaving an allowance of 5 µm. Next, a semicylindrical finish was performed with the R5 ball end mill used for the fine groove test. Figure 4(b) shows the result of measuring the semicylindrical shape created by this procedure with a coordinate measuring machine. The roundness was 2.26 µm. When a fine groove machining test is performed with this tool, the tool shape error affects the machining result by approximately ±1 µm.



(a) Cutting test.



(b) Measurement results

Fig. 4 Error of geometrical profile of tool cutting edge

4.1.2 Machining error resulting from geometric error of the rotation axis

The machining error due to the geometric error of the rotation axis is considered to be caused by the difference between the rotation axis centerline set in computer-aided manufacturing (CAM) or NC and the actual rotation axis centerline. Here, $\boldsymbol{V_1}$ is the coordinate value rotated around the actual center of the rotation axis, and $\boldsymbol{V_2}$ is the coordinate value rotated around the centerline of the rotation axis set in NC. By converting the difference between $\boldsymbol{V_2}$ and $\boldsymbol{V_1}$ into the work coordinate system, the error vector that appears owing to the influence of the rotation axis centerline error can be derived, as shown in Eq. (9).

$$\begin{cases} V_1 = R(D_{AB},\phi)\big(\big(R(D_{AA},\varepsilon)(P_P + P_W - P_{AA}) + P_{AA}\big) - P_{AB}\big) + P_{AB} \\ V_2 = R(D_{NB},\phi)\big(\big(R(D_{NA},\varepsilon)(P_P + P_W - P_{NA}) + P_{NA}\big) - P_{NB}\big) + P_{NB} \\ V_{E1} = R_T(V_2 - V_1) \end{cases} \tag{9}$$

Here, D_{AA} is the unit direction vector of the actual A-axis centerline, D_{AB} is the unit direction vector of the actual B-axis centerline, P_P is the program command value, P_W is the machining origin position in the machine coordinate system, P_{AA} is the actual center of rotation of the A-axis, P_{AB} is the center of rotation of the B–axis, D_{NA} is the unit direction vector of the centerline of the A-axis set in NC, DNB is the unit direction vector of the B-axis centerline set in NC, PNA is the A-axis rotation center set in NC, PNB is the B-axis rotation center set in NC, and RT is a transformation matrix from the machine coordinate system to the work coordinate system.

4.1.3 Machining error caused by thermal displacement

It is also necessary to consider that the effect of the thermal displacement of the 5-axis MC appears on the machined surface during actual machining. Therefore, with the work material fixed to A0B0, a fine groove cutting test was conducted every 10 min immediately after spindle rotation under the machining conditions shown in Table 3 to confirm the thermal displacement of the 5-axis MC. Figure 5 shows an excerpt of the machining results. The horizontal axis in Fig.5 is the depth of cut commanded, and the vertical axis is the elapsed time. Owing to space limitations, detailed data are omitted, but immediately after the spindle rotation, the behavior was observed to extend by several micrometers in the Z-direction.

Table 3 Experimental machining conditions

Spindle speed	8000 min^{-1}
Feed rate	400 mm/min
Work material	NAK80
Tool	R5 mm ball end mill

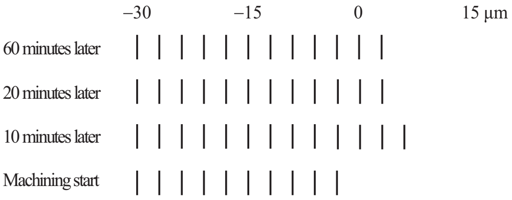


Fig. 5 Influence of thermal displacement on the groove matrix

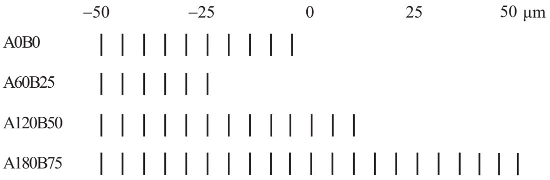


Fig. 6 Comparison of simulation and experimental result

4.2 Fine groove cutting test

Considering the rotation axis stroke and tool interference of each axis of the processing machine, a fine groove cutting test was performed on the upper surface of the work material with four types of tool postures in which rotation axis angles A0B0 to A180B75 were equally divided. The rectangular parallelepiped-shaped work material was set at positions (−63.72, −70.71, 258.75) mm from the coordinate system defined in Section 2.2, with the top surface in front of the left end as the origin of the work coordinate system. The other machining conditions were the same as those used to confirm the thermal displacement, as listed in Table 3. The machining results of the microgroove cutting tests are shown in Fig. 6. To confirm whether the proposed measurement and compensation methods are effective, as shown in Section 3.5, an experiment was conducted by intentionally setting a large A-axis centerline angle error.

4.3 Rotation axis geometric error compensation

As shown in Fig. 7, fine grooves were machined from point P_1 to point P_2 with an arbitrary tool posture. Here, NC and CAM have items to set the center of rotation, but the angle error is often processed as zero (the design value is used as it is). However, in reality, it is difficult to make the angle error zero, and machining errors occur. Therefore, in this study, it was assumed that the NC data could be corrected, and that the machining accuracy could be improved by calculating the points obtained by rotating the machining points by a specified angle using the estimated rotation axis centerline parameters. Specifically, points P_3 and P_4 obtained by rotating points P_1 and P_2 by a specified angle with the estimated rotation axis centerline parameters were calculated. NC data were created for all points used in the machining, and the micromachining test was repeated. The machining results are shown in Fig. 8. As the figure shows, the machining accuracy is improved by making corrections, confirming that the proposed method is effective.

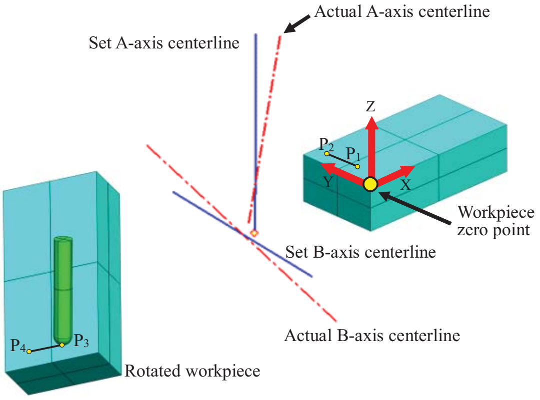


Fig. 7 Schematic diagram of groove matrix machining

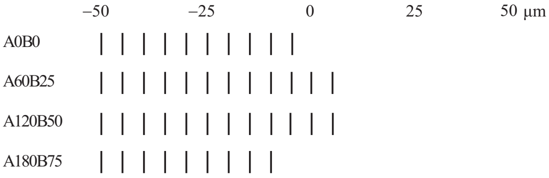


Fig. 8 Compensated machining result

5. Conclusions

1) The geometric error of the axis of rotation can be determined by inputting the measured values obtained by the measuring instrument, which is considered to be in the field, into the proposed formula.

2) A method was proposed to correct the rotation axis angle error that cannot be easily corrected by using a program. The effectiveness was demonstrated through machining experiments.

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