https://doi.org/10.20965/ijat.2017.p0171

Paper:

Evaluation Method for Behavior of Rotary Axis Around Motion Direction Changing

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[Received July 19, 2016; accepted November 8, 2016]

Several methods for evaluating the motion accuracy of the rotary axes in five-axis machining centers have been proposed till date. As it is known that particular motion errors exist around the motion direction changing points, it is important to evaluate the behavior of the rotary axes around these points. However, the influence of the motion error in the translational axes is included in the conventional evaluation results, as the translational axes reverse at the motion direction changing points about the rotary axes. In this study, an evaluation method which can assess the behavior of a rotary axis around motion direction changes by synchronous motion of translational and rotary axes is proposed. In this method, the direction of translational axes does not change when the motion direction of a rotary axis changes. A measurement test and actual cutting tests are carried out to clarify the influence of the behaviors of rotary axes on the motion trajectory and machined surface, caused by the change in the motion direction of the rotary axis. Simulations of the motion are also carried out to discuss the causes of inaccuracy.

Keywords: 5-axis controlled machining center, rotary axis, dynamic behavior, motion direction changes, machined surface

1. Introduction

The 5-axis controlled machining centers can operate with respect to both the relative position and angle of tools and workpieces; hence, they are generally applied to machine mechanical and aero dynamic parts having complex shapes, such as impellers. The 5-axis controlled machining centers have many advantages, but they also have the disadvantage of motion accuracy; therefore, they have more error sources than the conventional 3-axis machining centers.

One of the static error sources in 5-axis controlled machining centers is the position and orientation error of the rotational centers, which is called geometric error. The error reduces the geometrical accuracy of machined parts. Therefore, several researches have been carried out to identify and compensate these errors [1, 2, 5]. A dynamic error also has a significant influence on the geometric errors observed on the machined surface. The methods for measuring and evaluating dynamic error sources, such as motion errors of each axis or synchronous errors between translational and rotary axes, have been also investigated [6, 7].

In particular, the behavior of the rotary axis around the motion direction changing point has a significant impact on the machined surface. Hence, it is important to evaluate the behavior of the rotary axes around motion direction changing points. It is also important to note that the angular error of rotary axes has a larger influence on the machined surface than the error of the translational axes as it is amplified by the distance between the center of the rotary axis and the machining point.

The motion accuracy of the 5-axis controlled machining center is typically measured by using a ball-bar system, R-tests, and cone-frustum cutting tests which have been previously proposed [8–13]. These methods measured the synchronous accuracy of translational and rotary axes. The motion direction of translational axes also changed when the motion direction of rotary axes changed in these proposed methods.

It had also been investigated that the influence of the behavior of the rotary axes can be evaluated by the cone-frustum cutting motion tests [14–16]. However, the normal direction of the machined surface in the cone-frustum cutting motion tests is not similar to the tangential direction of the rotary axes, although the maximum motion error of the rotary axes is due to the tangential direction. Hence, the behavior of the rotary axes cannot be evaluated correctly.

The authors proposed a measuring method to evaluate the dynamic characteristics of the rotary axes around the motion direction changing point that can eliminate the influence of translational axes by using a special measurement device [17]. However, the proposed tests require a special measurement device and a program, which is difficult to design, for evaluating the motions.

Therefore, in this study, a measurement method to evaluate the dynamic characteristics of the rotary axes around the motion direction changing points, excluding the influence of the translational axes, is proposed. The pro-

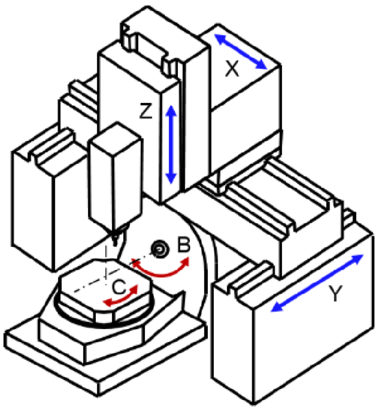
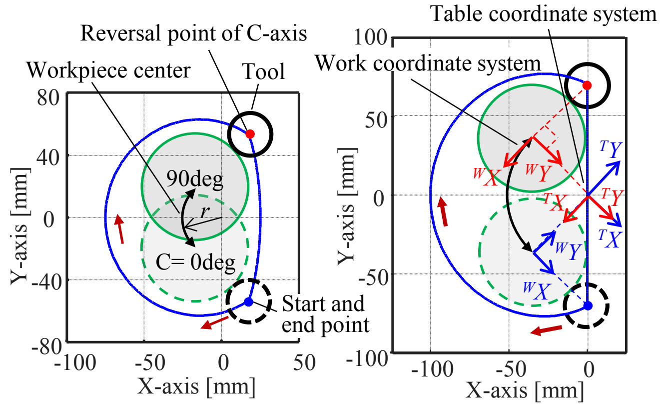
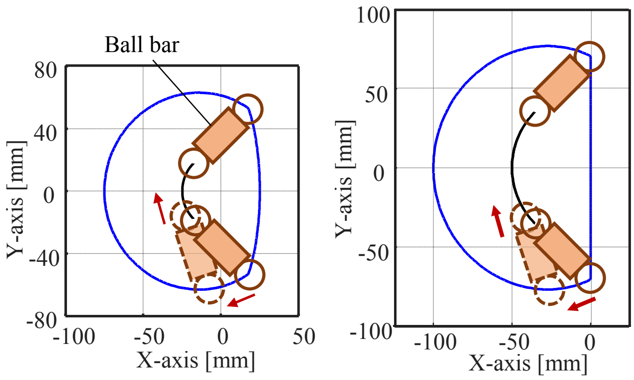


Fig. 1. Construction of a 5-axis controlled machining center.



(a) $r = 25$ mm (b) $r = 50$ mm

Fig. 2. Proposed cutting motion.



(a) $r = 25$ mm (b) $r = 50$ mm

Fig. 3. Proposed measurement motion.

posed measurement method uses a ball-bar system which is widely used in the machine tool industry. In addition, a machining method is proposed to confirm the influence of the behavior of the rotary axis on the machined surface. A simulation of the proposed motion is also carried out to verify the the behavior of the rotary axis around the motion direction changes.

2. Configuration of 5-Axis Controlled Machining Center

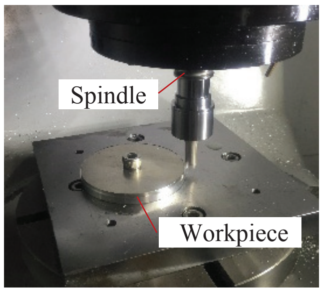
All measuring and square-end milling tests in this study were carried out by using a vertical type 5-axis controlled machining center NMV1500DCG (DMG Mori Seiki Co. Ltd.) having two rotary axes (B-axis and C-axis) on the table side, as shown in **Fig. 1**. In this study, the original compensation functions of NC machine tools around the motion direction changing point were turned off.

3. Proposed Synchronous Motion

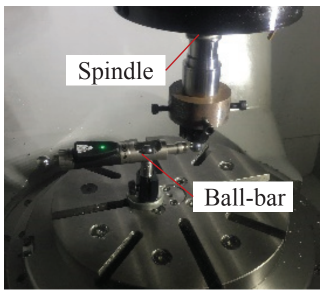
In this study, both cutting and measurement tests are carried out. These tests use the synchronous motion of the rotary and translational axes.

The motion trajectory is set as a circular interpolation motion in the table coordinate system. The table coordinates and the work coordinate systems are defined to represent the motion trajectory in this study. The table coordinate system turns with the rotation of a rotary axis, and the origin of this coordinate system is set at the center of the rotary axis, as shown in **Fig. 2**. In addition, the work coordinate system is defined to display the motion trajectories, and the origin of the coordinate system is set at the center of the cylindrical work piece.

The table coordinate system can be transformed to the work coordinate system by shifting the origin of the coordinates, and the work coordinate system moves along with the workpiece by the motion of a rotary axis, as shown in **Fig. 2**. **Figs. 2** and **3** illustrate the motion trajectory for the cutting and the measurement motions, and **Fig. 4** shows the experimental set-up.



(a) Cutting



(b) Measurement

Fig. 4. Experimental set-up.

The actual cutting and measurement tests were proposed to evaluate the dynamic characteristics of the rotary axis around the motion direction change point solely by using the synchronous motion of one rotary axis and two translational axes. C-axis was chosen as the measurement subject among the two rotary axes (B- and C-axis).

A workpiece with a cylindrical shape was used for the cutting test because the surface geometry of the machined workpieces can be measured by a roundness measurement machine, which is a typical measurement machine. The cylindrical cutting test and the measurement test by using a ball-bar system are possible by utilizing the synchronous motion of C-axis, X- and Y-axis.

The measurement system used in this study is a double ball-bar QC20-W (RENISHAW plc.). This system consists of two steel balls, two magnetic sockets, and a variable length bar with a displacement sensor. The sensors measures the distances between each steel ball on a socket and the spindle; the distance between each steel ball on a socket and the table is measured as well. The ball-bar system was set to measure the distance between the center of the workpiece and the spindle tip in the cutting test. Herewith, the comparison between the motion error of the rotary axis around the motion direction changing point and the results of the cutting test is facilitated.

In the proposed motion, the C-axis makes a reciprocal motion, and X- and Y-axis make an interpolated motion to make a circular trajectory in the table coordinate system as shown in **Figs. 2** and **3**. C-axis starts at 0°, then reverses at 90°, and eventually returns to 0°. The influence of the dynamic behavior around the motion direction changing points of C-axis can be evaluated approximately at 180° in the work coordinate system. The feed rate between the tool and the machined surface is kept constant.

In addition, the motion of the translational axes is designed such that the tangential direction of the C-axis around the motion direction changing point and the machined surface become perpendicular. Thus, the motion error of C-axis is copied onto the machined surface directly.

In the proposed motion, the motion direction of the translational axes remains in the same quadrant in the X-Y plane of the machine coordinate system before and after the C-axis reversal, as shown in **Fig. 5**; the motion errors due to the motion direction changes of translational axes do not influence the motion trajectories. Therefore, the position vector between the center of the workpiece and the center of the tool is not parallel to both X- and Y-axes in the machine coordinate system around the motion direction changing point of C-axis.

Figure 6 shows the displacement of each axis during this movement, and it can be observed that the motion direction of X- and Y-axis is not changed when the motion direction of C-axis changes.

Table 1 lists the cutting condition for the cutting test. The radius of the trajectory of the workpiece center can be altered to evaluate the influence of the motion errors of the rotary axis. The motion of C-axis is reciprocated at a 90° amplitude, and the translational axes (X- and Y-axis) follow the motion to sustain the circular path in the table coordinate system. The radius of the motion trajectory of the workpiece center r is set to 25 mm and 50 mm in this study. In addition, the influence of the feed rate is evaluated. Each spindle speed and feed rate is set to keep the feed per flutes constant.

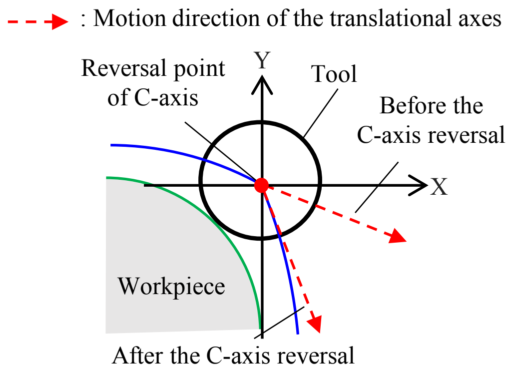


Fig. 5. Motion direction of the translational axes before and after the C-axis reversal.

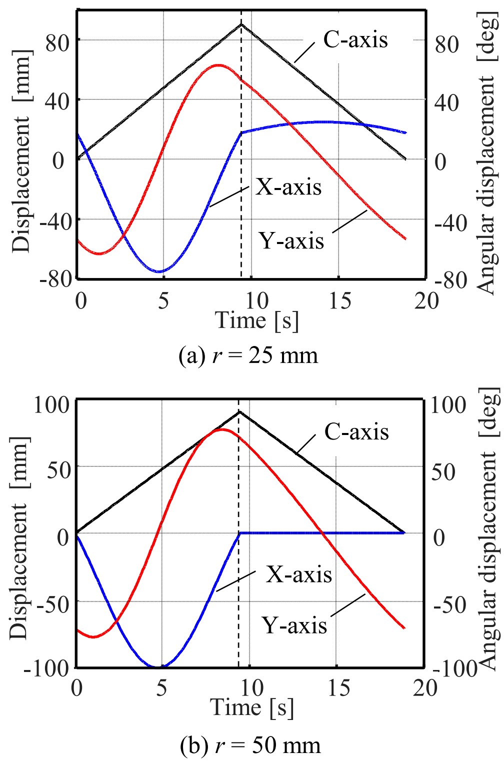


Fig. 6. Displacement of each axis.

Table 1. Cutting condition.

Tool shape	ϕ 12 square-end mill
Number of flute	2
Workpiece	Aluminum (A5052P)
Feed rate F	1000, 2000, 3000 mm/min
Spindle speed	12000, 24000, 36000 rpm
Feed per flutes	42 μm/tooth
Axial depth of cut	3 mm
Radial depth of cut	0.2 mm
Radius r	25, 50 mm

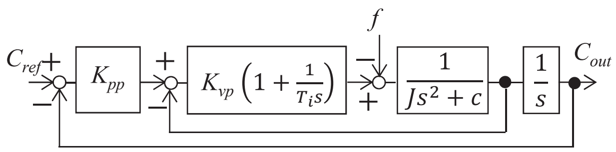


Fig. 7. Block diagram of C-axis.

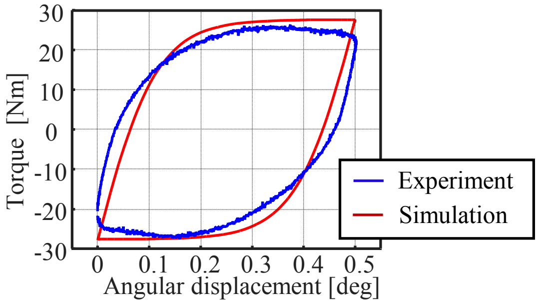


Fig. 8. Relationship between angular displacement and friction torque of C-axis.

4. Simulation Method

4.1. Feed Drive System Model

Axes of NC machine tools are actuated by feed drive systems. To investigate the influence of the dynamic behavior of the axes on the synchronous motion, in this study, translational and rotary axes motions are reproduced by a block diagram considering the feed drive mechanism as a single-inertia system [18, 19]. **Fig. 7** shows the block diagram of a C-axis feed drive system used for the simulations in this study. The frictional torque of the bearing in C-axis, f, is introduced into the block diagram.

Motion trajectory in the table coordinate system ${}^{T}\mathbf{X}_T$ can be obtained from the simulated displacement of the translational axes ${}^{M}\mathbf{X}_T$ and the angular displacement of C-axis C_{out} using Eq. (1).

$$ {}^{T}\mathbf{X}_T = \begin{bmatrix} \cos C_{\text{out}} & -\sin C_{\text{out}} & 0 \\ \sin C_{\text{out}} & \cos C_{\text{out}} & 0 \\ 0 & 0 & 1 \end{bmatrix} {}^{M}\mathbf{X}_T \quad . \ . \ . \quad (1) $$

4.2. Friction Model

It is known that the contouring accuracy of a synchronous motion is influenced by the friction force or torque. Generally, the friction characteristics change remarkably when the motion direction of each axis changes.

To investigate the friction characteristics during motion direction changes of C-axis, the motor torque and angular displacement of the table are measured under a sine wave motion with a long wavelength [20]. **Fig. 8** shows the measured and simulated results of the relationships between angular displacement and friction torque. Generally, the friction behaves as a nonlinear spring in small displacements. In this study, the nonlinear spring friction model, shown in Eq (2) [20], is adopted to model the friction characteristics.

$$ f = f_c \left(2\tanh\left(a \cdot |x'|\right) - 1\right) \operatorname{sgn}\left(dx'/dt\right) \quad . \ . \quad (2) $$

In this equation, f_c is the Coulomb's friction torque [N.m], x' is the table orientation from motion direction changing point [rad], and a is the inclination coefficient of the friction torque.

5. Measured and Simulated Results

5.1. Influence of Feed Rate

Figures 9, **10**, and **11** show the measured and simulated results of the proposed test in the work coordinate system. Figure (a) shows the results of the cutting test, while figure (b) demonstrates the results of the measurement test using a ball-bar, and figure (c) illustrates the simulated results. It is crucial to note that the radial error is enlarged in the figures. It can be seen from the figures that stepwise errors can be seen approximately at 180° (C-axis = 90°) of the trajectories. In particular, in the case of late feed F, the error is higher. The reason behind the previously mentioned errors is the decrease in the radius of the trajectory of the translational axes as the translational axes follow the inner course on the left side, shown in **Fig. 2**.

It is known that the rotational center of C-axis does not correspond to the nominal center. Hence, the origin of the table coordinate system used in the experiments is set to coincide with the actual rotational center of the C-axis; this is done to avoid the influence of the offset of the rotational center.

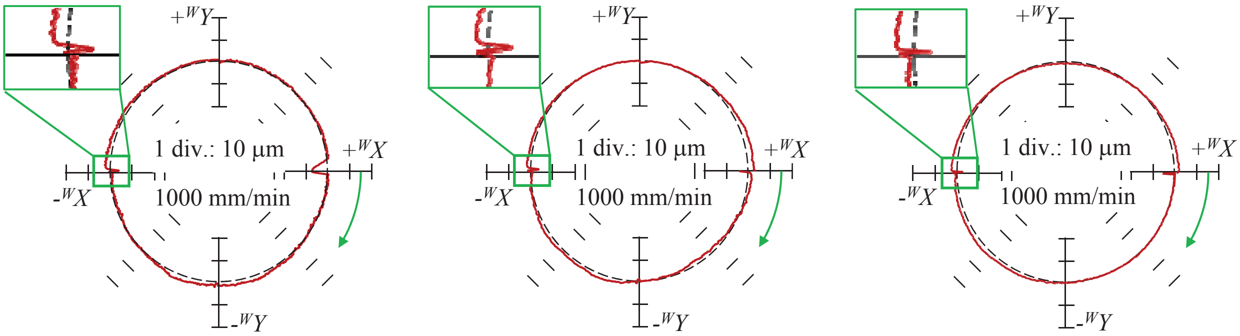
5.2. Influence of Workpiece Setting and Friction

Figures 12 and **13** show the results with different workpiece settings. The radius of the trajectory of the workpiece center r is set to 25 and 50 mm. A dent can be observed approximately at 180° of the trajectories, from the figures, when motion direction of C-axis changes. Furthermore, the error is directory proportional to the radius r. This fact indicates that the error is caused by the motion error of C-axis.

It can be seen from **Figs. 2(b)**, **3(b)**, and **6(b)** that the X-axis stops when the motion direction of C-axis changes in the case where r is 50 mm, even though the motion direction of X-axis does not change. However, it is confirmed that the velocity change in translational axes only influences the radius of the trajectories; it does not influence the spike like errors due to the motion direction changing of C-axis.

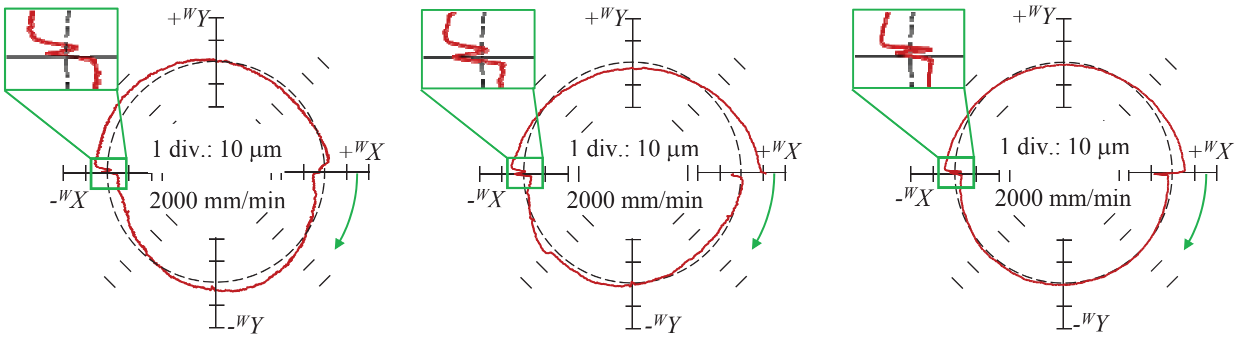
Figure 14 shows the simulated results of the motion. **Fig. 14(a)** shows the result without friction torque for C-axis, and **Fig. 14(b)** shows the result with friction. As the dent at approximately 180° cannot be observed in the case where friction is not introduced into the model, it is clear that the error is caused by the friction torque of C-axis.

As discussed above, the proposed evaluation method can evaluate the radial decrease of the translational axes



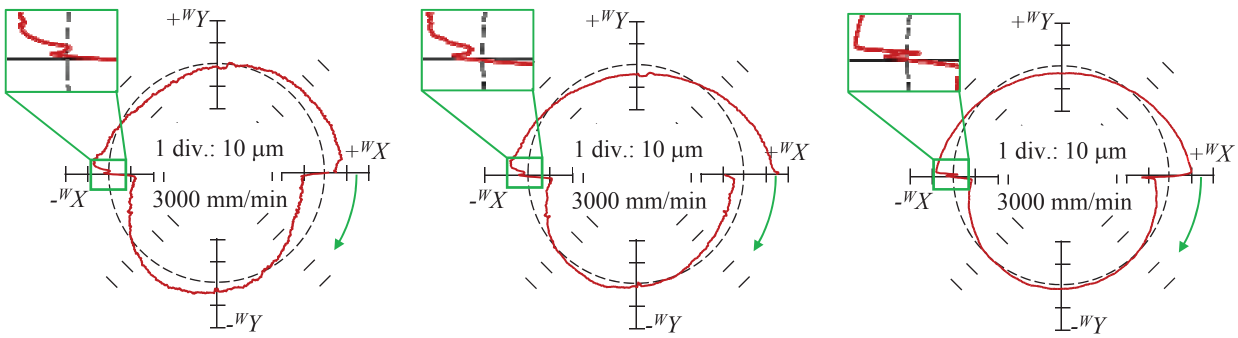
(a) Cutting test (b) Measurement test (c) Simulation

Fig. 9. Comparison of circular trajectories ($F = 1000$ mm/min, $r = 25$ mm).



(a) Cutting test (b) Measurement test (c) Simulation

Fig. 10. Comparison of circular trajectories ($F = 2000$ mm/min, $r = 25$ mm).



(a) Cutting test (b) Measurement test (c) Simulation

Fig. 11. Comparison of circular trajectories ($F = 3000$ mm/min, $r = 25$ mm).

and the behavior of rotary axes around motion direction change points. It is also confirmed that the behaviors can be accurately predicted by the proposed simulation method.

6. Conclusion

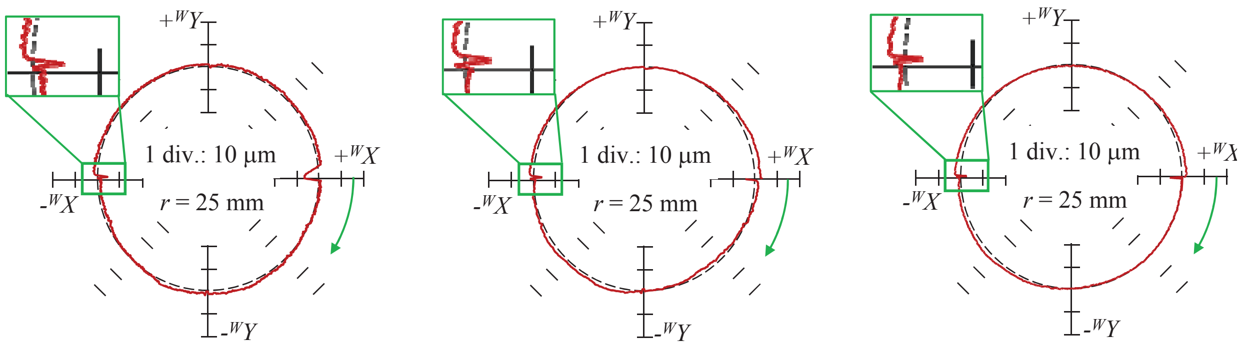
A synchronous motion of translational and rotary axes is proposed to evaluate the behavior of the rotary axes during motion direction change regardless of the influence of the translational axes. The conclusions can be summarized as follows:

1) The proposed evaluation method can evaluate the decrease in the radius of the translational axes and the behavior of the rotary axis around the motion direction change point.

2) Dents can occur when the motion direction changing point of C-axis is caused by the friction torque.

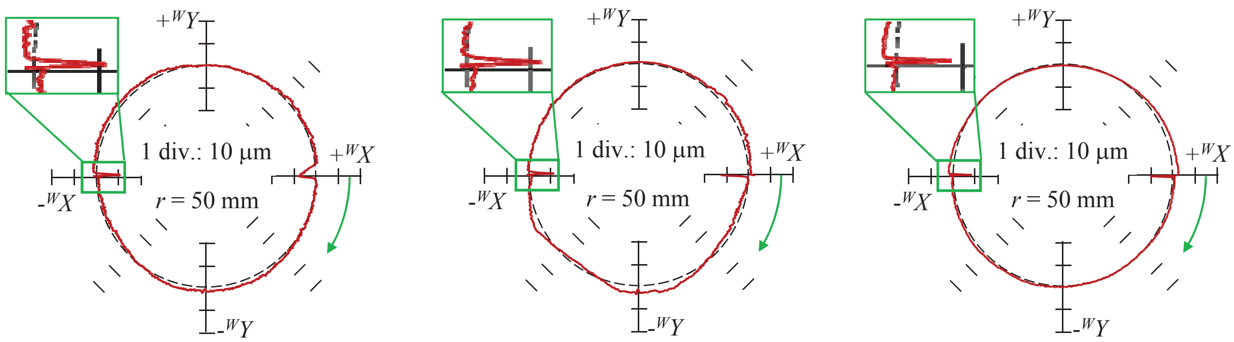
3) The behaviors can be accurately predicted by the proposed simulation method.

It is expected that the proposed evaluation method can be applied to the tuning of the friction compensator of the rotary axes.



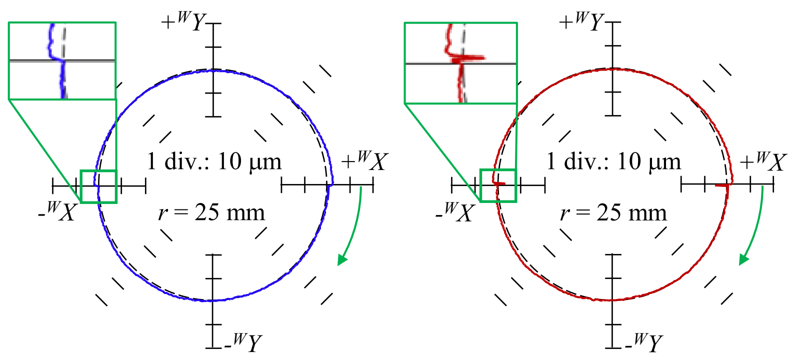
(a) Cutting test (b) Measurement test (c) Simulation

Fig. 12. Comparison of circular trajectories ($F = 1000$ mm/min, $r = 25$ mm).



(a) Cutting test (b) Measurement test (c) Simulation

Fig. 13. Influence of workpiece setting ($F = 1000$ mm/min, $r = 50$ mm).



(a) Without friction (b) With friction

Fig. 14. Influence of friction torque ($F = 1000$ mm/min, $r = 25$ mm, simulation).

Acknowledgements

The authors would like to sincerely acknowledge all support from the MTTRF (Machine Tool Technologies Research Foundation). This study is financially supported by JSPE KAKENHI (Grant-in Aid for Scientific Research (C)) Grant Number 15K05724 and MAZAK foundation.

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