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Paper:

Improvement of Simultaneous 5-Axis Controlled Machining Accuracy by CL-Data Modification

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As the motion accuracy of 5-axis machining centers directly influences the geometrical shape accuracy of the machined workpieces, accuracy enhancement of the 5-axis machining centers is strongly needed. To improve the shape accuracy during the machining by a 5-axis machine tool, a method that modifies the CL-data based on the motion trajectory errors normal to the machined surface at each command point has been proposed. In this study, the proposed method is applied to simultaneous 5-axis controlled machining to improve motion accuracy. A normal vector calculation method for the simultaneous 5-axis controlled motion is newly proposed, and the compensation method is applied to turbine blade machining by 5-axis controlled motion. Measurement tests of the cutting motion for blade shape machining by a ball-end mill were carried out with a different control mode of NC. The CL-data for the machining tool path was also modified based on the calculated trajectory of the tool center point. Experimental results reveal that the feed speed and machining accuracy significantly depend on the control mode of NC, and that the shape accuracy can be improved by applying the proposed compensation method without any decrease in motion speed.

Keywords: 5-axis machine tool, 5-axis controlled motion, CL-data, motion accuracy, compensation

1. Introduction

As the motion accuracies of numerical control (NC) machine tools influences the machined surface of the machined pieces, it is important to improve them. 5-axis machining centers, which can control both the relative position and angle between tool and workpiece, are now often used for the machining of complex shaped parts [1, 2]. It has been established that the motion accuracy of the 5-axis machining centers deteriorates owing to several error sources. For example, the rotary axes of the 5-axis machining centers have positional and angular errors of the rotational centers called geometrical errors [3]. As it is known that the geometrical errors deteriorate the geometrical accuracy of the machined parts, several studies have been carried out to identify and compensate for the errors [4]. A machining test for evaluating the geometric errors has also been proposed [5–7]. The geometrical errors can be compensated for in the latest 5-axis machining centers by using compensation functions.

The dynamic synchronous errors between the translational and rotary axes also need to be considered. The dynamic synchronous errors during the simultaneous multi-axis motions of the translational and rotary axes have been investigated [8, 9]. It was also confirmed that the dynamic synchronous errors during simultaneous 5-axis motion deteriorate the geometric accuracy of the machined shape [10]. To avoid the inaccuracy due to the dynamic synchronous errors, several studies have been carried out. One of the effective methods for improving the geometric accuracy is eliminating the servo delays of each axis by feed forward compensators [11]. Sato and Tsutsumi [12] successfully applied feed forward compensators for the synchronous motion of translational and rotary axes. Other researchers have applied cross-coupled controllers [13, 14], which can control the nominal component of the tracking errors [15].

Although this conventional method can effectively improve the motion accuracy, unfortunately, it is difficult to implement its control algorithms in commercial NCs because the NCs have to be replaced to implement new control algorithms.

Currently, the design velocity profile during the machining motion is used to avoid the dynamic synchronous errors due to rapid velocity changes [16, 17]. Velocity planning approaches based on the look-ahead interpolation approach are also generally implemented in commercial NCs [18–20]. However, they result in increases in machining time rather than improvements in accuracy. The relationship between the accuracy and actual feed rate of commercial NCs has been investigated [21, 22]. The machining time is an important factor in industry. Hence, correction methods of NC programs based on motion errors are proposed [23–25] as another approach to improve

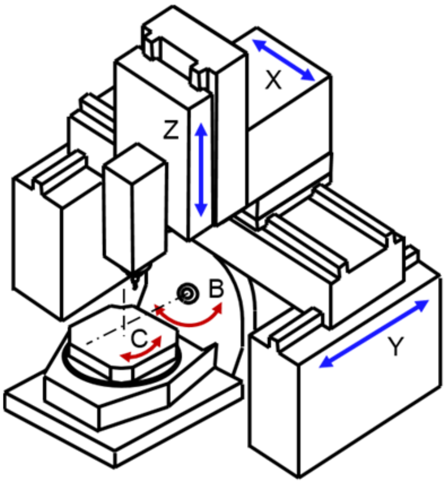


Fig. 1. Construction of a 5-axis machining center.

Table 1. Maximum feed speed of axes.

X-axis	50000 mm/min
Y-axis	45000 mm/min
Z-axis	40000 mm/min
B-axis	18000 deg/min
C-axis	54000 deg/min

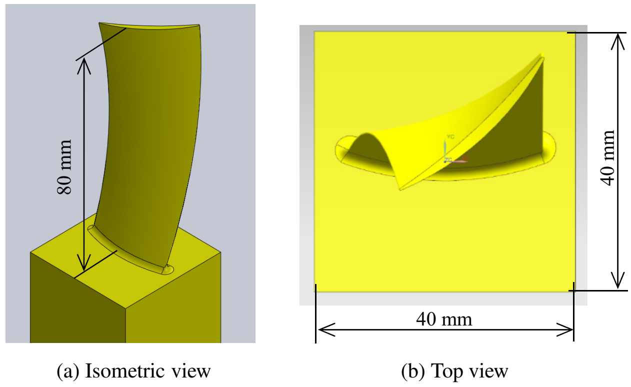


Fig. 2. 3D model of the twisted blade.

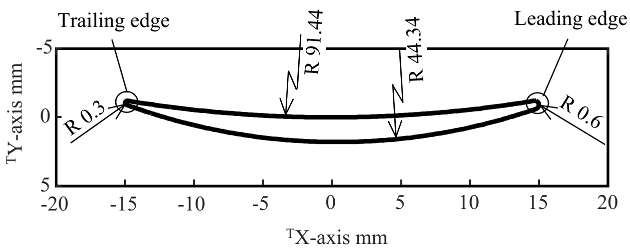


Fig. 3. Sectional profile of the blade.

the motion accuracy without machining time changes. However, to the best of our knowledge, no studies have successfully improved the dynamic synchronous accuracy of 5-axis machine tools by correcting the NC programs. The authors of this paper also clarified that conventional compensation methods cannot be applied to simultaneous multi-axis control machining with rotary axes, and a CL-data modification method based on the tool center point (TCP) trajectory is newly proposed [26]. It is confirmed that the proposed method can enhance the accuracy of the machined shape in simultaneous 3-axis machining motion with two translational and one rotary axes.

The goal of this study is to improve motion accuracy of machining by applying the proposed method [26] to simultaneous 5-axis controlled machining motion. To achieve this goal, twisted blade machining, which requires simultaneous 5-axis control motion, is performed, and the proposed method is applied to the machining motion. By comparing not only the machining accuracy but also machining time before and after the compensation, it is clarified that the proposed method can improve machining accuracy without affecting machining time.

2. Blade Shape Machining

2.1. 5-Axis Machining Center

A vertical type 5-axis machining center that has B- and C-axes on the table side as shown in **Fig. 1** was used in this study. Three translational axes are located on the spindle side. The translational axes are driven by AC servo motors and ball screws, and two rotary axes are driven by direct drive (DD) motors. It is confirmed that the machining center has sufficiently high geometric accuracies. **Table 1** shows the maximum feed speeds of the axes. The positional and angular commands and feedback signals of each axis during the machining process can be acquired by using a servo monitoring software (FANUC servo guide) provided by the manufacturer of the CNC.

2.2. Blade Shape

Twisted blade shape machining motion tests were carried out in this study to investigate the influence of dynamic synchronous errors. **Fig. 2** shows the 3D CAD model of the blade shape, and **Fig. 3** shows the cross-sectional shape of the blade. The cross-sectional shape of the blade does not depend on the cross-sectional position of the blade. To machine the twisted shape of the blade, a complicated simultaneous 5-axis machining motion is required. It is also expected that rapid speed changes are required as the radii of leading and trailing edges are small.

2.3. Machining Method

Figure 4 describes the machining method for the blade. The tool path is designed to machine the blade spirally from the top to the bottom end of the blade by a ball-end mill with a diameter of $\phi 6$. The radial depth of the cut is 0.1 mm. Commanded points are specified on the surface with a 0.05 mm interval along the feed direction. The feed rate, which means the relative velocity between the tool functional point and the workpiece surface, is set

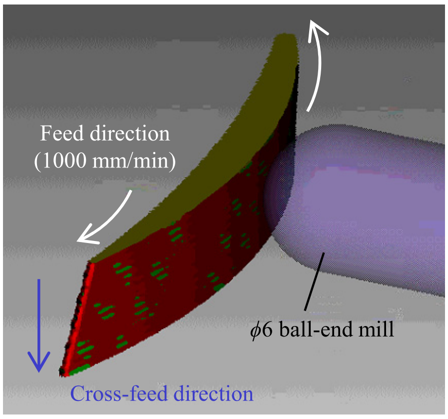


Fig. 4. Twisted blade machining method.

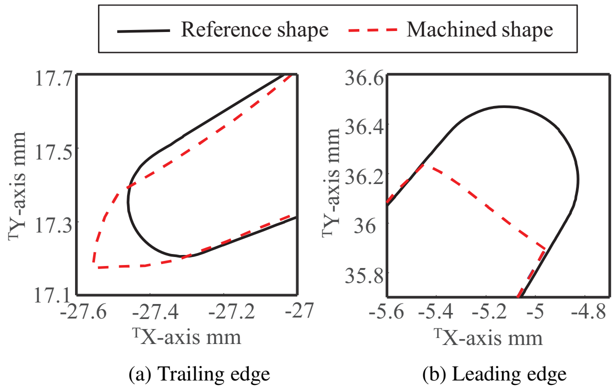


Fig. 5. Comparison of machined shape around the edges (without high precision control function).

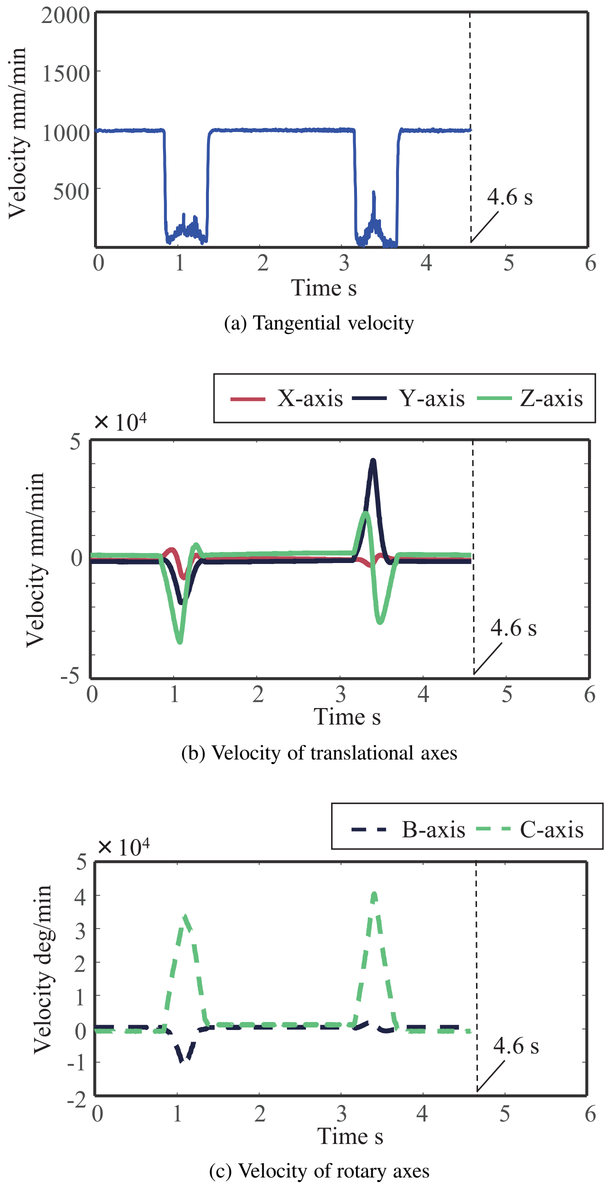


Fig. 6. Velocity profile during a cycle of machining motion (without high precision control function).

to 1000 mm/min. The lead and tilt angles are set to 0° so that the tool top point can be used as the functional point.

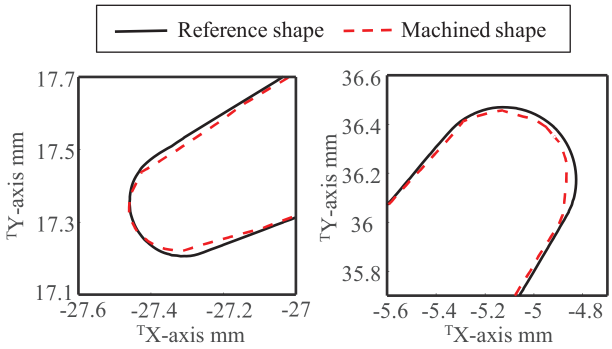
The influence of the high precision control mode function, which is implemented in the NC controller, on the machining accuracy and machining time is investigated. A high precision control mode could be activated by an NC code (in the NC program for FANUC control system, "G05 P10000" activates the high precision control mode). The TCP control mode, which can control the position and angle in the table coordinate system, was also applied in this study.

3. Machined Shape Without the Proposed Compensation Method

Position and angle feedback data in the area between 4 mm and 6 mm from the top end of the blade is acquired during the motion test. The motion trajectory of the tool in the table coordinate system is obtained based on the acquired data, and the cross-sectional shape of the machined shape at 5 mm from the top end of the blade is simulated by using a cutting simulator (VERICUT, CGTech Co., Ltd.).

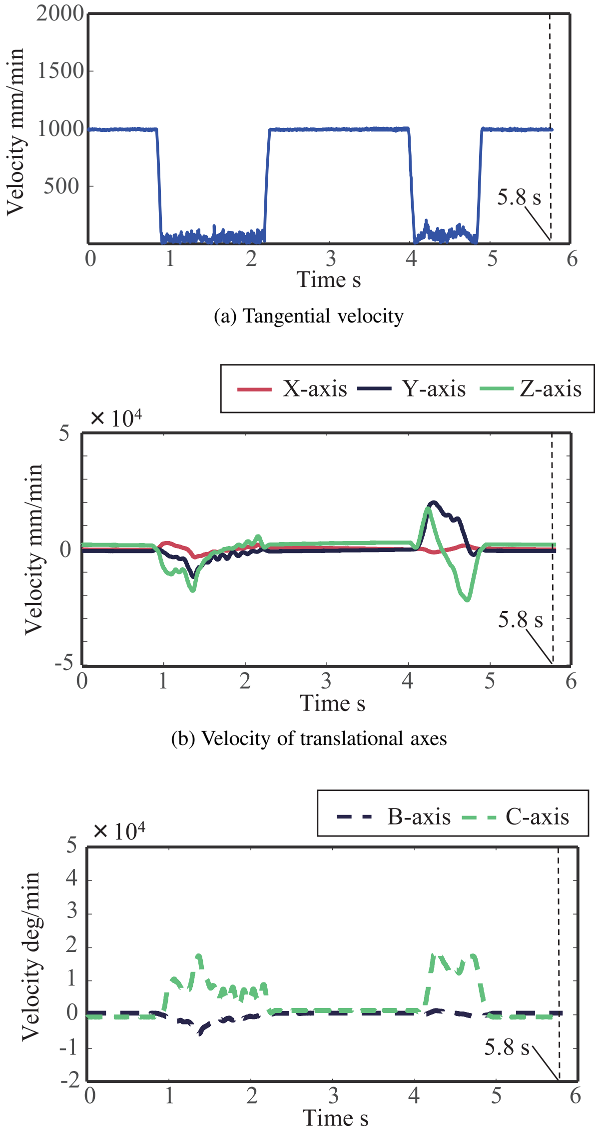
Figure 5 shows the simulated machined shape around the edges that was obtained without the high precision control function. Large shape errors can be observed around the edges. **Fig. 6** shows the velocity changes during the machining motion. **Fig. 6(a)** shows the tangential velocity of the tool top point along the feed direction, and **Figs. 6(b)** and **(c)** show the velocities in each axis. It can be seen from **Fig. 6** that the velocity of the C-axis and the Y- and Z-axes become quite high around 1 and 3.5 s, where each edge is being machined. On the other hand, the tangential velocity becomes much smaller than the commanded velocity (1000 mm/min) around both edges because the acceleration of the axes reaches the maximum acceleration of the machine. This velocity change causes the large shape errors around the edges. The cycle machining time is 4.6 s in this case.

Figure 7 shows the simulated machined shape around



(a) Trailing edge (b) Leading edge

Fig. 7. Comparison of machined shape around the edges (with high precision control function).



(a) Tangential velocity

(b) Velocity of translational axes

(c) Velocity of rotary axes

Fig. 8. Velocity profile during a cycle of machining motion (with high precision control function).

the edges that was obtained with the high precision control function. It is clear that the high precision control function can considerably improve the shape accuracy around the edges. **Fig. 8** shows the velocity changes during the machining motion with the high precision control function. As can be seen from **Fig. 8**, the velocity around the edges becomes smaller than that in the case where the high precision control function is not applied. The velocity limitation can improve the motion accuracy, as can be seen in **Figs. 7** and **8**. However, the cycle machining time becomes 5.8 s, which is 1.2 s longer than that in the case in which the high precision control function is not applied. This is because the feed rate limit is maintained by the high precision control mode to avoid the occurrence of the large tracking errors.

It can be clarified from the results that the conventional high precision control function can considerably improve the motion accuracy by limiting the velocity; on the other hand, as a result, the cycle machining time increases.

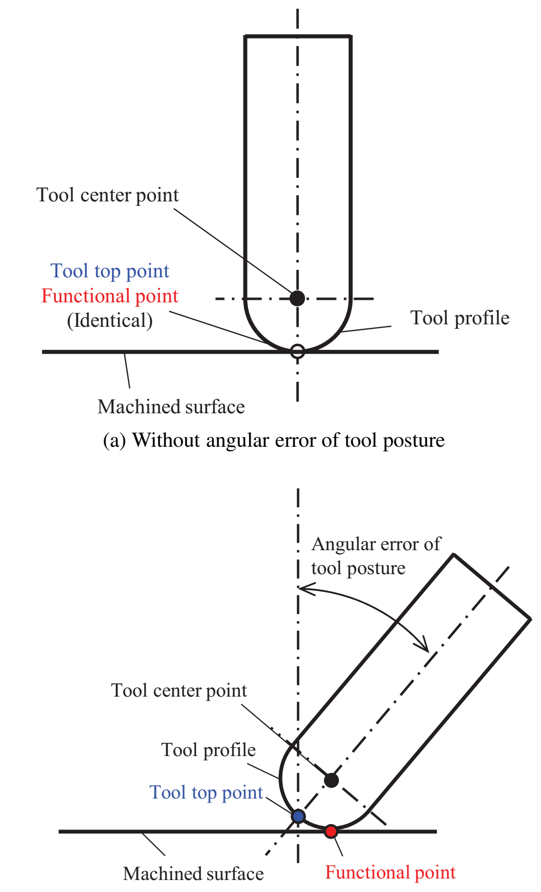
4. Compensation Method

Several CL-data modification methods based on the machined shape have been proposed [24, 25]. It is known that the conventional method can effectively improve the machined accuracy in 3-axis controlled machining without rotary axes control. In 5-axis machining, however, both the relative position and angle are influenced by the dynamic behavior of the feed drive systems.

Figure 9 illustrates the relationship between the tool and workpiece surface with a definition of each point of the tool. In cases where the tilt and lead angles are zero, the functional point and the tool top point are identical as shown in **Fig. 9(a)**. In the 5-axis machining motion with rotary axes control, however, the motion of the feed drive systems influences both the TCP position and tool posture. If the tool orientation error exists, the functional point does not align with the tool's top point as shown in **Fig. 9(b)**. This means that the machined shape by 5-axis machining does not represent the motion trajectory of the tool directly. The TCP trajectories need to be obtained to determine the motion trajectories.

From this point of view, a CL-data modification method based on the TCP trajectory is newly proposed in [26]. **Fig. 10(a)** shows the flow chart of the proposed modification method. In this method, the TCP trajectory is obtained from the acquired feedback positions and angles of each axis during the machining motion, and the normal direction errors between the obtained TCP trajectory and ideal TCP trajectory are calculated. The CL-data can be modified based on the calculated normal direction errors. The TCP trajectory is not influenced by the angle error of the tool posture.

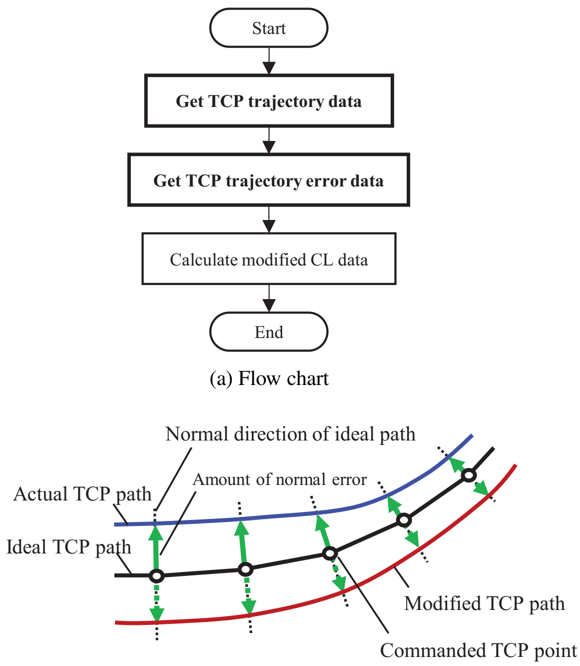
The modification method shown in **Fig. 10** [26] was applied without any problem for the machining of a blade shape without twisting. However, for the machining of a twisted blade shape by simultaneous 5-axis motion, the normal direction of the machined surface was not constant



(a) Without angular error of tool posture

(b) With angular error of tool posture

Fig. 9. Influence of angular error on the functional point.



(a) Flow chart

(b) CL-data modification based on TCP path

Fig. 10. CL-data modification method [26].

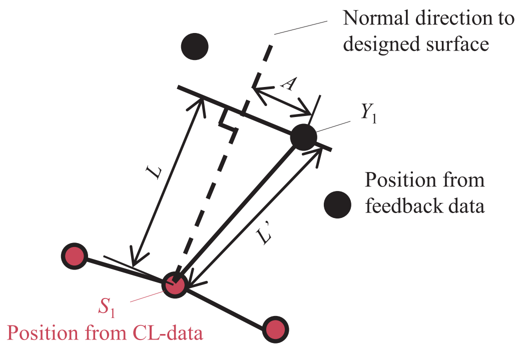
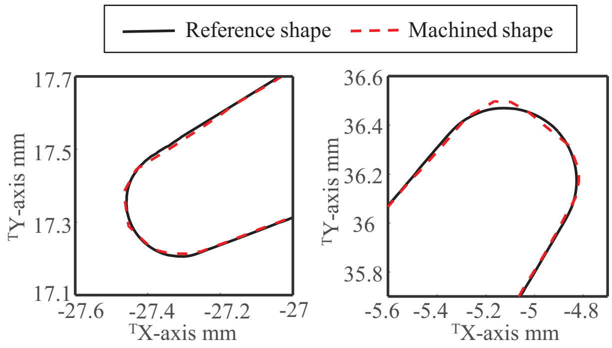


Fig. 11. Calculation method for normal error.



(a) Trailing edge (b) Leading edge

Fig. 12. Comparison of machined shape around the edges (with modified CL-data).

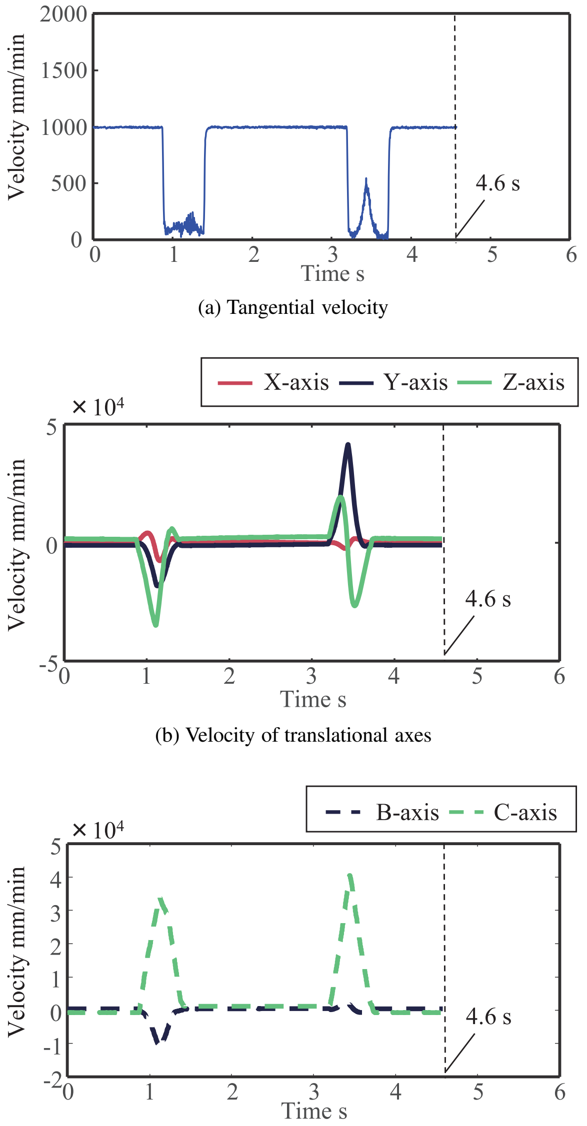
as the motion trajectory is three-dimensional. In that case, the normal direction lines from each command point and the motion trajectory do not intersect each other typically. Thus, it is impossible to calculate the normal direction error.

In this study, therefore, the approximated normal error is applied as the normal direction error of the 3D shape machining motion. **Fig. 11** shows the schematic of the approximation method. First, a point obtained from positional and angular feedback data Y_1, which is the nearest point from the reference point defined in CL-data S_1, is found. As the CL-data point S_1 has both the position and orientation information of the tool, the normal direction to the designed workpiece surface can easily be obtained.

From the coordinates Y_1 and S_1, the distance between the points L can be calculated. The approximated normal directional error L' can be obtained as the projection of L onto the normal direction to the surface as shown in **Fig. 11**.

5. Machined Shape Obtained with the Proposed Compensation Method

The proposed compensation method is applied based on the positional feedback data obtained without using the high precision control function. The CL-data is modified through the steps mentioned above. **Fig. 12** shows the

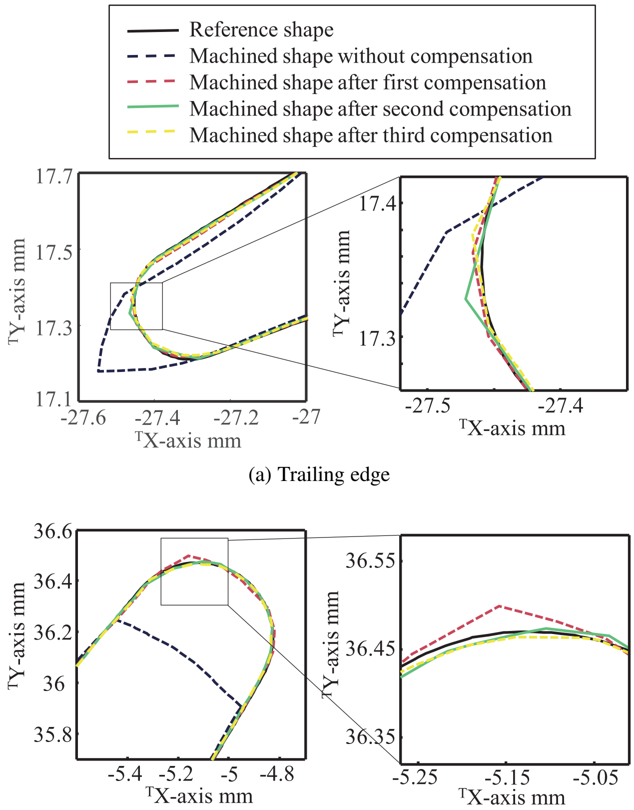


(a) Tangential velocity

(b) Velocity of translational axes

(c) Velocity of rotary axes

Fig. 13. Velocity profile during a cycle of machining motion (with modified CL-data).



(a) Trailing edge

(b) Leading edge

Fig. 14. Effect of the repetitive compensation.

simulated machined shape with the proposed compensation method. It is clear from **Fig. 12** that the accuracy of the machined shape is significantly improved by the proposed compensation method. **Fig. 13** shows the velocity changes during a cycle of the machining motion. **Fig. 13(a)** shows the tangential velocity of the tool top point along the feed direction, and **Figs. 13(b)** and **(c)** show the velocities in each axis. Through a comparison with **Fig. 6**, it can be seen that the proposed compensation method does not affect the machining time.

As shown in **Fig. 12**, however, small shape errors can still be observed. Therefore, we verified whether this error can be reduced by applying the repetitive approach of the compensation method. **Fig. 14** shows the result of the repetitive compensation, confirming that the accuracy of the machined shape can further be improved by applying the repetitive approach of the compensation method, especially on the leading edge shape shown in **Fig. 14(b)**. However, the accuracy is not further improved by the second and third repetitive compensations. In addition, the accuracy of the trailing edge is not improved by the repetitive approach as shown in **Fig. 14(a)**. The reasons for the error observed on the leading edge after the first compensation and the effect of multiple repetitive compensations have not been clarified yet, although it is expected that the approximated evaluation of the normal error vector as shown in **Fig. 11** affects the compensation accuracy.

6. Actual Machining Test

In order to confirm the effectiveness of the proposed method in real machining processes, actual machining tests were carried out under three conditions: 1) without either the high precision control function or the proposed compensation method, 2) with the high precision control function only, and 3) with the proposed compensation method only. The cutting conditions for the tests are listed in **Table 2**. In the real machining process, the lead angle is set to 10° to avoid machining by the tool top, which has zero cutting velocity. It is clear that the motion of each axis does not change owing to the lead angles although the initial angles and positions are changed. **Fig. 15** shows the entire view of the machined workpiece. Both the edges of each workpiece are observed with a digital micro scope.

Table 2. Cutting condition.

Workpiece material	A7075 aluminum alloy
Tool	$\phi 6$, ball-end mill
Cutting direction	Up-cutting
Radial depth of cut	0.2 mm
Spindle speed	6000 rpm
Feed rate	1000 mm/min
Lead and tilt angles	10° and 0°

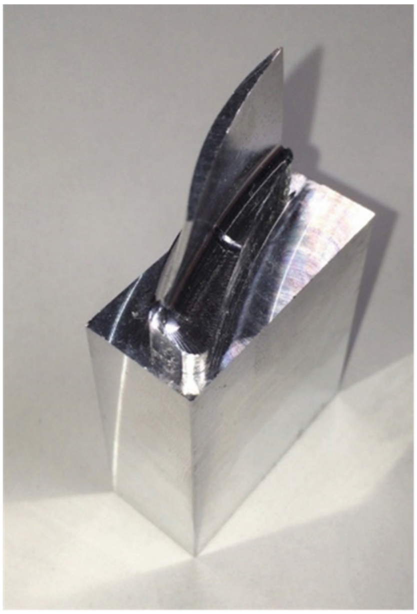
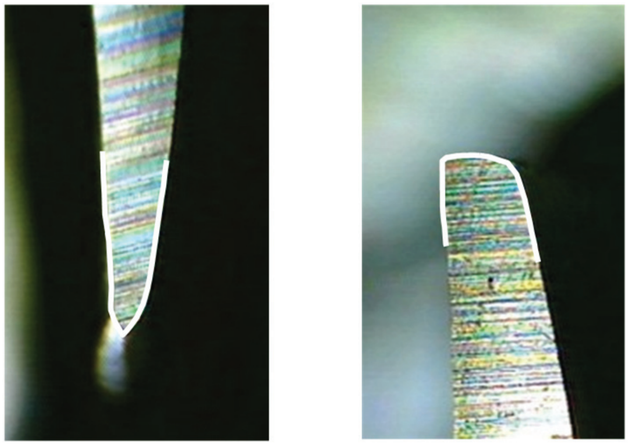


Fig. 15. Machined workpiece.

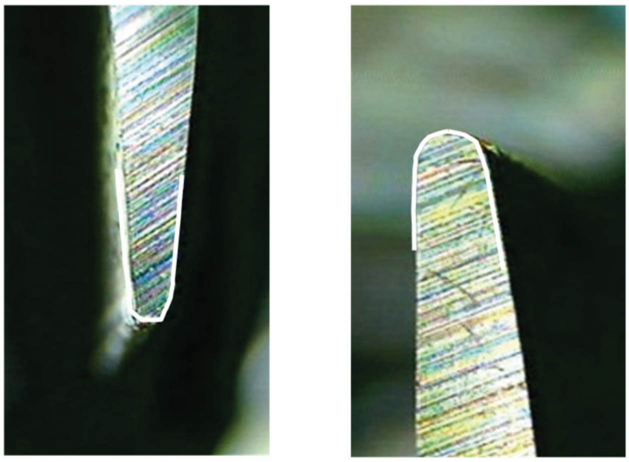
Figures 16–18 show the enlarged views of the trailing and leading edges. It can be seen from **Figs. 16–18** that the geometrical shape of the edges deteriorate when both the high precision control function and proposed compensation method are not applied. On the other hand, the geometrical shapes around the edges do not deteriorate in cases with the high precision control function or with the proposed compensation method. However, note that the machining time is not changed by applying the proposed compensation method, whereas the machining time increases when the high precision control function is applied.

The comparison of accuracy and machining time with and without compensation is summarized in **Table 3**. As mentioned above, the geometrical shape accuracy of the machined workpiece can significantly be improved by applying the proposed compensation method. The accuracy is identical to that achieved with the high precision control function that was implemented in the NC controller, especially with the repetitive approach of the proposed method. In addition, the machining time is not affected by the proposed method, whereas the high precision control function increases the machining time.



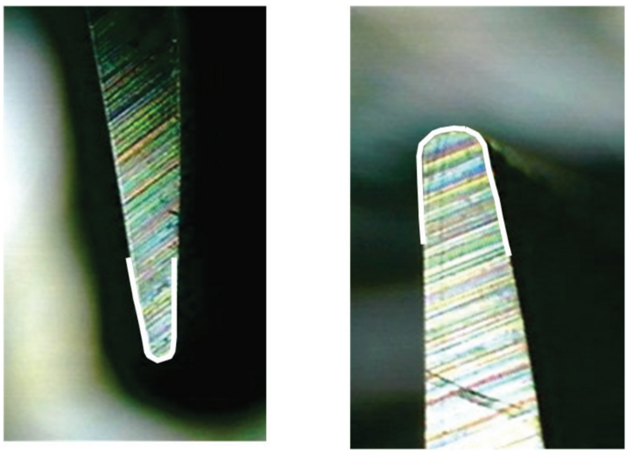
(a) Trailing edge (b) Leading edge

Fig. 16. Comparison of the machined edges (without high precision control function).



(a) Trailing edge (b) Leading edge

Fig. 17. Comparison of the machined edges (with high precision control function).



(a) Trailing edge (b) Leading edge

Fig. 18. Comparison of the machined edges (with modified CL-data).

Table 3. Comparison of accuracy and machining time.

	Accuracy	Time
High precision control function: OFF CL-data modification: OFF	×	4.6 s
High precision control function: ON CL-data modification: OFF	○	5.8 s
High precision control function: OFF CL-data modification: ON	○	4.6 s

7. Conclusions

In this study, a CL-data modification method based on TCP trajectory was applied to simultaneous 5-axis controlled machining motion. A twisted blade machining process that requires simultaneous 5-axis control motion was performed to evaluate the CL-data modification. By comparing not only machining accuracy but also machining time before and after compensation, the following conclusions can be drawn.

1) The geometrical shape accuracy of the machined workpiece can significantly be improved by applying the proposed compensation method.

2) The accuracy is identical to that obtained with the high precision control function that was implemented in the NC controller.

3) The machining time is not affected by the proposed method, whereas the high precision control function increases the machining time.

It is expected that the proposed CL-data modification method can be an effective tool for improving both the machining accuracy and productivity of 5-axis machining processes. The authors will also attempt to apply the proposed method to other types of machine tools and workpieces.

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• "Finished Surface Simulation Method to Predicting the Effects of Machine Tool Motion Errors," Int. J. Automation Technol., Vol.6, No.8, pp. 801-810, 2015.
• "Influence of Motion Error of Feed Drive Systems on Machined Surface," J. of Advanced Mechanical Design Systems and Manufacturing, Vol.6, No.6, pp. 762-767, 2012.
• "Generation Mechanism of Quadrant Glitches and Its Compensation of Feed Drive Systems for NC Machine Tools," Int. J. Automation Technol., Vol.6, No.2, pp. 154-162, 2012.

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• "Voxel Based End-Milling Simulation Considering Elastic Deflection of Tool System," J. of the Japan Society for Precision Engineering, Vol.84, No.6, pp. 572-577, 2018.
• "Automatic process planning system for end-milling operation considering CAM operator's intention," Trans. of the JSME, Vol.84, No.860, 17-00563, doi: 10.1299/transjsme.17-00563, 2018 (in Japanese).

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• T. Kobayashi, T. Hirooka, A. Hakotani, R. Sato, and K. Shirase, "Tool Motion Control Referring to Voxel Information of Removal Volume Voxel Model to Achieve Autonomous Milling Operation," Int. J. Automation Technol., Vol.8, No.6, pp. 792-800, 2014.
• M. M. Isnaini, Y. Shinoki, R. Sato, and K. Shirase, "Development of CAD-CAM Interaction System to Generate Flexible Machining Process Plan," Int. J. Automation Technol., Vol.9, No.2, pp. 104-114, 2015.
• K. Shirase, "CAM-CNC integration for innovative intelligent machine tool," Proc. of the 8th Int. Conf. on Leading Edge Manufacturing in 21st Century (LEM21), A01, 2015.
• I. Nishida, R. Okumura, R. Sato, and K. Shirase, "Cutting Force Simulation in Minute Time Resolution for Ball End Milling Under Various Tool Posture," ASME J. of Manufacturing Science and Engineering, Vol.140, No.2, 021009, doi: 10.1115/1.4037427, 2018.

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