Using Power Spectral Density Analysis of Accelerometer-Measured Signals to Adjust CNC Machine Tool Cornering Motion Control Parameters

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Abstract—**The dominant frequency peak value (PV) of the power spectral density of accelerometer-measured signals is used to discuss the computer numerical control (CNC) machine tool controller cornering motion control parameters, and then a systematic parameter adjustment procedure is designed to balance the cornering error and cornering speed of the machine tool cornering motions. Because the dominant frequency PV of the power spectral density distribution of the accelerometer-measured signals changes owing to the acceleration and deceleration status of the machine tool cornering motion, this study uses the dominant frequency PV as a reference indicator to adjust and design the control parameters. The Taguchi method and analysis of variance are employed to determine the effects of the control parameters on the machine tool cornering motions, and then power spectral density analysis is used to build the mathematical model of the control parameters for designing the best-fitted control parameters. A CNC machine tool is applied to validate the feasibility of the proposed design and the adjustment method for the control parameters. The results show that the difference in the cornering error of the test path is 7%, and the difference in the motion time is 43%; thus, the control parameter setting values can be used to balance the cornering accuracy and cornering speed of the test path.**

Index Terms—**Power spectral density, cornering motion, accelerometer, CNC machine tools**

I. INTRODUCTION

UPGRADING the workpiece machining quality and reducing the machining time are the goals of the computer numerical control (CNC) machine tool, which can be attained with a small cornering error and high cornering speed when the machine tool performs cornering motions [1]. However, the small cornering error is closely bound to the high cornering speed. Generally, if the machine tool can perform high-speed cornering motion, the cornering error in performing the cornering motion is increased [2, 3]. Therefore, designing cornering motion control methods or adjusting the cornering motion-related control parameters is important for developing the machine tool CNC controller.

Owing to the importance of the machine tool cornering motion, several experts and scholars have been devoted to related research in recent years. The methods for handling related problems include machine tool axial motion control design, cornering path modification and planning, acceleration and deceleration (ACC/DEC) control, and feedrate planning. Machine tool axial motion control design is the servomechanism control system design method for analyzing the axial feed motion of a machine tool in order to improve the contouring and tracking errors in the cornering motion of the machine tool [4, 5]. Rahaman et al. [6] compared the machining accuracy provided by different motion control systems, such as cross-coupled control, zero phase error tracking control, and real-time frequency-modulated interpolation through the use of circular and corner interpolations. Sencer et al. [7] proposed a real-time trajectory generation algorithm with finite impulse response filters to smooth discontinuous axial velocity commands at the junctions of sharp corners, in order to achieve high-speed and high-precision cornering motions of CNC machine tools.

Cornering path modification and planning involve planning or modifying the adjacent linear paths connecting the corner to the arc corner [8–11] or spline corner [12–18]. The smooth cornering motion of an arc corner or spline corner can reduce the cornering error when the machine tool performs cornering motions, reducing the cornering time. For example, owing to improper accelerations and decelerations around tiny corners, additional motion time and inaccurate cornering velocity computations usually degrade the accuracy and time of the cornering motions of CNC machine tools. Therefore, Chen et al. [8] proposed the unit arc length increment scanning method to improve the cornering efficiency by considering chord errors, axial accelerations, and cornering velocity limitations. To improve the cornering efficiency, Zarifmansour and Seethaler [9] proposed a feedrate and trajectory optimization algorithm that uses circular movement at each corner to regenerate the trajectory of the given tool path. Then, a feedrate optimization method with acceleration constraints was developed to maximize the cornering velocity of each corner. Sencer et al. [15] proposed a corner smoothing algorithm that considers the axial acceleration limits and uses quintic B-splines to blend the adjacent straight lines of a corner path, so that the CNC machine tool can move with

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smooth and continuous cornering motions; moreover, both the cornering accuracy and time can be improved through a proper scheduled feedrate profile.

ACC/DEC control and feedrate planning aim at the process of performing cornering motions using a machine tool and refer to the limit value of the cornering error and the maximum values of the machine tool motion feedrate, acceleration, and jerk. An appropriate cornering speed and acceleration are designed so that the machine tool can rapidly perform cornering motions and limit the cornering errors within the relevant range. Tajima and Sencer [3] proposed a corner smoothing technique to generate continuous feed motions of a CNC machine tool through the planning of jerk limited velocity transitions; moreover, the proposed approach accurately calculates the cornering speed and duration around sharp corners and therefore can limit cornering errors within certain ranges. Short segmented linear tool paths usually exist in part programs for machining free-form surfaces in dies, molds, and automotive and aerospace parts; however, the improper ACC/DEC and cornering velocity around corners usually degrade the machining accuracy and efficiency. Therefore, Tajima and Sencer [19] proposed an interpolation algorithm to generate rapid and continuous feed motions along short segmented linear tool paths by blending axial velocities with limited jerk and acceleration profiles. To achieve both high-efficiency and high-quality machining results, Zhang et al. [20] considered the axial acceleration limits, which could be significantly different in conventional machine tools, and then proposed a local corner transition algorithm and a global motion planning strategy to generate the transition trajectory for G01-code composed linear tool paths with a tangent discontinuity.

While numerous techniques regarding machine tool cornering motions have been continuously proposed in recent years, there tend to be many limits to the commercialized machine tool CNC controller: the control system structure of the CNC controller and the axial feed drive servomechanism motion control system are sometimes established and unchangeable [21, 22]. A part program with a cornering path is usually generated by computer-aided design/manufacturing software or by the manual input of the machine tool operator; thus, modifying the cornering path may place a burden on the part programmer. ACC/DEC control and feedrate planning mainly refer to the motion path of the machine tool and the CNC controller cornering motion command generation. As the design result disregards the dynamic characteristics of the machine tool, it may fail to reflect the cornering motion performance of the machine tool [23, 24]. Owing to the importance of the ACC/DEC characteristics in interpolation for high-speed CNC machining, Chang and Yeh [25] considered the situation where the ACC/DEC period spans multiple numerical control (NC) blocks and developed an interpolation method with kinematic constraints to generate positional motion commands so that the cutting tool can smoothly move along the piecewise-continuous machining segments in an ACC/DEC period in order to reduce the machining time, maintain the machining quality, and increase the tool lifetime.

To satisfy the requirements of the manufacturing industry for upgrading the workpiece machining quality and reducing the machining time, the CNC machine tool controller develops adjustable cornering path control parameters [26] for achieving a high speed and high accuracy. This study refers to the FANUC controller (CNC controller), where the main control parameters influencing the machine tool cornering motion include the maximum allowable acceleration rate in ACC/DEC before interpolation for each axis (MAAR), the acceleration change time of the bell-shaped ACC/DEC before interpolation (ACT), the maximum allowable feedrate difference for feedrate determination based on the corner feedrate difference (MAFD), and the maximum allowable acceleration rate for the deceleration function based on the acceleration in artificial intelligence contour control for each axis (AIC). Thus, the control parameters are adjusted appropriately for small cornering errors and high cornering speeds [26]. However, the adjustment of these control parameters usually causes problems for the operator of the machine tool CNC controller, even when a description of the operational manual of the CNC controller is provided for reference, as the adjustment of the control parameters depends on trial and error. While there is tuning software (e.g., the Servo Guide of Fanuc [27]) for online control-parameter adjustment, time-consuming trial and error is still required. Therefore, the appropriate adjustment or design of the cornering motion control parameters is an important issue for machine tool CNC controller parameter adjustment. Generally, control-parameter adjustment requires experienced operators for obtaining excellent adjustment results; thus, a method to rapidly and precisely adjust the control parameters will be a great contribution to the application of the CNC machine tool. However, as there are very limited studies regarding the use of the cornering motion performance of a machine tool for the adjustment of the cornering path control parameters, the control-parameter adjustment method is still employed to observe the cornering motion results of the machine tool, which involves time-consuming trial and error according to the adjustment results.

For referring to the actual cornering motion performance of a machine tool as the basis for the adjustment of the cornering motion control parameters, it is necessary to use appropriate sensing devices to measure the cornering motion of the machine tool. Using the position feedback signals of a servomotor encoder as the parameter adjustment criteria for control parameters depends on the machine tool CNC controller providing real-time position feedback signals, because an overlong signal sampling time sometimes fails to truly reflect the cornering motion performance of the machine tool. Although linear encoders and grid encoders can measure the actual motion performance of the machine tool, they are difficult to install and expensive [28]. As the cornering motion control parameters can affect the ACC/DEC characteristics of a machine tool during cornering motions, an accelerometer can be used for sensing the cornering motion of the machine tool; this method is significantly cheaper than linear and grid encoders, and it is easily applied to various machine tools [29]. However, when the accelerometer is used for sensing the ACC/DEC of machine tool motion, two integral calculations are required for obtaining the position signals of the actual motion of the machine tool from the accelerometer-measured signals and to calculate the cornering error, which is likely to cause the machine tool to have cumulative position errors due to measurement noise, which influences the calculation results of the cornering error. Sato and Nagaoka [29] proposed a cumulative error compensation method for the referenced position feedback signal. This method is limited to the sampling time for the position feedback signals of the machine tool CNC controller, and its calculation accuracy depends on the two integral periods of the accelerometer-measured signals. Therefore, this study analyzes the power spectral density distribution of accelerometer-measured signals and directly refers to the dominant frequency peak value (PV) of the power spectral density distribution as the machine tool CNC controller for controlling cornering motions, in order to adjust the reference indicators of the cornering error and cornering speed.

When the micro-vibration signals of a stationary machine tool are filtered out, the dominant frequency PV of the power spectral density distribution of accelerometer-measured signals changes owing to the ACC/DEC status of the machine tool when a cornering motion is performed. When the acceleration of the cornering motion performed by a machine tool is high, the dominant frequency PV of the power spectral density of the acceleration signal increases. Therefore, for achieving a small cornering error and high cornering speed, the dominant frequency PV of the power spectral density of the acceleration signal can be used as a reference frame. The high dominant frequency PV of the power spectral density of an acceleration signal indicates that the machine tool performs cornering motions with high ACC/DEC; thus, while the cornering speed can be increased to reduce the cornering motion time, this increases the cornering error. Therefore, to reduce the cornering error when the machine tool performs cornering motions, the cornering ACC/DEC control parameters must be adjusted. Thus, while the dominant frequency of the power spectral density of the acceleration signal has a lower PV, the cornering motion time is increased. The Taguchi method has been extensively used to achieve the optimal setting and adjustment of mechanical system control parameters [30]; thus, in this study, the Taguchi method and analysis of variance (ANOVA) are employed to analyze the effect of the cornering ACC/DEC control parameters on the dominant frequency PV of an acceleration signal when the machine tool performs cornering motions. As the MAAR value has a more significant effect than the other control parameter values, the MAAR model is built by using the MAAR values for the ACT and MAFD, while the fuzzy-logic modeling method is used to create the ACT/MAFD model and obtain the best-fitted parameter values. As the AIC control parameter uses artificial intelligence contouring control to analyze the corner variations of all the motion paths of the machine tool, the values of the cornering acceleration, deceleration, and speed can be automatically adjusted [26]. Finally, the AIC control parameters are used to balance the small cornering errors (high-accuracy machining requirement) and high cornering speed (high-speed machining requirement).

This paper is organized as follows. Section II describes the experimental and measurement equipment used in the study and presents the four CNC controller cornering ACC/DEC control parameters to be adjusted: MAAR, ACT, MAFD, and AIC. Section III describes the analysis, selection, and adjustment methods for the proposed ACC/DEC control parameters. The Taguchi method is used to analyze the influence of the control parameters, and fuzzy-logic rules are employed for the creation of a control parameter model and for the selection and adjustment of the control parameters. Section IV describes the parameter adjustment experiments and presents the results and discussion, validating the feasibility of the proposed adjustment method for the cornering ACC/DEC control parameters. Section V concludes the paper.

II. INTRODUCTION TO EXPERIMENTAL EQUIPMENT AND ADJUSTMENT OF CONTROL PARAMETERS

This section introduces the machine tool and measuring equipment used in the study. The machine tool is a CNC milling machine, and a fixture is used for installing the accelerometer and measuring the motion performance of the machine tool. The data-acquisition (DAQ) component transmits measurement signals to a computer to perform signal analysis for control-parameter adjustment. As shown in Fig. 1, the work volume of the CNC milling machine tool used in this study is 560 × 410 × 450 mm. The CNC controller is the FANUC 32i series CNC controller, which is equipped with automatic cornering bell-shaped ACC/DEC before interpolation [26] and is applicable to the high-speed CNC machine tool. The machine tool has a C-shaped mechanical structure. The Y-axis feed drive servomechanism is installed on the base, and the ballscrew drives the saddle. The X-axis feed drive servomechanism for driving the work table is installed above the saddle, and the workpiece to be machined is fixed to the work table. The Z-axis feed drive servomechanism perpendicular to the work table is installed on the column to control the feed motion of the spindle, and the cutting tool used for machining is installed on the spindle.

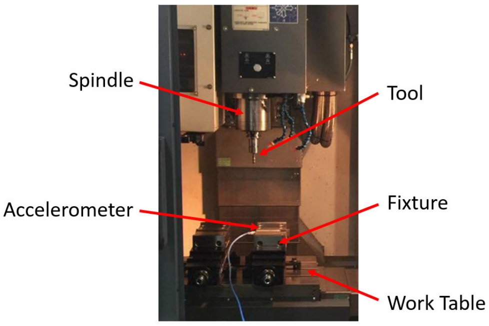
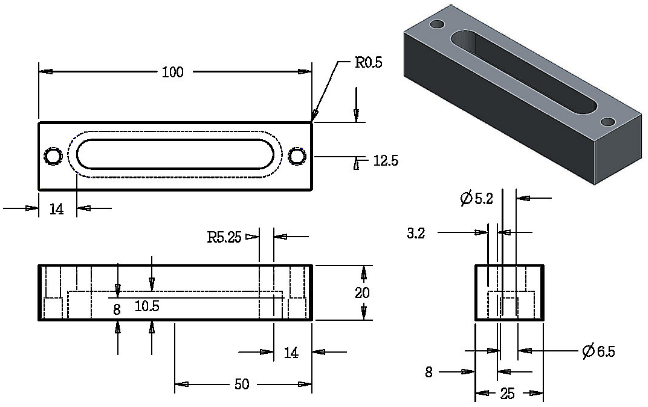


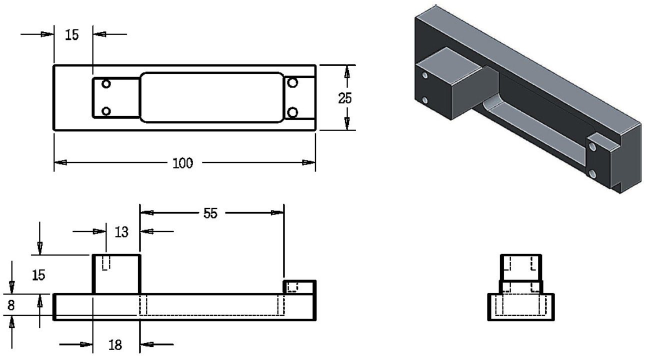
Fig. 1. Installation of experimental equipment used in this study.

To make the accelerometer close to the actual machining condition, a fixture is manufactured, and the accelerometer is installed on the fixture (Fig. 2). Then, the fixture is installed on the vise, which is similar to the situation of a workpiece moving along the motion path. The fixture design for installing an accelerometer is divided into three parts. The bottom part is fixed on the work table of the machine tool (Fig. 2(a)). The middle part is used for installing the accelerometer and accessories (Fig. 2(b)). The top part is used for coverage (Fig. 2(c)). The accelerometer is model GY-61 ADXL335 (Fig. 2(d)). The NI9215 model DAQ component (National

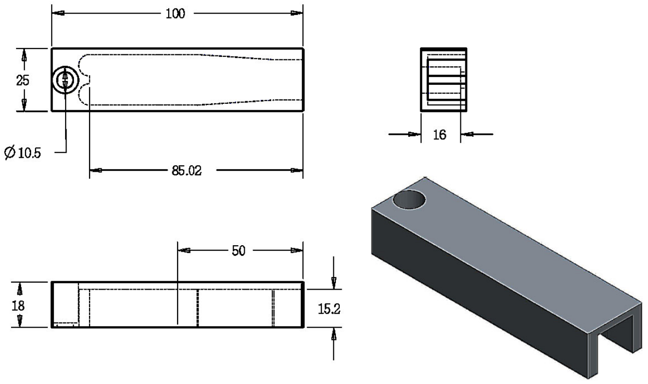
Instruments) is used for this experiment. The sensing signals obtained by the DAQ component are displayed by the software LabVIEW, and the signal-processing package provided by LabVIEW is applied to the power spectrum to perform power spectral analysis.



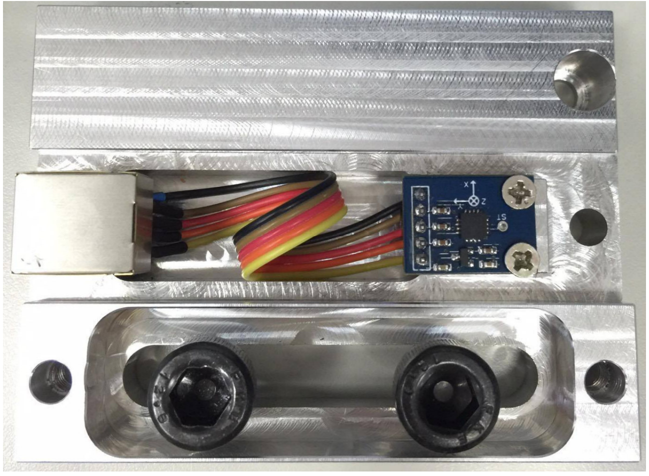
(a) Engineering drawing of the bottom part of the fixture



(b) Engineering drawing of the middle part of the fixture



(c) Engineering drawing of the top part of the fixture



(d) Accelerometer installed on the fixture

Fig. 2. Fixture design for the installation of the accelerometer.

The cornering ACC/DEC control parameters adjusted in this study are described as follows [26]:

1) The maximum allowable acceleration rate in ACC/DEC before interpolation for each axis (MAAR) has a parameter unit of mm/sec^2. Setting the MAAR to a larger value can improve the response time of the axial motion, which significantly increases the tangential speed of the work table (Fig. 3); however, an excessive value results in the vibration of the feed drive servomechanism, which makes it noisy, increasing the following error.

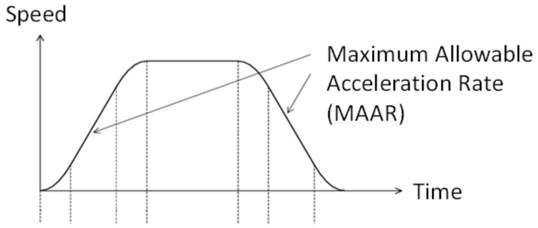


Fig. 3. Illustration of the MAAR during ACC/DEC periods.

2) The acceleration change time of bell-shaped ACC/DEC before interpolation (ACT) has a data unit of milliseconds. Setting the ACT to a larger value slows the response of the axial motion, which increases the motion time owing to the longer response time, and the speed profile becomes smoother, reducing the following error. Setting the ACT to a smaller value reduces the response time and thus reduces the motion time. As shown in Fig. 4, setting the ACT to a larger value increases the axial motion time during the ACC/DEC periods.

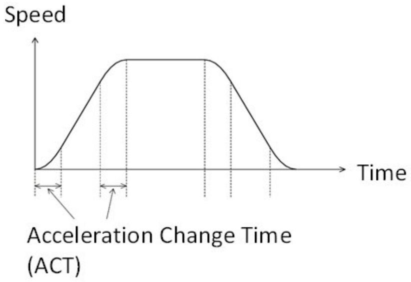


Fig. 4. Illustration of the ACT during ACC/DEC periods.

3) The maximum allowable feedrate difference for feedrate determination based on the corner feedrate difference (MAFD) has a data unit of mm/min. Setting the MAFD to a larger value improves the response time of the axial motion, but an excessive value results in the vibration and noise of the feed drive servomechanism. Setting the MAFD to a smaller value slows the response and reduces the following error. At the connection of adjacent linear paths, if the axial-speed difference is larger than the value of the MAFD, the CNC controller determines the appropriate feedrate (usually lower than the original feedrate); thus, the axial-speed difference is lower than the setting value of the MAFD for performing ACC/DEC before interpolation for each axis. Therefore, this MAFD control parameter can reduce the cornering errors. Fig. 5 shows that although setting the MAFD to a smaller value results in smaller cornering errors, it increases the motion time.

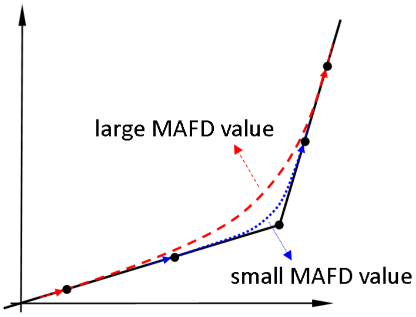


Fig. 5. Parameter MAFD corresponding to cornering contours with different MAFD values.

4) The maximum allowable acceleration rate for the deceleration function based on the acceleration in artificial intelligence contour control for each axis (AIC) has a unit of mm/sec^2. This AIC control parameter is effective when a CNC machine tool executes multiple NC blocks with piecewise-continuous motion paths. As shown in Fig. 6, as the CNC controller automatically adjusts the ACC/DEC process of piecewise-continuous motion paths, when the AIC is set to a smaller value, the CNC machine tool performs work table motions with larger cornering errors; however, the contouring errors of the other paths are smaller. On the contrary, when the AIC is set to a larger value, while the cornering error can be reduced, the contouring errors of the other paths may be increased. That is, by adjusting the AIC control parameter, a tradeoff can be achieved between the cornering and contouring errors when the machine tool executes multiple NC blocks with piecewise-continuous motion paths.

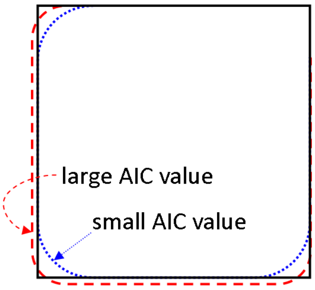


Fig. 6. AIC parameter corresponding to piecewise- continuous motion paths with different AIC values.

The four control parameters adjusted in this study are the MAAR, ACT, MAFD, and AIC. As the AIC influences the motion accuracy and motion time of a CNC machine tool, it executes multiple NC blocks with piecewise-continuous motion paths to achieve the adjustment.

III. CONTROL PARAMETER ANALYSIS, MODELING, AND SELECTION

A. *Use of Taguchi Method to Analyze Influence of Control Parameters*

Taguchi quality engineering was developed by Dr. Genichi Taguchi in the 1950s and employs simple orthogonal array experimental design and compact ANOVA with few experiment data for analysis; thus, the quality of a product can be effectively upgraded [31]. The Taguchi method determines the optimal settings of controllable factors according to the concept of robustness and manufacturing process design, so that the quality of a product is free of the effect of noise factors. The major characteristic of the Taguchi method is to obtain design information with minimal experimental combinations. While this method is not as good as full-factorial experiments, which determine the exact optimal combination, it can indicate the optimal trend with few experiments; thus, its feasibility is greater than that of full-factorial experiments.

The measurement performed in this experiment is related to the quality characteristics. The quality characteristics in this study are the PVs of the dominant frequency of the power spectral density distribution of the accelerometer-measured signals when the machine tool performs cornering motions. The factors influencing the quality characteristics are divided into signal factors and controllable factors. A signal factor is a factor that the system operator can change, i.e., a system input. In dynamic systems, the ideal value of quality characteristics varies with respect to the signal factors. The controllable factors are all the factors other than the signal factors and affect the quality characteristics. In this experiment, as the system is static, there is no signal factor; thus, there are three controllable factors: the MAAR, ACT, and MAFD. An $L_9(3^4)$ orthogonal array is used for the experiment, and the S/N ratio is established in an ANOVA. The degree of contribution of each controllable factor to the quality characteristics is considered; a larger contribution indicates that the factor has a greater effect on the quality characteristics. Table I shows that the MAAR has the highest contribution; thus, it is adjusted first. The ACT and MAFD have lower contribution and are adjusted together.

TABLE I
MAAR/ACT/MAFD ANOVA TABLE

Factor	Degrees of freedom	Sum of squares	F ratio	Contribution
MAAR	2	4.8100	3273.8730	95.57%
ACT	2	0.0194	13.2223	0.39%
MAFD	2	0.2018	137.3731	4.01%
Error	2	0.0015		0.03%
Total	8	5.0327		100%

In this study, MAAR analysis is performed. The relationship between the PV and MAAR is experimentally investigated, and the MAAR parameter value is designd according to this relationship. Different MAAR parameter values are set for the experiments, and then the ACT and MAFD parameter values are adjusted under the preset MAAR parameter value for experimentation. The average of the observed PVs is recorded, and the relationship between the MAAR control parameter and the average PV is obtained via regression analysis [32], as shown in Fig. 7 and (1). Clearly, when the MAAR parameter value increases, the PV gradually increases to a steady value. That is, an excessive MAAR parameter value has a limited effect on the PV. This experiment aims at high-speed machining requirements (a high speed is preferable when the machine tool performs cornering motions) as the goal of the control-parameter design; thus, the MAAR parameter value is selected as 800.

$$PV = 1.1779\times10^{-4} + 6.6730\times10^{-5}\times(1-e^{-0.01*(MAAR-300)}) \qquad (1)$$

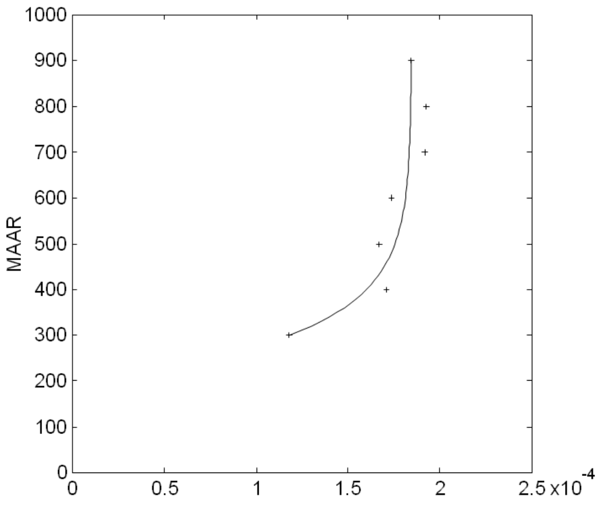
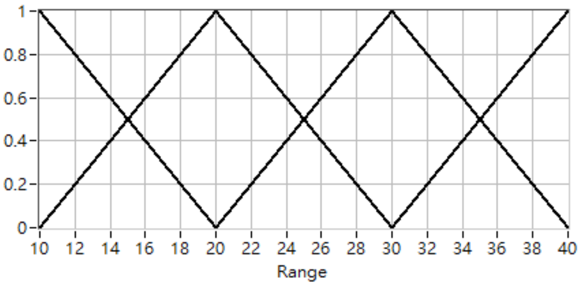


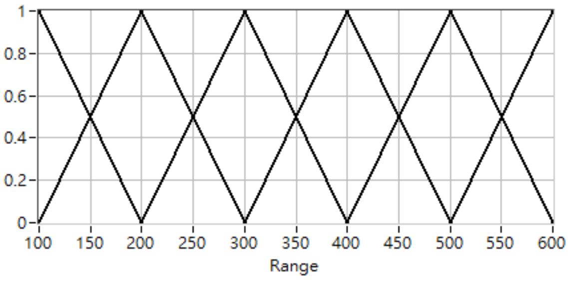
Fig. 7. PV–MAAR curve.

B. *Use of Fuzzy-Logic Rules to Build ACT/MAFD Linguistic Model*

According to the Taguchi method and the ANOVA, as the MAAR has the greatest influence among the three control parameters, two different modeling approaches are employed: MAAR modeling and fuzzy-logic modeling for the ACT and MAFD. The MAAR model shows the trend of the effect of the MAAR parameter value on the PV. The ACT/MAFD fuzzy-logic modeling aims to build a linguistic model for the ACT and MAFD using the determined MAAR parameter value. According to the MAAR model, the MAAR parameter value can be determined as 800; thus, under this MAAR parameter value, the inputs of the fuzzy-logic linguistic model are set as the ACT (Fig. 8(a)) and MAFD (Fig. 8(b)), and the model output is the normalized PV (Fig. 8(c)). The ACT/MAFD model can be obtained according to the established fuzzy linguistic rules, inference, and defuzzification, as shown in Fig. 8(d).

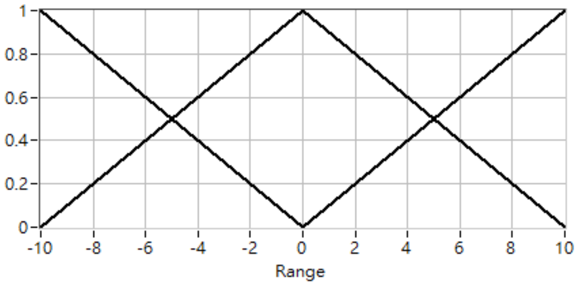


(a) ACT input

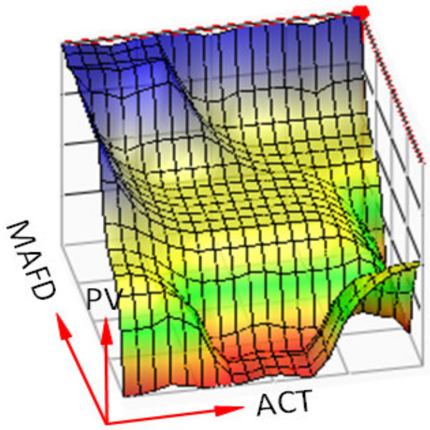


(b) MAFD input

Fig. 8. Fuzzy-logic modeling using the ACT and MAFD control parameters. (cont'd)



(c) Normalized PV output



(d) ACT/MAFD model

Fig. 8. Fuzzy-logic modeling using the ACT and MAFD control parameters.

C. *Selection of Control Parameters*

The optimum ACT and MAFD control parameters are selected according to the maximum PV output of the ACT/MAFD fuzzy-logic model. The selection, which is based on the high-speed machining requirement, can avoid an overlong cornering time when the machine tool performs cornering motions. When different MAAR values are set, the corresponding ACT/MAFD fuzzy-logic model can be built, the optimum ACT and MAFD values are obtained, and the MAAR/ACT/MAFD parameter checklist is established, as shown in Table II. Here, it is observed that when the MAAR parameter value changes, the ACT and MAFD variations are close to the averaged ACT parameter value of 22 and MAFD parameter value of 98.4, and the experimental results are the same as the expected contribution of the Taguchi ANOVA, meaning that the ACT control and MAFD control parameters have far less influence on the cornering motions than the MAAR.

TABLE II
EXPERIMENTAL RESULTS FOR DIFFERENT SETS OF MAAR/ACT/MAFD VALUES

MAAR	300	500	700	800	900	
ACT	20	30	10	20	30	22.0 (AVG)
MAFD	98	100	102	91	101	98.4 (AVG)

IV. PARAMETER ADJUSTMENT EXPERIMENTAL RESULTS AND DISCUSSION

In the experimental process of parameter adjustment, the machine tool performs the test path motion, and then the power spectral density distribution of the accelerometer-measured signals is used.

1) Taguchi method and ANOVA and MAAR modeling

2) ACT/MAFD fuzzy-logic modeling and selection of parameter values
3) Design cornering speed and accuracy of intended parameter adjustment

Items 1 and 2 can determine the appropriate MAAR, ACT, and MAFD values. Item 3 involves the designs of five sets of control-parameter combinations with the AIC control parameters for the parameter adjustment of the speed or accuracy requirements when the machine tool performs test path cornering motions. According to the aforementioned analysis, the MARR parameter value is set as 800, the ACT parameter value is 20, and the MAFD parameter value is 91. The AIC parameter values are the values defined by the machine tool manufacturer: 500, 300, 200, 175, and 150. The aforementioned parameter values are designed as five combination sets, and the cornering speed and intended accuracy parameter setting can be established, as shown in Table III.

TABLE III
PARAMETER SETTINGS FOR CORNERING SPEED AND ACCURACY

	Speed<==============>Accuracy				
Set	1	2	3	4	5
MAAR	800				
ACT	20				
MAFD	91				
AIC	500	300	200	175	150
Motion time (sec)	8.33	9.33	10.72	11.26	11.89

A larger AIC parameter value yields a shorter motion time but a larger contouring error. Set 1 of this experiment has the intended speed and aims to reduce the motion time, as it has the shortest motion time and largest cornering error. Set 5 has the intended accuracy and aims at the cornering accuracy, as it has the smallest cornering error and longest motion time. The cornering error is based on set 5. Set 1 has a larger cornering error than set 5 by 7%, set 2 is higher than set 5 by 8%, set 3 is higher than set 5 by 1%, and set 4 is higher than set 5 by 0%. The motion time is based on set 1, as it increases from set 2 to set 5. Set 5 is higher than set 1 by 43%, set 4 is higher than set 1 by 36%, set 3 is higher than set 1 by 28%, and set 2 is higher than set 1 by 12%, as shown in Table IV. Fig. 9 shows the machine tool motion contours of each set parameter. According to Fig. 9, set 1 has the worst accuracy and largest cornering error, while set 5 has a smaller cornering error, as it is apparently closer to the command path.

TABLE IV
EXPERIMENTAL RESULTS FOR CORNERING SPEED AND INTENDED ACCURACY PARAMETER COMBINATIONS

	Speed<=============>Accuracy				
Parameter set	1	2	3	4	5
AIC value	500	300	200	175	150
rate of difference of cornering error	7%	8%	1%	0%	0%
rate of difference of motion time	0%	12%	28%	36%	43%

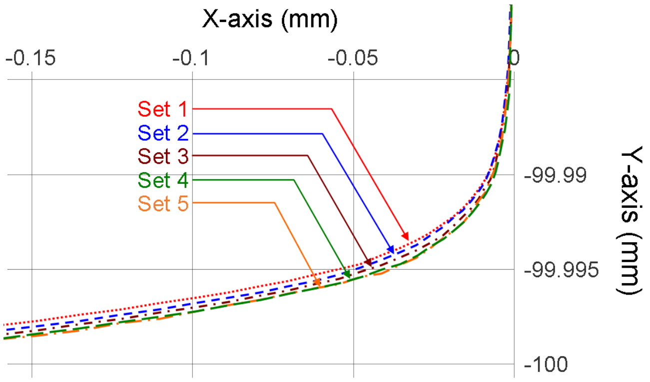


Fig. 9. Cornering motion contours of the speed and accuracy parameter sets.

The motion speed and accuracy of the machine tool usually contradict each other; increasing the motion speed reduces the cornering time but increases the cornering error. Although increasing the motion accuracy increases the cornering time, it reduces the cornering error. To achieve a balance, a control-parameter design that considers both the speed and accuracy can be obtained according to the rate of difference of the cornering error and the rate of difference of the motion time, as shown in Fig. 10 and Table IV. The AIC parameter value of the balanced cornering error and cornering time is 427. Fig. 11 shows the contour of the machine tool cornering motion with balanced control parameters.

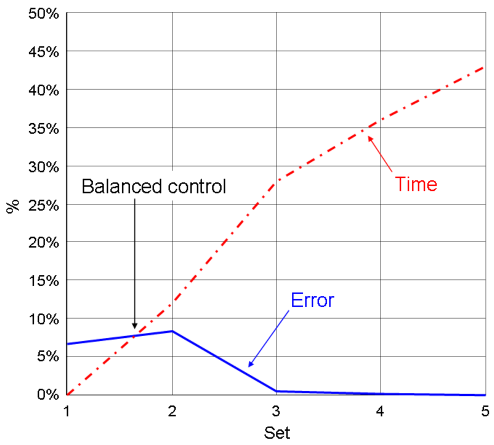


Fig. 10. Graph of the relationship between rate of difference of the cornering error and the rate of difference of the motion time.

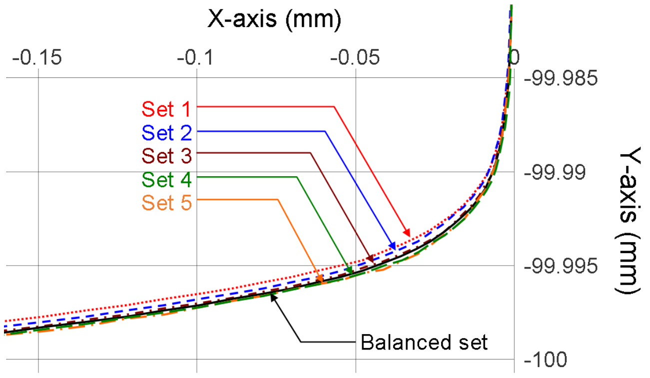


Fig. 11. Contour of the cornering motion with balanced control parameters.

V. CONCLUSION

Using the dominant frequency PV of the power spectral density distribution of accelerometer-measured signals when a machine tool performs cornering motions, the four major control parameters of the CNC controller influencing the machine tool cornering motion performance were investigated: the MAAR, ACT, MAFD, and AIC. On the basis of the results, a systematic parameter adjustment procedure was designed to balance the machine tool cornering error and cornering time. To upgrade the workpiece machining quality and reduce the motion time, the machine tool CNC controller has a high speed and high accuracy, which can be adjusted to control the cornering parameters. However, the adjustment of the control parameters sometimes creates problems for the machine tool operator. While there are tuning methods and software for online control-parameter adjustment, they require time-consuming trial and error for obtaining appropriate control parameters, in order to balance the accuracy and speed when the machine tool performs cornering motions. According to the trial and error results, when the machine tool performs cornering motions, the dominant frequency PV of the power spectral density distribution of the accelerometer-measured acceleration signal changes owing to the acceleration status of the machine tool cornering motion. Therefore, in this study, the dominant frequency PV of the power spectral density distribution of accelerometer-measured signals when the machine tool performs cornering motions was used as a reference indicator for control-parameter adjustment and design, in order to avoid the cumulative error resulting from the two integral calculations in position analysis.

As the AIC parameter automatically performs cornering ACC/DEC adjustment according to the corner variations when the machine tool performs all cornering motion paths, the Taguchi method and an ANOVA were used to examine the effects of the MAAR, ACT, and MAFD on the machine tool cornering motions. A mathematical model of the parameter values and the dominant frequency PV was constructed for determining the most influential MARR parameter; thus, the relationship between the parameter value and the dominant frequency PV was determined, and the appropriate MARR parameter value was set according to these values. Regarding the ACT and MAFD, fuzzy-logic modeling was used to construct a highly nonlinear mathematical model of the parameter value and the dominant frequency PV, and the best-fitted parameter values were determined according to this model for optimizing the cornering motion of the machine tool. Finally, the AIC parameters were used to balance the high-accuracy (small cornering error) and high-speed (high cornering speed) requirements for the machine tool cornering motions. The proposed power spectral density analysis procedure for the accelerometer-measured signals was used to design five sets of control parameters that satisfy the high-accuracy (small cornering error) and high-speed (high cornering speed) requirements, the machine tool test path cornering motion was performed according to the parameter settings, and the feasibility of the proposed parameter setting method was validated. Regarding the test path used in this study, the experimental results for the machine tool cornering motion show that the proposed control-parameter design can satisfy the high-accuracy and high-speed cornering motion requirements. The difference in the cornering error of the five sets of control parameters designed in this study was 7%, and the difference in the motion time was 43%. According to the machine tool cornering motion performance curves of the high-accuracy machining and high-speed machining requirements of the five sets of control parameters, the curve intersection point design can balance the control-parameter combination of the cornering accuracy and cornering speed. The experimental results prove that this control-parameter combination (not the average value of the parameter adjustment range) can balance the cornering accuracy and cornering speed of the test path.

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