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Development of a Virtual Machine Tool – Part 2: Dynamic Cutting Force Model, Thermal Behavior Model, Feed Drive System Model, and Comprehensive Software Environment

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ABSTRACT

In Part 2 of this paper, the dynamic cutting force model, thermal behavior model, and feed drive model used in the development of a virtual machine tool (VMT) are briefly described. Some results are presented to verify the proposed models. Experimental data agreed well with the predicted results for each model. A comprehensive software environment to integrate the models into a VMT is also proposed.

Key Words : Virtual machine tool, Dynamic cutting force model, Thermal behavior model, Feed drive model, Comprehensive software environment

1. Introduction

The role of CAE technology has been rapidly increasing in almost every industry. ADAMS and DADS are widely used for vehicle kinetic analysis, ANSYS and IDEAS are structure analysis tools that are based on FEM, and CMOLD and MOLDFLOW are application software packages that were developed to analyze plastic injection molding. However, an analysis tool for metal cutting is still not available, even though one could be used to optimize the cutting process. Existing CAM software is not able to evaluate cutting forces, machined surfaces, and machining stability.

Until now, many researchers have concentrated on the development of individual models, but since various complex phenomena influence the machining process, machining error should be estimated using an integrated approach that includes a cutting process model and separate models for each part of the machine tool. Furthermore, a compensation/control module is required to reduce machining error.[1]

The structure of the virtual machine tool (VMT) presented in this paper is shown in Fig. 1. The cutting process module examines the machining state beforehand and supplies the proper cutting conditions to the operator. The compensation/control module is composed of a thermal behavior model and an adaptive control model. It compensates and controls the machining process to improve the accuracy and productivity of the machine tool. Additional modules may be continuously incorporated into the VMT.

The concept and structure of the VMT was presented in Part 1 of this paper. The cutting process module was considered, which includes the mechanistic cutting force model, machined surface error model, and off-line feed rate scheduling model.[2] Part 2 of this paper considers the

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dynamic cutting force model, thermal behavior model, and feed drive system model, and proposes the software that is needed to integrate the models into a VMT.

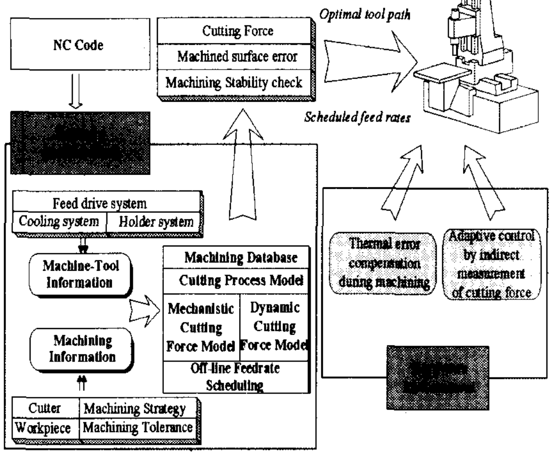


Fig. 1 Structure of the VMT

2. Dynamic Cutting Force Model

As the cutter rotates during endmilling, cutting configurations change periodically; uncut chip thickness changes continuously as the multi-point tool rotates and makes interrupted cuts. The dynamic cutting force model simulates the dynamic component of the cutting force by evaluating the relative displacement between the tool and the workpiece that is caused by vibrations resulting from variations in chip thickness.[3]

The cutting system model was developed first, based on structural dynamics and the cutting force model. Relative motion of the tool occurs as the cutting force is applied during NC machining, and this results in variations in the cutting force, which subsequently influence the relative motion. The relative motion of the tool can be calculated by numerical integration using the fourth-order Runge-Kutta method.[4]

The dynamic cutting force model is used to estimate machining stability and evaluate machinability. Machining stability involves detecting chatter using computer simulation, whereas machinability is an estimate of machining deficiency, such as surface deterioration generated by excessive relative movements of the tool. Most research into the occurrence of chatter uses the Lobe diagram to avoid excessive cutting conditions. However, in the transient case of corner machining, chatter may occur at lighter cutting conditions than those indicated by the Lobe diagram.[5] Thus, this paper examines chatter under changing cutting conditions, and demonstrates the difference between the stability of a transient (*e.g.*, corner) cut and the stability encountered during fixed cutting conditions.[6]

An experiment was performed to test the dynamic cutting force model. A 20-mm diameter HSS tool was used; the workpiece material was aluminum 2014-T6. Table 1 shows the cutting conditions for two cases. Generally, the width of a cut increases during corner machining and approaches the same width used in slot cutting. Thus, two machining cases were selected to compare the stability of transient and steady cuts.

Table 1 Cutting conditions

	Cut type	Width of cut
Case A	Corner cut	10 mm → 20 mm
Case B	Straight cut	20 mm

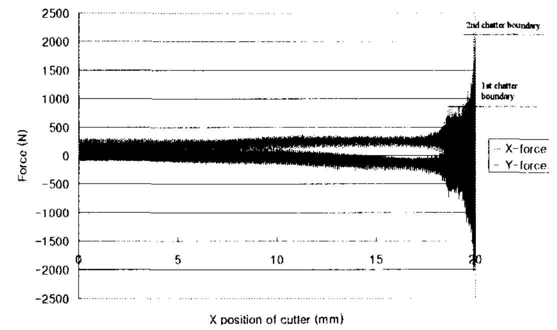


Fig. 2 Measured corner cutting forces for Case A

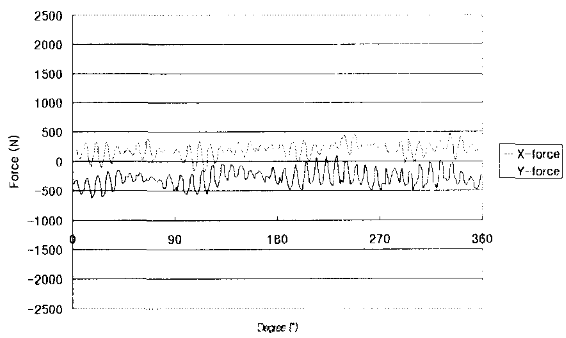


Fig. 3 Measured straight path cutting forces for Case B

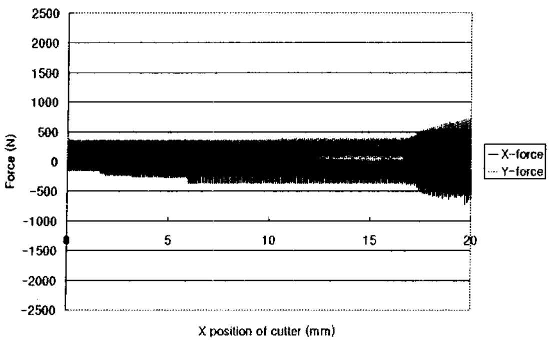


Fig. 4 Predicted corner cutting forces for Case A

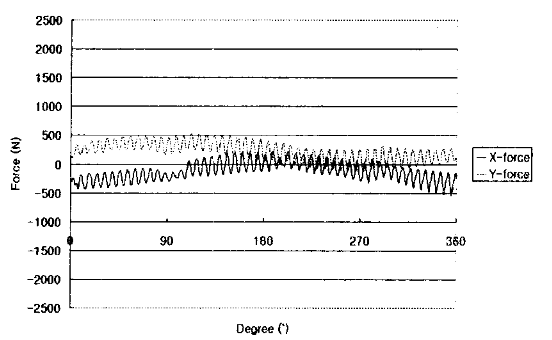


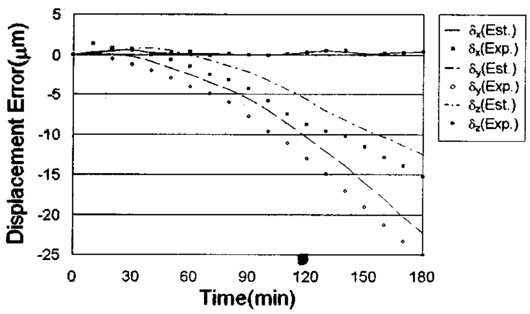
Fig. 5 Predicted straight path cutting forces for Case B

Case A represents a cutting configuration in which the width of the cut increases from 10 to 20 mm. Case B is a slot-cutting state, in which the width of the cut is fixed at 20 mm. Figure 2 shows the chatter measured in Case A. Chatter did not occur in Case B (see Fig. 3). Figures 4 and 5 show the predicted cutting forces for Cases A and B, respectively. The predicted cutting forces corresponded well with the measured values.

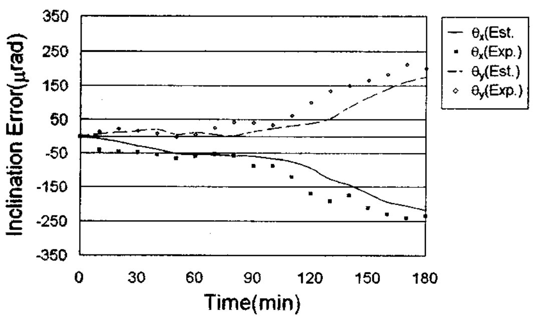
3. Thermal Behavior Model

The accuracy of machine tools is defined as the error in the relative movement between the cutting tool and the ideal workpiece. For a three-axis machine, this relative error can vary widely across the machine working zone due to the following effects: position errors, angular errors of the machine linkage, time variant thermal changes, tool run-out errors, and tool deflection errors. Of these, thermal errors comprise between 40-70% of the workpiece error in precision machining. Research has been undertaken to minimize or control the thermal deformation of machine tools from various viewpoints. These include modification of the machine design, separation of the heat sources, cooling of the machine structure, compensation for thermal error, and so on. Empirical models are generally more effective than other models when predicting thermal errors.[7] None of these models, however, can accurately estimate thermal errors during cutting. In the present research, a compact measurement system was developed to measure time-invariant machine-tool errors. A practical and reliable method is proposed to estimate the thermally induced errors of a machine tool during cutting by applying a neural network approach.[8,9]

To test the thermal behavior model, an experiment was performed using a vertical machining center (Daewoo Heavy Industries Ltd., ACE-V30). The error prediction model was trained using the cutting conditions and measurement system from four cases. The performance of the model was then verified by estimating the thermal error of the machine tool for another case using a neural network model.



(a) Displacement errors



(b) Inclination errors

Fig. 6 Comparison between model estimates and experimental results

Figure 6 shows a comparison between the measured and predicted errors. Figure 6(a) and (b) give the displacement and inclination errors, respectively.[9] If the present thermal error prediction model is trained using various cases, the thermal error for a general machining state can be estimated. Furthermore, the present model can be used as a basic tool for reducing thermal error.

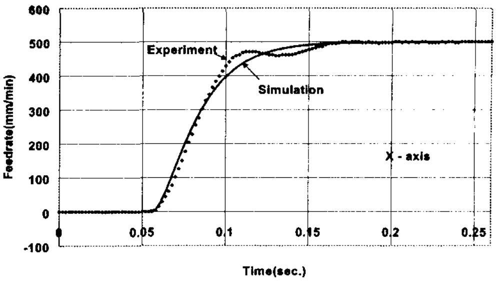
4. Feed Drive System Model

Various control strategies can be simulated before applying cutting force regulation control to a machine tool. For this purpose, transfer function modeling, cutting force regulation simulation, indirect measurement of the cutting force, and verification of the cutting force regulation strategy must be performed.

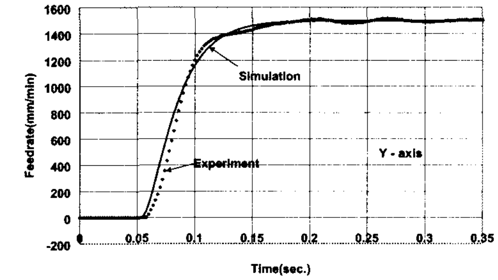
The feed drive system model can be constructed by modeling the transfer function, which gives the actual movement of a machine tool, including the acceleration and deceleration characteristics. The transfer function is used to obtain the proper control strategy by simulating the cutting force regulation. Figure 7 shows the simulated and measured step responses of the feed drive system, which could be accurately simulated. From this result, an accurate feed rate during machining can be estimated.

Measurement of cutting force using a commercial dynamometer is very expensive, and it is difficult to use a dynamometer in industry. Thus, an adaptive control module has been developed that uses fuzzy logic and indirect measurements of the cutting force from the feed motor current.[10] This controller provides better responses than a discrete proportion integral controller; however, a scaling factor for the input and output values of the fuzzy controller is required. Thus, a way to determine real time changes in the scaling factor was proposed.[10]

The adaptive control strategy was applied to control the cutting force normal to the machined surface. After the cutting force in the cross-feed direction had been estimated using the indirect measurement method, the normal cutting force was regulated at 700 N. Figures 8(a) and (b) show the measured normal cutting force and feed rates, respectively, before and after adaptive control. The results show that the cutting force was maintained within an error of ± 100 N.

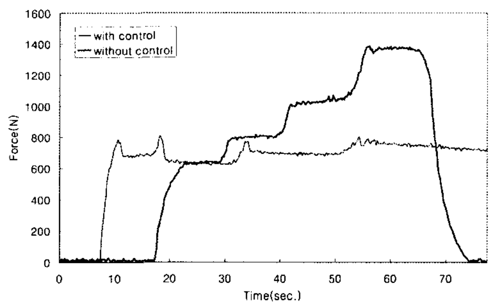


(a) Step response of the x-axis, 500 mm/min

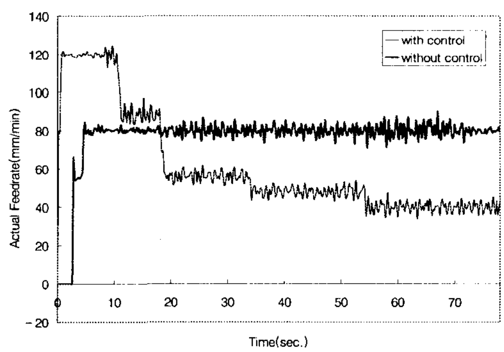


(b) Step response of the y-axis, 1500 mm/min

Fig. 7 Comparison of experimental and simulated results



(a) Forces normal to the machined surface



(b) Comparison of feed rates

Fig. 8 Experimental results.

5. Integration of a Virtual Machine Tool and Software Development

The entire operation of a VMT should be analyzed in terms of the machined surface quality and cutting performance. This paper proposes a cutting force model, chatter prediction model, thermal behavior model, feed drive system model, and machined surface prediction model, which fulfill the requirements of a VMT. Furthermore, additional models may be continuously incorporated into the VMT.

The developed models can be used independently, or together, according to the given machining conditions, analysis target, and purpose. For example, adaptive control can be used after off-line feed rate scheduling. This application is important for high-performance tools as a precaution against sudden disturbances and as a technique to improve productivity.

The cutting force model, machined surface error model, off-line feed rate scheduling model, and machining state monitoring have been integrated into one piece of software for a VMT. When the NC code and machining information are provided to the software, the cutting force and machined surface error can be predicted, and an NC code with a scheduled feed rate can be generated.

Figure 9 shows the software screen constructed for a VMT. The left and right windows of the screen are used to monitor the machining state and illustrate the cutting forces and NC code, respectively. As an example, Fig. 10 illustrates a three-dimensional machined surface profile for pocket machining.

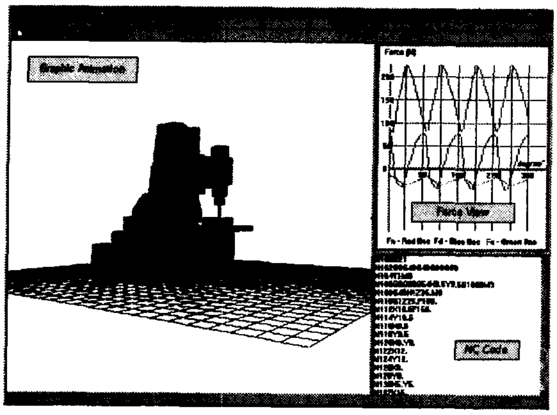


Fig. 9 Main screen of the VMT software

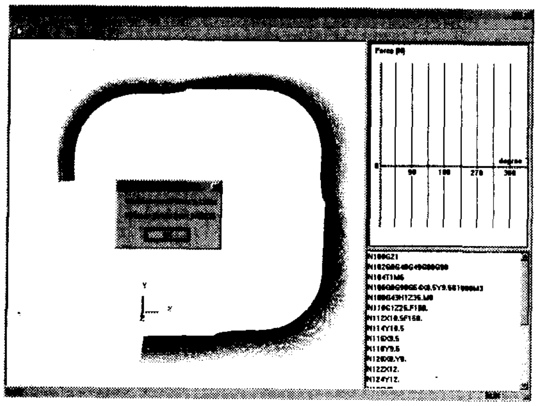


Fig. 10 Three-dimensional error map of a machined surface (maximum error = 118 ㎛, minimum error = 2 ㎛)

6. Conclusion

A virtual machine tool can be used to analyze an actual machine tool. The operator can improve the productivity and accuracy of the actual tool by experiencing "pseudo-real machining" and modifying the cutting conditions. A novice operator can also use a virtual machine tool to plan the machining process. Furthermore, a tool designer can build a tool structure, controller, or compensator by estimating machining error components separately or synthetically.

To date, the individual models in the virtual machine tool have been developed separately, and have been shown to perform well. In the future, an improved system for integrating the developed models will be constructed that is expected to offer the means to achieve higher precision and accuracy than can be attained using conventional techniques.

Acknowledgments

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