International Journal of the Korean Society of Precision Engineering, Vol. 4, No.2, March 2003.

Development of a Virtual Machine Tool – Part 1: Mechanistic Cutting Force Model, Machined Surface Error Model, and Feed Rate Scheduling Model

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ABSTRACT

A virtual machine tool (VMT) is presented in this two-part paper. In Part 1, the analytical foundation for a virtual machining system is developed, which is envisioned as the foundation for a comprehensive simulation environment capable of predicting the outcome of cutting processes. The VMT system undergoes "pseudo-real machining", before actual cutting with a CNC machine tool takes place, to provide the proper cutting conditions for process planners and to compensate or control the machining process in terms of the productivity and attributes of the products. The attributes can be characterized by the machined surface error, dimensional accuracy, roughness, integrity, and so forth. The main components of the VMT are the cutting process, application, thermal behavior, and feed drive modules. In Part 1, the cutting process module is presented. When verified experimentally, the proposed models gave significantly better prediction results than any other methods. In Part 2 of this paper, the thermal behavior and feed drive modules are developed, and the models are integrated into a comprehensive software environment.

Keywords : Virtual machine tool, Virtual machining system, Attributes of products, Cutting process module, Application module

1. Introduction

CNC machine tools are widely used in manufacturing industry. Improvements in the productivity and accuracy of machine tools are required due to increased global competitiveness in the manufacturing environment. Thus, various industry and research institutes have performed theoretical studies and introduced new developments to enhance the capability of CNC machine tools. However, machine tool operators and manufacturers still depend on trial and error to develop and improve the capabilities of CNC machine tools. Because of this difficulty, manufacturing industry has reached a technological limit with regard to the accuracy and productivity of its products. The virtual manufacturing system (VMS) [1~3] was introduced to overcome this problem.

Recently, the virtual machine tool (VMT) has been recognized as the key module in a VMS. A VMT compensates and controls machining operations and simulates the actual machining state. This can be accomplished using a cutting process model and a physical model of the machine tool components.

A VMT must be able to perform the machining operation in a comprehensive simulation environment and to predict the physical output of any product attribute.[4] The product attributes generated by various error components of a machine tool can be represented by dimensional accuracy, machined surface error, surface roughness, and so on. The VMT presented in this paper focuses on machining errors. A VMT also requires a cutting process model and various other application models, such as thermal behavior and feed drive system models of a machine tool structure.

VMT operators will be able to predict the machining state and obtain the optimal machining conditions by experiencing "pseudo-real machining". Also, the integrated VMT software will allow a machine tool designer to evaluate processes and determine the optimal machine configuration before the actual hardware is built.

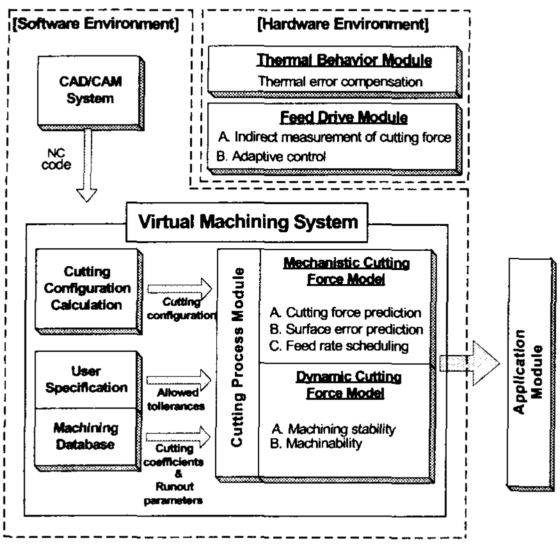


Fig. 1 Framework of the VMT

2. VMT Structure

Figure 1 shows the overall structure of the VMT proposed in this research. The VMT is composed of both hardware and software. Part 1 of this paper focuses on the virtual machining system, which corresponds to the software environment of the VMT. When the NC code is loaded into the VMS from a commercial CAD/CAM system, the cutting configuration is calculated for the cutting process simulation. Hereafter, the term cutting configuration will be used to designate the nominal position and entry/exit angles of the cutter, cutting conditions (width of cut, depth of cut, and feed), and feed direction at the nominal cutter position. If the cutting coefficients and runout parameters are known from the machining database, along with the cutting configuration and user specifications such as the tolerances, then the cutting process module can simulate the cutting forces and the machined surface errors. Moreover, the machining stability and machinability can also be evaluated by the module, using a dynamic cutting force model. Various application modules can be further developed and included in the cutting process module according to users' needs.

In addition to the cutting process, other components must be considered to achieve high-speed high-precision machining in the VMT hardware environment. Among these are thermal deformations, which are considered using a separate thermal error model for the machine tool structure. Also, adaptive control through indirect measurements of cutting forces is included, using a feed drive module, so that unstable machining states that might occur due to tool breakage, sudden disturbances, etc., can be detected.

Using the simulation results obtained from the cutting process module, and prior to actual machining, the attributes of a machined part can be understood and a set of optimal and stable cutting conditions can be obtained. In addition, machining performance and accuracy may be enhanced by employing proper compensation.

3. Cutting Process Module

Kimura[5] considered product and cutting process modeling as the key component for a virtual manufacturing environment. To predict the machining state in general cutting processes, the cutting process module must be able to effectively estimate cutting forces for various cutting conditions.

The cutting process module presented in this paper extracts the cutting configuration from an NC code provided by a commercial CAM system. Then the tolerance, cutting coefficients, and cutter runout values are supplied by the user. Finally, the module estimates the cutting forces, machined surface errors, and schedule feed rates. The cutting process module is composed of a mechanistic cutting force model and a dynamic cutting force model. Part 1 of this paper deals mainly with the mechanistic cutting force model, from which the machined surface error and feed rate scheduling models are derived.

3.1 Mechanistic Cutting Process Model

A number of models for predicting cutting forces and machined surface errors have been developed. However, since their cutting coefficients are verified in a specific range of cutting conditions, they cannot accurately estimate the cutting forces of transient cuts with cutting conditions that change.[6,7]

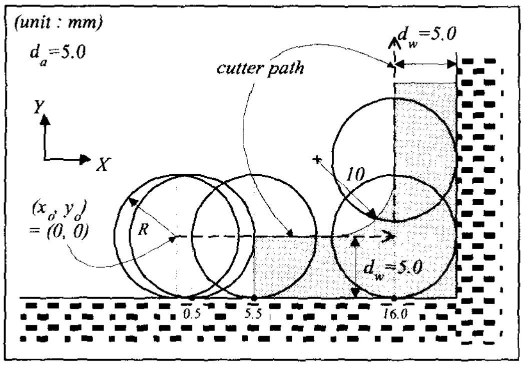
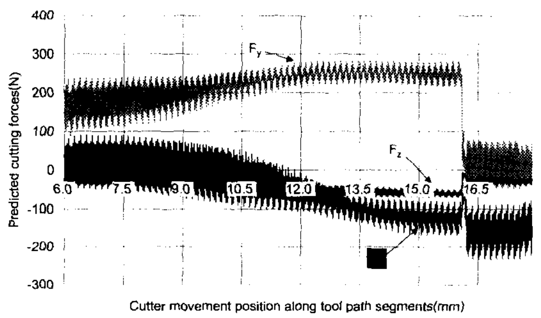
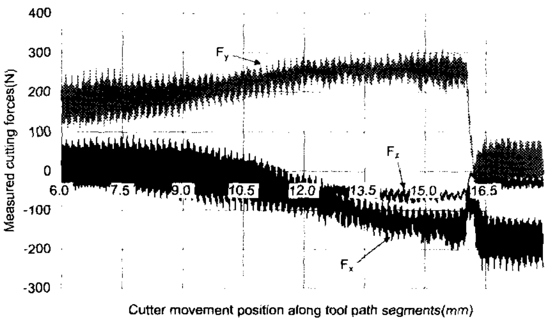


Fig. 2 Transient cut example



(a) Predicted cutting forces



(b) Measured cutting forces

Fig. 3 Predicted and measured cutting forces for the transient cut shown in Fig. 2

In the present research, a mechanistic cutting force model capable of predicting cutting forces and machined surface errors for transient cuts has been developed. The cutting coefficients are independent of cutting conditions, and are considered as a material property that is related to the tool and workpiece. Therefore, the cutting coefficients do not change under various cutting conditions. There is approximate a linear relationship between cutting forces and uncut chip thickness; however, nonlinearity exists at small uncut chip thicknesses due to a size effect. Thus, a nonlinear relationship was modeled in the present study to predict cutting forces more accurately.[8,9] The cutting coefficient model developed makes it easy to construct machining databases, since cutting coefficients can be obtained irrespective of cutting conditions.

As an example, corner machining is illustrated in Fig. 2. Figure 3(a) shows the cutting forces predicted using the cutting-condition-independent coefficients obtained during the transient cut shown in Figure 2. To obtain the actual cutting forces for this example, an experiment was performed using HSS end mills with four 10-mm diameter flutes, a 30° helix angle, and an 11° rake angle in a vertical-type machining center (Daewoo Heavy Industries Ltd., ACE-V30). A tool dynamometer (Kistler, type 9257B) was used to measure the three force components, F_X, F_Y, and F_Z, of the instantaneous cutting forces. The workpiece material was aluminum 2014-T6. Figure 3(b) illustrates the measured cutting forces for the transient cut shown in Figure 2. These corresponded well with the predicted cutting forces.

3.2 Machined Surface Error Model

The machined surface error model was derived from the mechanistic cutting force model that was developed. Tool runout and deflection were considered as contributing factors to machined surface error, which was estimated by following the movement of an actual tool. This makes it easy to construct a three-dimensional error map for general machining.

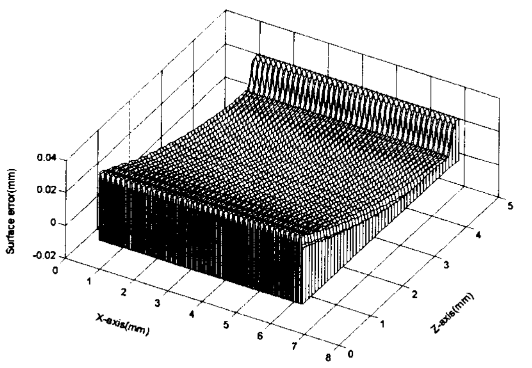
Table 1 lists the cutting conditions used to verify the developed model. Table 2 shows that the predicted peak-to-valley errors were in good agreement with the measured errors. Figure 4 shows the predicted and measured surface error profiles for Test 7 in Table 1. The "kink" shape appears in both the measured and predicted results at approximately the same position. To illustrate a transient cut example, Figure 5 shows the three-dimensional surface error map for the corner machining given by Figure 2.

Table 1 Cutting conditions

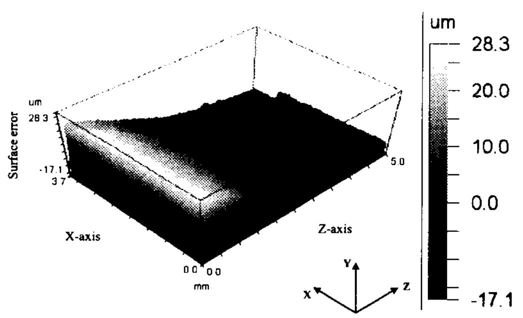
Test No.	d_a (mm)	d_w (mm)	f_t (mm/tooth)	*RPM*
1	2.0	5.0	0.0375	1000
3	5.0	5.0	0.0375	1000
7	5.0	2.5	0.0375	1000
17	5.0	5.0	0.0500	1000
18	5.0	5.0	0.0375	800

Table 2 Comparison of peak-to-valley of the predicted and measured surface

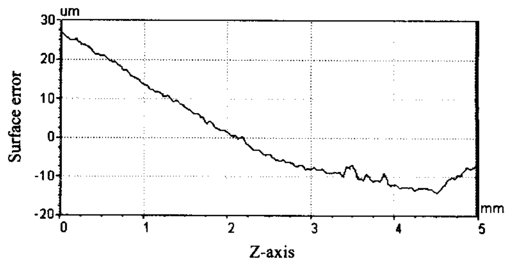
Test No.	Peak-to-valley of predicted surface error(μm)	Peak-to-valley of measured surface error(μm)	Prediction error(%)
1	33.01	31.00	6.5%
3	47.60	46.04	3.4%
7	37.65	41.06	8.3%
17	61.60	66.31	7.1%
18	58.30	61.17	4.7%



(a) Predicted surface error



(b) Measured surface error– three-dimensional plot



(c) Measured surface error– two-dimensional plot

Fig. 4 Predicted and measured surface errors for Test 7

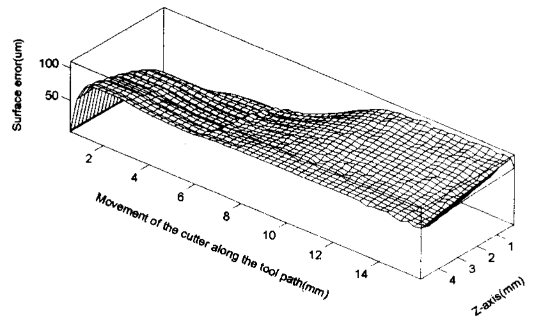


Fig. 5 Predicted surface error map for the cut shown in Fig. 2

4. Off-Line Feed Rate Scheduling Model

Tool breakage may occur owing to excessive cutting forces during NC machining. Thus, stable cutting conditions should be selected to prevent tool breakage and damage to workpieces. Previously, an operator depended on the experience of the machinist or on a machining database handbook. However, this conservative strategy may result in low productivity.

Since existing CAM software packages consider only geometric aspects when generating a tool path, they cannot help an operator to select the optimal cutting conditions. However, an off-line feed rate scheduling module can be used to improve productivity and to select a stable feed rate. Furthermore, the model can be incorporated into a CAM or a DNC system.

Figure 6 shows the workpiece geometry, in which the cutting depth continuously changes while the tool moves along the inclined tool path. The spindle speed and the original feed rate were 1000 rpm and 100 mm/min, respectively. Figure 7 illustrates the scheduled feed rate when the reference cutting force was given as 350 N. It can be shown that the maximum feed rates, 1000 mm/min, which was given before feed rate scheduling, was applied under air cutting state. The machine tool controller needs acceleration and deceleration time to follow the feed rate given in NC code. The acceleration or deceleration time was set as 60 ms in the machine tool (Daewoo Heavy Industries Ltd., ACE-V30) used in the experiment. When the blocks of a given set of NC code were divided into smaller segments, their time intervals were set as at least double the acceleration or deceleration time so that the controller can follow the desired feed rate determined by the off-line feed rate scheduling. Figure 8 presents the comparison between the measured and predicted cutting forces for the inclined tool path before and after feed rate scheduling. It is shown that cutting forces were well adjusted to 350 N with 5 % average error. As a result, the feed rate scheduling saved cutting time by 70 %.

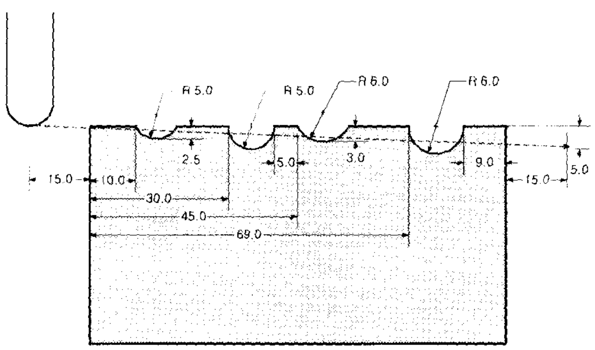


Fig. 6 Workpiece geometry for machining along the inclined path

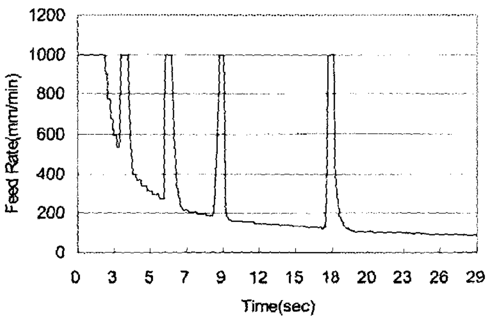


Fig. 7 Scheduled feed rates when the reference cutting force is given as 350 N

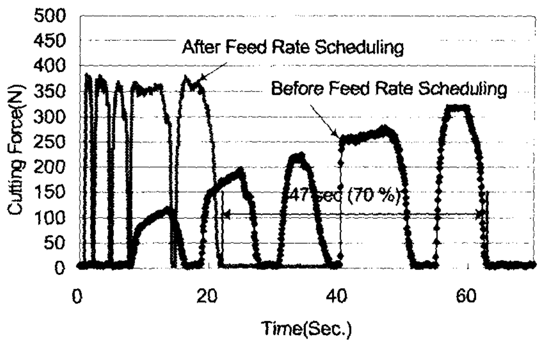


Fig. 8 The measured cutting forces before and after feed rate scheduling for the inclined tool path

5. Conclusion

This paper proposed an overall structure for a virtual machine tool, composed of software and hardware environments. The cutting process module, which is the core of a virtual machine tool, can estimate the cutting force and the machined surface error under changing cutting conditions. This capability was verified by comparisons between predicted and measured values. Also, proper feed rates can be scheduled to regulate the cutting force to a reference value preset by the operator.

Since the cutting process module described in this paper uses cutting-condition-independent coefficients, machining results can be accurately predicted for transient cuts. This means that the cutting process module can be effectively used for developing various application models, which can then be incorporated into a virtual machine tool.

Acknowledgments

The authors would like to thank the Korea Institute of Science & Technology Evaluation and Planning (KISTEP) for supporting this work through the International Joint Project Research Fund (98-I-01-03-A-023). The support of the National Science Foundation (USA) through the Machine Tool Agile Manufacturing Research Institute (MTAMRI) is also gratefully acknowledged.

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