620 *KSME International Journal, Vol. 11, No. 6, pp. 620~628, 1997*

System Identification and Admittance Model-Based Nanodynamic Control of Ultra-Precision Cutting Process

Sang-Hwa Jeong* **and Jong-An Park****

(Received August 29, 1996)

The control of diamond turning is usually achieved through a laser-interferometer feedback of slide position. The limitation of this control scheme is that the feedback signal does not account for additional dynamics of the tool post and the material removal process. If the tool post is rigid and the material removal process is relatively static, then such a non-collocated position feedback control scheme may suffice. However, as the accuracy requirement gets tighter and desired surface contours become more complex, the need for direct tool-tip sensing becomes inevitable. The physical constraints of the machining process prohibit any reasonable implementation of a tool-tip motion measurement. It is proposed that the measured force normal to the face of the workpiece can be filtered through an appropriate admittance transfer function, providing an estimated depth of cut. This can be compared to the desired depth of cut to generate the adjustment control action in addition to position feedback control. In this work, the design methodology on admittance model-based control with a conventional controller is presented. The recursive least-squares algorithm with forgetting factor is proposed to identify the parameters and update the cutting process in real time. The normal cutting forces are measured to identify the cutting dynamics in the real diamond turning process using a precision dynamometer. Based on the parameter estimation of cutting dynamics and the admittance model-based nanodynamic control scheme, simulation results are shown.

Key Words: Diamond Turning Machine, Admittance Model, Nanodynamic Control, Modulation, System Identification

1. Introduction

Diamond turning machines have, been used for the processing of surface like a mirror with the control scheme of minimizing shape error. Surface finish and shape precision are determined according to the shape of the diamond tool, tool sharpness, material properties, rake angle, and the material properties of the workpiece.

However, this approach is limited to improving the shape precision and the surface finish. The control of diamond turning is usually achieved through a laser-interferometer feedback of slide position. The limitation of this control scheme is that the feedback signal does not account for additional dynamics of the tool post and the material removal process. If the tool post is rigid and the material removal process is relatively static, then such a non-collocated position feedback control scheme may suffice. However, as the accuracy requirement gets tighter and the desired surface contours become more complex, the need for direct tool-tip sensing becomes inevitable. The physical constraints of the machining process prohibit any reasonable implementation of a tool tip motion measurement. It is proposed that the measured force normal to the face of the workpiece can be filtered through an appropriate admittance transfer function to obtain the estimated depth-of-cut. This can be compared to the

---

* Assistant professor, Department of Mechanical Engineering, Chosun University, Factory Automation Research Center for Parts of Vehicles

** Professor, Department of Electronic Engineering, Chosun University, Factory Automation Research Center for Parts of Vehicles

desired depth-of-cut to generate the adjustment control action in addition to position feedback control. One of the most powerful parameters in precision machining is tool force. It can be measured rapidly and it contains information about the fabrication process, the tool, and the material. One crucial aspect of characterizing the force surface roughness relationship is understanding the dynamics of the tool-workepiece interface. Depending on machining parameters such as tool sharpness, rake angle, and the material properties of the workpiece, the dynamc relationship between the cutting force and the position of the tool can be changed.

Moriwaki (1976) and Tlusty (1978) have proposed a theoretical model of the cutting dynamics and machining structure for cutting process and presented experimental verification of their model. For diamond turning, Luttrell and Dow (1987) developed a mathematical model of the interaction dynamics by first assuming a simple stiffness and damper model and experimentally obtaining the parameters of the model of the cutting dynamics for different materials and tool conditions. However, sufficient information about the force-based control algorithm has not been known to improve the surface roughness. The aim of this work is to develop techniques to improve the surface finish of a precision turning operator using force-based feedback control. Feedback will be provided by position information from the tool and the workpiece as well as forces in the cutting and normal direction measured by a sensor near the tool edge. The addition of force feedback will enhance control of the surface by improving the characterization of the system over that possible with position feedback alone.

In this work, we measure the cutting force using a precision dynamometer in the real diamond turning process, and the parameters of the cutting process are identified by the least-squares algorithm with forgetting factor. In addition, as a first step of nanodynamic control using cutting force, an admittance model is proposed for the overlapping cutting condition and conventional control schemes (P or PI control) are applied to compare the performance for surface roughness improvement.

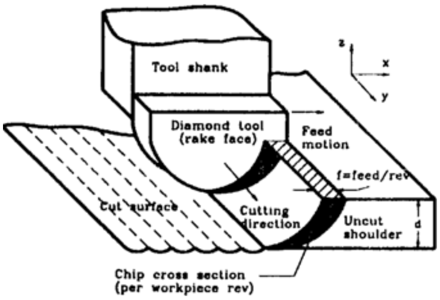

Fig. 1 Three-dimensional diamond cutting process

2. Admittance Model-Based Feedback Control

Single-point diamond cutting is a complex three-dimensional process that involves the removal of material from a workpiece. A basic configuration for single point turning is shown in Fig. 1, where the workpiece is rotating around the z-axis and the tool is moving along the x-axis. Since it is hard to directly measure the nanometer-level surface roughness in real time, the basic concept behind the admittance model is to extract surface roughness variations from force feedback information. The role of the admittance model in the feedback path, as shown in Fig. 2, is to properly map the relationship between the force variation and the surface roughness to obtain an accurate tool position error signal. The inputs to the admittance block are the force measurements from a high resolution force sensor. This kind of nanodynamic control problems, such as admittance model-based feedback control, is focused on input and output disturbance rejection and measurement noise reduction. In this work, an admittance model in an overlapping machining operation is proposed by using the damper-stiffness dynamic model, and two conventional controllers (P and PI control) are applied for rejecting input disturbances due to the z-slide structural vibration.

2.1 Overlapping factor

In general, face cutting in diamond turning is determined by the overlapping cutting factor. The schematic diagram of the overlapping cutting is

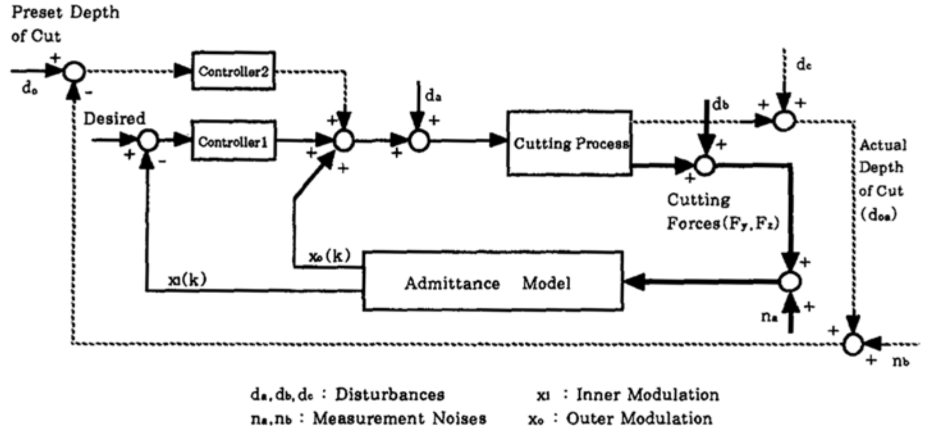

Fig. 2 Overall admittance model-based feedback control

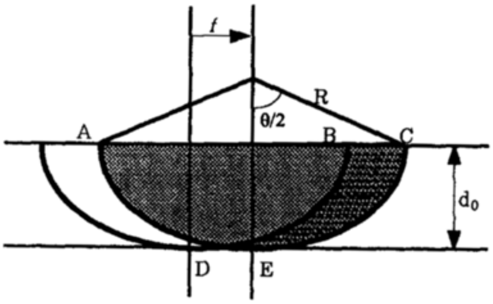

Fig. 3 Overlapping cutting

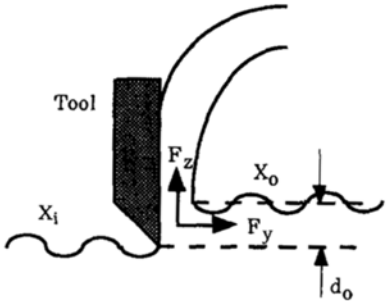

Fig. 4 Tool-workpiece interface model

shown in Fig. 3. The overlapping factor, μ, depends on the following four variables:

$$\mu = f(R,\ v_p,\ d_o,\ f_r) \tag{1}$$

where, R is the tool radius, v_p is the spindle speed, d_o is the cutting depth, and f_r is the feedrate. Since the overlapping factor is defined by the ratio of the overlapping area to the previously cut area, the overlapping factor can be written as the following expression:

$$\mu = \frac{Area(AEC) - Area(BCED)}{Area(AEC)} \tag{2}$$

where

$$Area(AEC) = \frac{1}{2}R^2\theta - R\cdot(R-d_o)\cdot\sin\frac{\theta}{2}$$
$$Area(BCED) = d_o \cdot f$$
$$\frac{\theta}{2} = \cos^{-1}\left(\frac{R-d_o}{R}\right)$$
$$f = f_r / v_p \text{ ; } Infeed\ rate$$

2.2 Admittance model with overlapping factor

The key to admittance model-based feedback control is to develop an admittance model which is generic for all machining conditions, material properties, and tool sharpness effects. The basic idea is to model the tool-workpiece interaction dynamics by assuming a spring-damper system. From the tool-workpiece interface model shown in Fig. 4, the uncut chip thickness at the k-th time step, $u(k)$, can be expressed by the preset depth-of-cut, d_o, the outer modulation, $x_o(k)$ and inner modulation, $x_i(k)$ as

$$u(k) = d_o + x_o(k) - x_i(k) \tag{3}$$

where $x_o(k)$ and $x_i(k)$ are unknown variables of which $x_i(k)$ represents the tool tip motions. Neglecting the residual component, the z-direction cutting force, $F_z(k)$, which is normal to the cutting direction, is proportional to the area of the cutting surface of the tool tip determined by the overlapping cutting factor. The overlapping factor, μ, is defined by the ratio of the overlapped area to the previously cut area and related to the tool radius, the spindle speed, preset depth-of-cut and the feedrate. An admittance model for the overlapping cutting can be written as

$$\begin{aligned} F_z(k) = {} & C[\dot{x}_o(k) - \dot{x}_i(k)](1-\mu)] \\ & + K[d_o + x_o(k) - x_i(k)] \cdot \\ & (1-\mu) \end{aligned} \tag{4}$$

where C is damping coefficient of the tool-workpiece interface model and K is the stiffness of the tool-workpiece interface model.

If the force $F_z(k)$ is measured, the relative modulation $x_o(k) - x_i(k)$ can be estimated by the above admittance model. In most instances of face cutting machining, since the outer modulation $x_o(k)$ is just a previous cut, it can be assumed that there is a time shift, d, between two modulations, i.e.,

$$x_o(k) = x_i(k) z^{-a} \tag{5}$$

where d is the time step per revolution. From Eqs. (4) and (5), two modulations, $x_o(k)$ and $x_i(k)$, can be estimated (provided $F_z(k)$ is measured).

2.3 On-line closed-loop control

A control structure based on the admittance model with a conventional controller is shown in Fig. 5. In Fig. 5, $\mathrm{F_{res}}$ is a z-directional cutting force when the cutting depth is zero during the normal cutting operation, the value of which is obtained from experiments. Two types of control schemes, P or PI control, are designed for this system. The transfer function for the PI controller (Tomizuka, 1988) is

$$C(z^{-1}) = \frac{(k_p + k_i) - k_p z^{-1}}{1 - z^{-1}} \tag{6}$$

where kp and ki are control gains of the proportional and integral action, respectively. The root locus plot for varying open loop gain can be obtained for the transfer function, $G_{open}(z^{-1}) = A(z^{-1}) P(z^{-1}) C(z^{-1})$. If the zero of the PI controller is chosen, the zero of a PI controller determines the relative magnitude between k_p and k_i. Based on the root locus plot and simulation trials, the zero of the PI controller is assigned at 0.6. In general, k_p is greater than k_i in the PI control. The general pole placement technique of the PI control is derived by Jeong (1994). In this work, the maximum magnitude of the proportional gains of each controller, P or PI, are selected to be the same for comparing the performance of the control schemes.

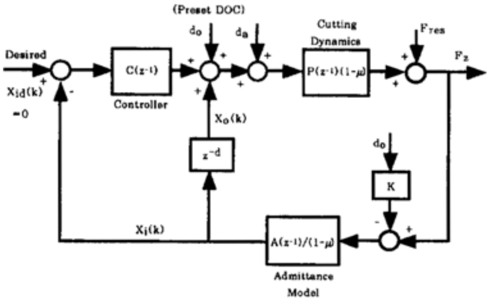

Fig. 5 Z-direction admittance model-based control scheme

3. Recursive Least-Squares Algorithm

Since the diamond turning dynamics is changing with time and cutting conditions, time varying parameters need to be identified recursively to obtain a more accurate model of the cutting dynamics in real time. A better estimation of the admittance model is the key to nanodynamic control for surface roughness. In this section, based on the recursive least square (RLS) identifier with exponential forgetting (Astrom, 1989), the real-time adjustment of admittance model parameters is discussed. The block diagram of this algorithm is shown in Fig. 6. It is an estimator with exponential forgetting. A diamond cutting process is selected in the form

$$P(z^{-1}) = \frac{b_o + b_1 z^{-1}}{1 - a_1 z^{-1}} \tag{7}$$

where a_1, b_o, and $\mathrm{b_1}$ are unknown parameters and can be determined from the cutting dynamics identified by the recursive least-squares estimator based on the actual cutting force data as well as the plant input. The applied recursive least-squares estimator with a constant forgetting factor (λ), whose value affects the response of the command tracking, is as follows:

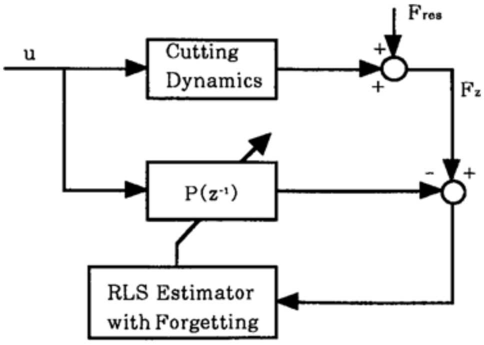

Fig. 6 System identification of diamond turning process

$$\hat{\theta}(k)=\hat{\theta}(k-1)+m(k)e(k) \quad (8)$$

$$m(k)=p(k-1)\Phi(k)(\lambda I+\Phi(k)p(k-1)\Phi(k))^{-1} \quad (9)$$

$$p(k)=(I-m(k)\Phi^{T}(k))p(k-1)/\lambda \quad (10)$$

$$e(k)=F_z(k)-\Phi^{T}(k)\hat{\theta}(k-1) \quad (11)$$

where $p(k)$ is a gain matrix, I is a unit matrix, $\hat{\theta}(k)=[a_1\ b_o\ b_1]^T$, and Φ is a regressor vector obtained from the measurement set. From Eqs. (7), (8), (9), (10), and (11), the unknown parameters, $\hat{\theta}(k)=[a_1\ b_o\ b_1]^T$, in the precision cutting can be identified.

4. System Identification of Cutting Process from Experiment

To identify the cutting process, the cutting force is measured by a precision dynamometer using a Nano Form 300 diamond turning machine installed at Samsung Electronics Co., Ltd. A Diagram of all the instrumentation for the cutting experiments and data acquisition is shown in Fig. 7, and the experimental apparatus is shown in Table 1. The basic set of cutting conditions used in this work is shown in Table 2. After measuring the cutting force under the cutting conditions of Table 2, the parameters of the cutting process are obtained from the Eqs. (7), (8), (9), (10), and (11) using MATLAB, and the estimated values of the parameters are shown in Fig. 8. It shows that the estimated parameters track the steady-state values quickly when $\lambda=0.9$. In the first order model, b0 converges faster than the other parameters due to the property of the initial value of the regressor vector as shown in Fig. 8

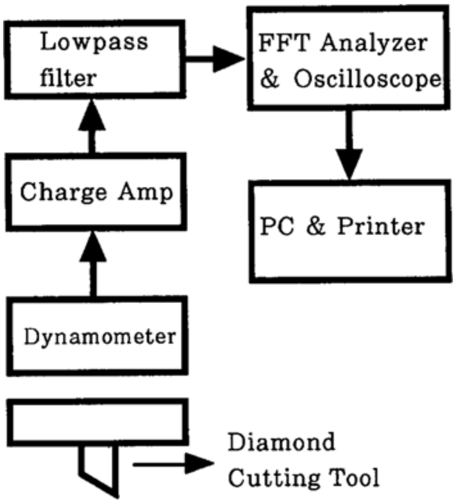

Fig. 7 Diagram of all the instrumentation for the cutting experiments and data acquisition

Table 1 Specification of apparatus and instruments

Apparatus	Model
Diamond Turning Machine	RTH Nano Form 300
Dynamometer	KISTLER 9257B
Charge Amp.	KISTLER Multi Channel Charge Amp. 5019A
FFT Analyzer	Hp 35670A
Surface Texture Measurement	Ikegami PM-930A

Table 2 Basic set of cutting conditions

Material : Copper	Cutting Speed : 774 mm/sec
Spindle Speed : 17.2 rps	Starting Radius of Workpiece : 45 mm
Cutting Depth : 6 μm	Feed Rate : 100 μm/sec
Infeed Rate : 5.8 μm/rev	Tool Radius : 0.8 mm
Overlapping factor : 0.98	Residual force(F_{res}) : 0.08 N
d : 174 time step	

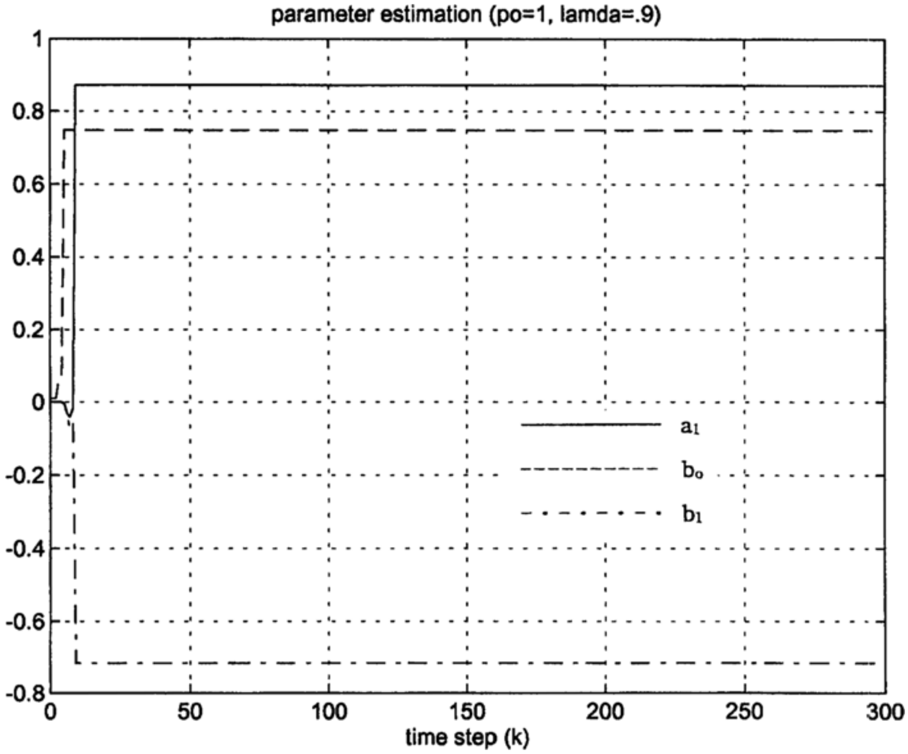

Fig. 8 Parameter estimation using RLS identifier

5. Simulation Result

The overlapping cutting process of diamond turning has been identified by experimental data and a recursive least-squares algorithm, and the nanodynamic control algorithm with a proposed admittance model is simulated using MATLAB. Based on the values of the parameter obtained in Fig. 8, the cutting process estimated from the experimental data of diamond turning can be written

$$P(z^{-1}) = \frac{0.7470 - 0.7164z^{-1}}{1 - 0.8725z^{-1}} \qquad (12)$$

The input disturbance, da, resulting from z-slide structure vibration, is assumed to be a colored low-frequency noise which has dominant frequency at 17 Hz, 52 Hz, 86 Hz, 113 Hz and 120 Hz. A random white noise with small magnitude is added to a more accurate model of the actual cutting process. The maximum proportional gains for P and PI control are selected as 10. The response of the discrete-time closed-loop system with a sampling frequency of 5 KHz is simulated using MATLAB for the open loop system, P, and PI control with the admittance model, respectively. When the system input contains disturbances and 6 μm preset depth-of-cut, the z-direction cutting force, F_z, and the inner modulation, x_i, are shown in Figs. 9 and 10. Figures 9 and 10 illustrate that the surface roughness related to the inner modulation has been improved by implementing the PI controller. In view of the simulated results shown in Figs. 11 and 12, it is clear that RMS and Peak to Valley(P-V) of the inner modulation can be reduced by applying the on-line feedback controllers(P or PI) with an admittance model to the overlapping cutting process. In Fig. 11, the RMS value of the inner modulation for just input disturbance (d_a) is reduced by about 34% for the closed loop feedback controlled system, while the P-V is improved by about 33%. Figure 12 shows that the

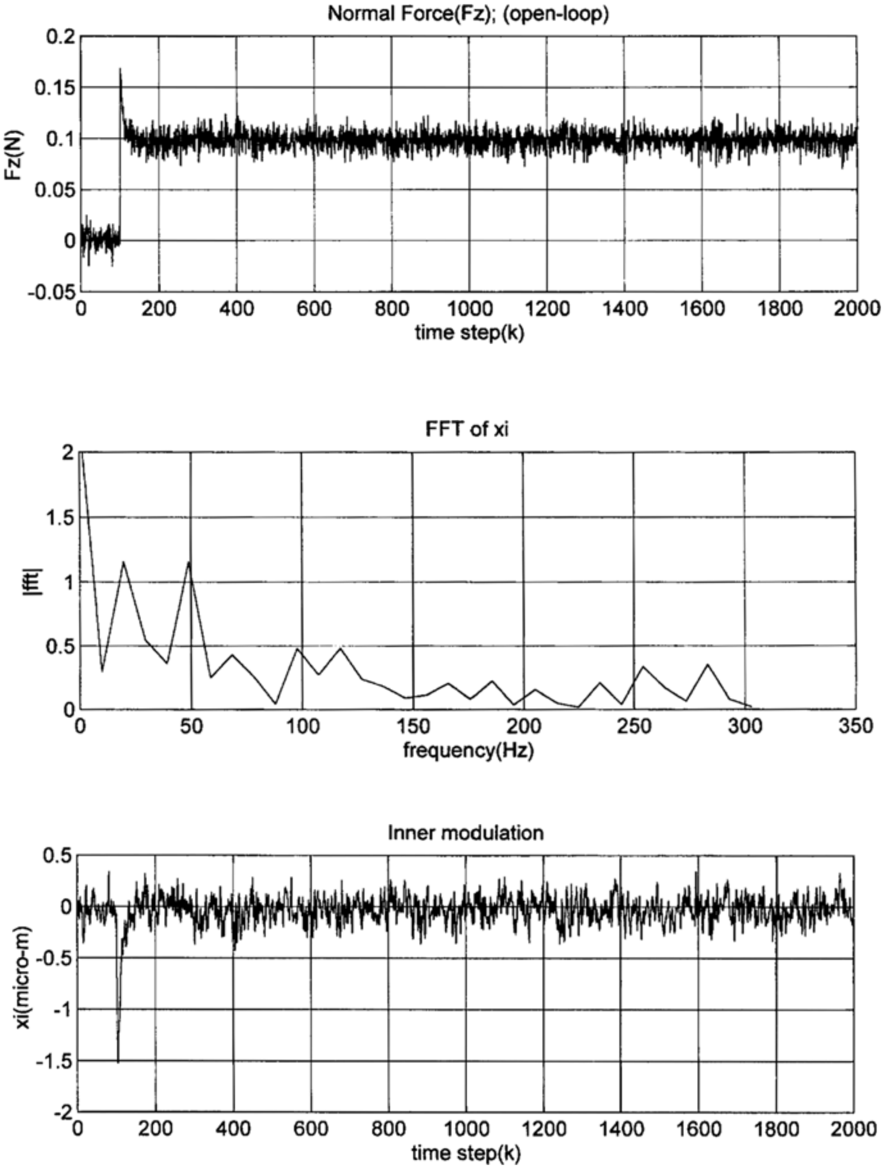

Fig. 9 Open-loop responses of normal force and inner modulation for 6μm depth-of-cut and input disturbance

RMS and P-V is reduced up to 51% and 72%, respectively, when the inputs to the cutting process are 6μm depth-of-cut (d_o) and the input disturbance (d_a).

6. Conclusions

The surface roughness directly related to the inner modulation can be reduced by applying on-line closed-loop feedback controllers (P or PI) with an admittance model to the overlapping cutting process. In this work, as a first evaluation of the admittance model-based control, the feasibility of the feedback control based on surface modulations estimated by the proposed admittance model is shown. The simulation results of nanodynamic control using an admittance model applied to the material removal process, which is

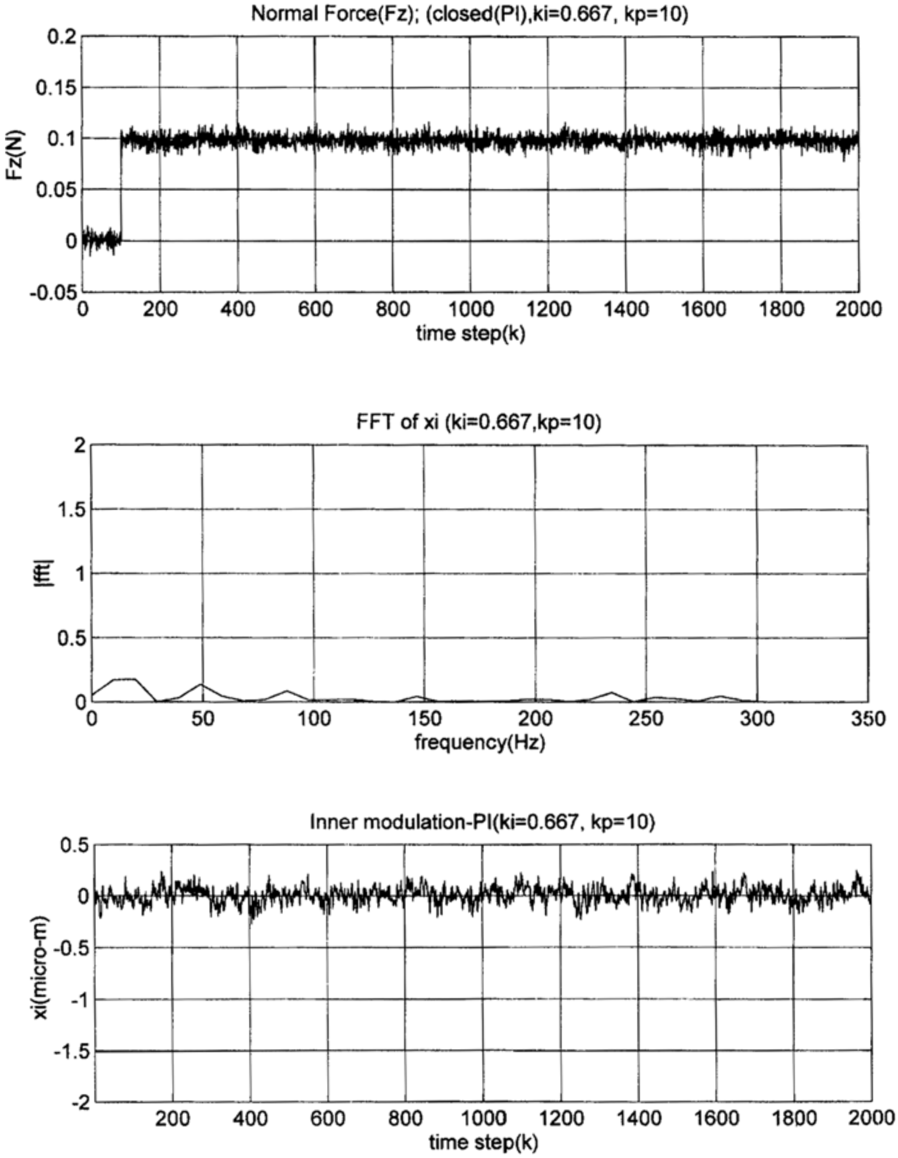

Fig. 10 Closed-loop responses of normal force and inner modulation for $6 \mu m$ depth-of-cut and input disturbance with PI controller

estimated from the real experimental data, shows that the surface roughness is greatly improved by applying the control scheme using this new algorithm.

Acknowledgment

This study was supported by the Factory Automation Research Center for Parts of Vehicles (FACPOV) at Chosun University, Kwangju, Korea. FACPOV is designated as a Regional Research Center of the Korea Science and Engineering Foundation (KOSEF) and operated by Chosun University.

References

Astrom, K. J. and B. Wittenmark., 1989,

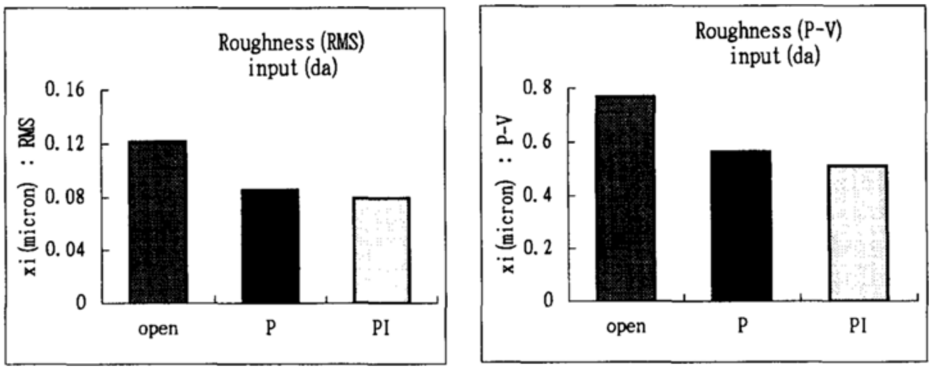

Fig. 11 Comparison of the surface roughness for input disturbance

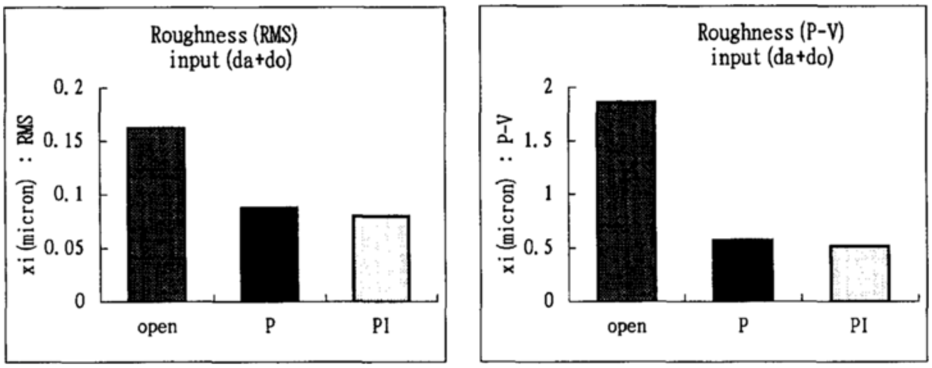

Fig. 12 Comparison of the surface roughness for input disturbance and 6μm depth-of-cut

Adaptive Control, Addison Wesley.

Drescher, J. D., 1989, "Tool Force Measurement in Diamond Turning," MS Thesis, North Carolina State University.

Jeong, S. H., 1994, "On Robust Dynamic Controller Design," *KSME Journal*, Vol. 8, No. 2, pp. 127~135.

Luttrell, D. E. and T. A. Dow., 1987, "A Proposed Method for Identifying the Dynamics of Single Point Diamond Cutting," *Precision Engineering Center Annual Report*, Vol. 5, pp. 171~185.

Moriwaki, T. and K. Iwata., Feb., 1976, "In-Process Analysis of Machine Tool Structure Dynamics and Prediction of Machining Chatter," *J. Eng. for Industry, Trans. ASME*, Paper No. 75DET-20, pp. 301~305.

Tlusty, J., 1978, "Analysis of the State of Research in Cutting Dynamics," *Annals of the CIRP*, Vol. 27[2], pp. 583~589.

Tomizuka, M. and S. Zhang., 1988, "Modeling and Conventional/Adaptive PI Control of a Lathe Cutting Process," *J. of Dynamic Systems, Measurement and Control, Trans. ASME*, Vol. 110, pp. 350~354.

Yang, S. and M. Tomizuka., 1988, "Adaptive Pulse Width Control for Precise Positioning Under the Influence of Stiction and Coulomb Friction," *J. of Dynamic Systems, Measurement, and Control, Trans. ASME*, Vol. 110, pp. 221~227.