A Study on the Improvement of Servo Control Characteristics of Ultra Precision Machine Tools by ANFIS-PID Controller

Su-Bom Yun [a*], On-Jong Sim [a], Yong Li [b], Yong-Il Kim [b], Song-Il Jeng [b] Un-Chol Ri [c]

[a*], [a], [b] Facaulty of machine engineering, Huichon industry university, Huichon, Democratic People's Republic of Korea

[c] Faculty of Machine Engineering, Ham Hung University of hydraulics and power ,Ham Hung , Democratic People's Republic of Korea

Corresponding author. * E-mail address: ysb8688@126.com

Abstract

The demand for ultra-precision machining is increasing day by day. In particular, demand for ultra-precision processing products is increasing in many fields such as defense industry, space industry, and economy. Accordingly, ultra-precision processing technology is also increasing. However, the precision of machining varies depending on the environment. The most influential factors are vibration, temperature, and wear.

Therefore, a special tool setting a micro-thermosensor is installed to measure the temperature change at the cutting point in real time. Recently, various artificial intelligence manipulation techniques have been studied to overcome these deficiencies.

In this paper, we describe the improvement of the control accuracy compared to the previous controllers by applying the adaptive neuro-fuzzy controller that takes into account the model uncertainty of the subject and by conducting the simulation.

Key words: Ultra-precision Machining, In-Process Monitoring, Thermosensor, ANFIS, Cutting Heat

1. Introduction

The demand of an ultra-precision machining has recently increased in a variety of industrial products, i.e., a mold for micro parts, an optical lens, a medical instrument, etc. In addition, higher accuracy and higher productivity are still desired. In order to meet these demands, it is effective to materialize a closed machining environment since this realize the best machining environment and allows isolation from external disturbance[1]. However, closed machining environment often limits operator's access, and hence it is necessary to install an effective in-process machining status monitoring system into ultra-precision machining tool and also optimally control the machining parameters as to maintain the stable cutting status during the overall machining process.

An adaptive control system requires an effective in-process machining status monitoring system which contains sensors, allied data transfer circuit, signal processing and status recognizing functions.

Although some studies on in-process cutting status monitoring or adaptive control for conventional process have been conducted by using a variety of sensors such as force, power, acoustic emission, vibration and temperature [2]; while there have been few studies for application for ultra-precision machining process so far.

Because the behaviors such as cutting force, power and acoustic emission, and the cutting heat generation during ultra-precision machining are quite small in comparison with conventional machining processes, it is difficult to realize an effective in process sensor. However, the cutting temperature at the cutting point is high enough to measure [6]. Therefore it is possible to monitor the cutting status during an ultra-precision machining by measuring the thermal behavior near the cutting point.

The problem is that measuring the temperature of the cutting point, and thus controlling the spindle speed and the sending speed of the table, produces a relatively complicated problem [4]. It can’t obtain its exact mathematical model under the condition that the characteristic of the object is very unstable and the effect of disturbance is severe, and it causes a serious error in the processing of the wicket.

Owing to its high measuring resolution and quick response, the micro-thermosensor can detect the thermal behavior near the cutting point during an ultra-precision machining. We have designed a self - adaptive control system to measure the temperature at the cutting point by using the already installed tool of the micro - thermosensor and determine the cutting speed based on it.

In addition, we conducted simulation in Matlab environment and analyzed its characteristics.

2. Analysis of temperature characteristics at cutting point

2.1 Recognition of the cutting conditions

An effective method of recognizing the status of ultra-precision machining, i.e. tool, workpiece, coolant, and chip-flow, is to monitor the thermal behavior near the cutting point. Figure 1 shows the micro-thermosensor structure of the tool be applied.

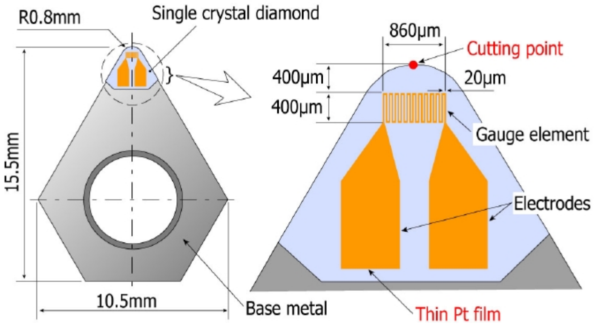

Fig. 1 Structure of the developed micro-thermosensor

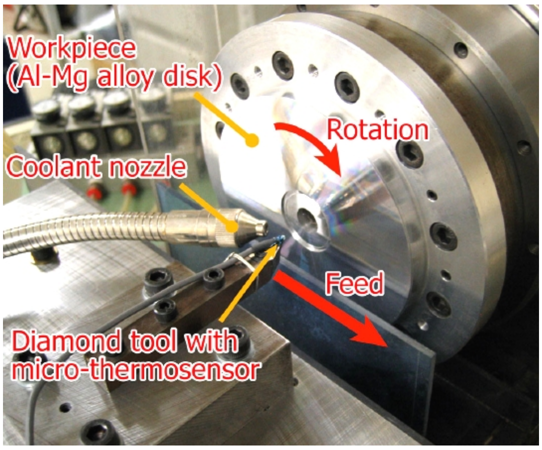

Fig. 2 Configuration of the cutting environment

In order to clarify the relationships between the sensor output patterns and cutting status, face turning experiments were performed without changing the cutting conditions during the cutting process. The cutting conditions are shown in table 1.

Table 1. cutting conditions

No	title	content	note
1	Tool	Single crystal diamond tool	Nose radius=0.8mm Rake angle=0°
2	workpiece	Al-Mg alloy disk	
3	Depth of cut	3,5,10,15㎛	
4	Feed rate	10, 15㎛ / *rev*	
5	Spindle speed	3000rpm(236~895m/min)	
6	Cutting speed	5000rpm(393~1492m/min)	

Figure 3 shows a typical temperature pattern near the cutting point during the cutting process. As shown in this Figure, the temperature changes quickly at the beginning and ending of the cutting process and it increases linearly during steady-state cutting. As both the spindle speed and the feed speed are constant, the cutting speed increases linearly according to feed motion from inside to outside.

In steady-state cutting, the relationship between the cutting speed and the rise of the temperature near the cutting point can be linear.

At the beginning of the cutting process, interrupted cutting was observed in cutting a workpiece on the vacuum chuck of the machine tool with decenterizing.

Figure 4 shows an example of measured temperature pattern at the beginning of the cutting process with a spindle speed of 5000rpm.

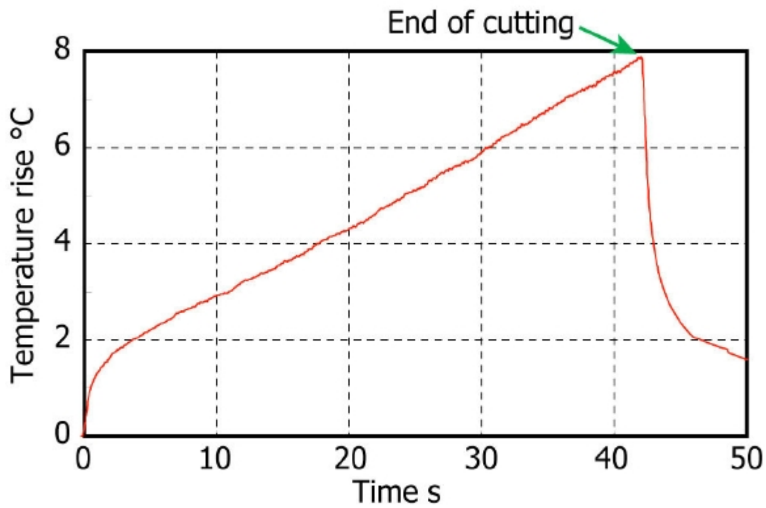

Fig. 3 Typical temperature patterns during cutting, with depth of cut of 5μm, feed rate of 10μm/rev, and a spindle speed of 5000rpm

As shown in this figure, the temperature near the cutting point changes quickly in a cycle of about 12ms synchronized with a spindle rotation.

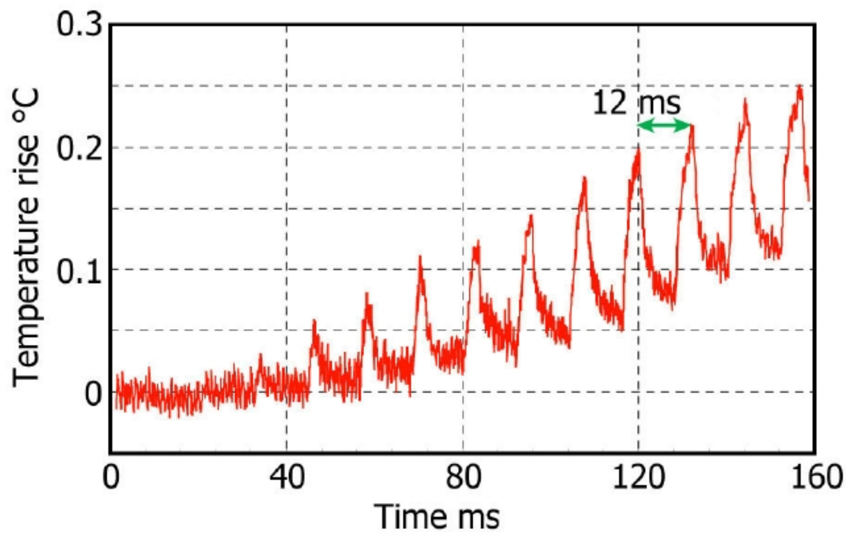

Fig. 4 Temperature patterns during interrupted cutting with depth of cut of 5μm, feed rate of 10μm/rev, and a spindle speed of 5000rpm

Figure 4 illustrates the correlations between the cutting speed and measured temperature at a spindle speed of 5000rpm, a depth of cut of 3μm and a feed rate of 15μm/rev.

Next, we will discuss about the time constant of the micro-thermosensor. If the system could be assumed as a first-order system which temperature can be given as the following equation, $T = a(1 - \exp(-t/t))$, where a, t, τ are constant, time and time constant, respectively. The time constant of the system could be obtained by fitting this formula to short periodic temperature rise (for example 128ms-132ms) shown in figure 5.

The estimated time constant of the micro-thermosensor could be approximately 2ms. Because of the micro-thermosensor is mounted on the diamond tool near the cutting point, the sensor achieves high response.

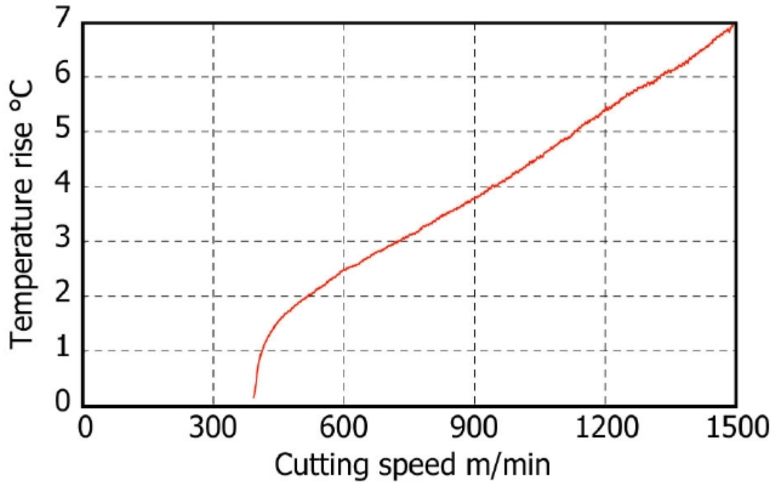

Fig. 5 Temperature rise vs cutting speed in cutting with depth of cut of 3μm, feed rate of 15μm/rev, and spindle speed of 5000rpm

In addition, to clarify the relationship between the sensor output and the depth of cut, cutting experiments were performed with the several depths of cut conditions. Figure 6 shows the temperature rise, a spindle speed of 3000rpm and a feed rate of 10μm/rev. As can be seen in this Figure, the liner relationship between the depth of cut and the temperature variation can be confirmed. The temperature rise is caused by a lot of factors not only the cutting speed and the depth of cut but also other environmental factors i.e., the spindle speed, coolant, chip-flow, etc. However, the sensor output tends to increase linearly as the cutting speed and the depth of cutting increased.

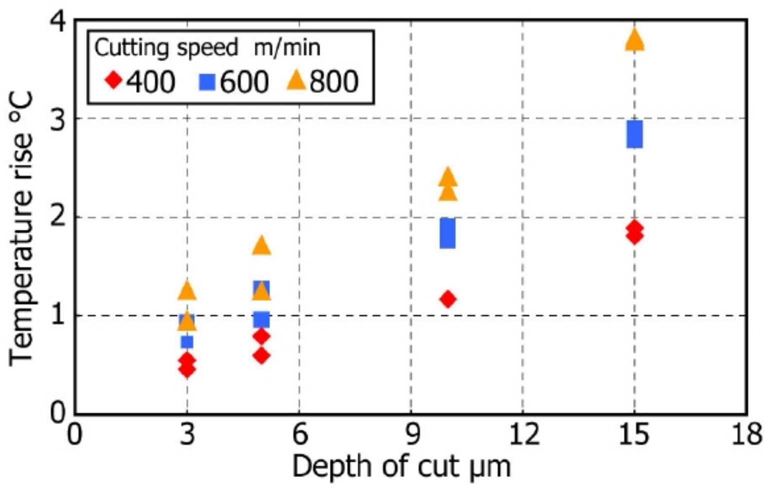

Fig. 6 Temperature variation vs depth of cut with a feed rate of 10μm, spindle speed of 3000rpm, cutting speed of 400m/min

2.2. Detection of an abnormal chip flow

In actual cutting process, occasionally, an abnormal chip-flow could be observed. At that time, if the cutting condition is equal, the temperature near the cutting point increases, and also the thermal behavior near the cutting point become unstable in comparison with a normal status.

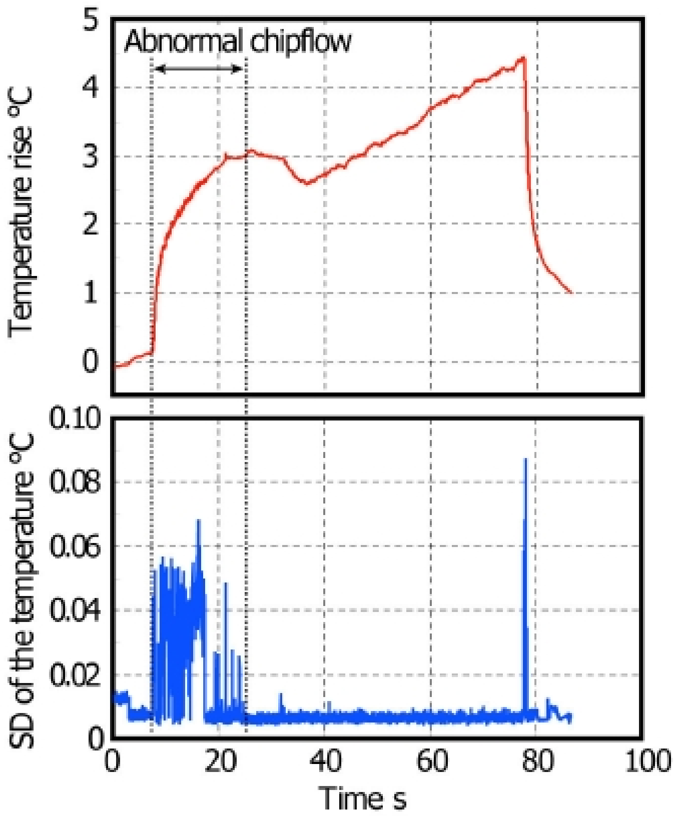

Fig.7 Temperature and standard deviation in cutting with abnormal chip flow.
Spindle speed is 1000rpm, depth of cut is 3μm and feed rate is 30μm/rev

Figure 7 shows an example of measured temperature and its standard deviation in case of chip stagnation. There may be two reasons for increasing those parameters. The first, as chip stagnates around the front of the tool tip, heat transfer from the cutting point to the micro-thermosensor becomes unstable. The second, although the gauge element of the micro-thermosensor is covered with the glass prate as electric insulator, the existence of the stagnated chip allows the electric noises to transfer from the machine tool or the environment to the gauge element of the micro-thermosensor easily. The variation ofthe standard deviation of the sensor output has no relationships with the cutting conditions i.e., a cutting speed, a depth of cut, a feed rate, etc. Thus,the developed micro-thermosensor can detect an abnormal chip-flow.

The mathematical model was determined from the characteristics of the object as follows. The system adopts the flying curve method. According to the curve fitted by the temperature and temperature, the three parameters of the controlled object model are obtained.

T_{min}=100s, T_{max}=300s, pure lag time t_{min}= 20s, t_{max}=80s, magnification is about K = 4.

$$G_{(s)} = \frac{Ke^{-ts}}{Ts+1}$$

3. Construction of ANFIS-PID control system for ultra-precision machine tools

3.1 Configuration of PID control system

Above mentioned experimental results confirm that the temperature near the cutting point has a linear relationship with the cutting speed.

Cutting conditions which can maintain the temperature near the cutting point constant are determined with a PID controller during the cutting process.

PID control is a typical control method. It is a kind of negative feedback control. It has the advantages of simple and convenient principle.

It has been widely used in various fields. PID control schematic diagram 8.

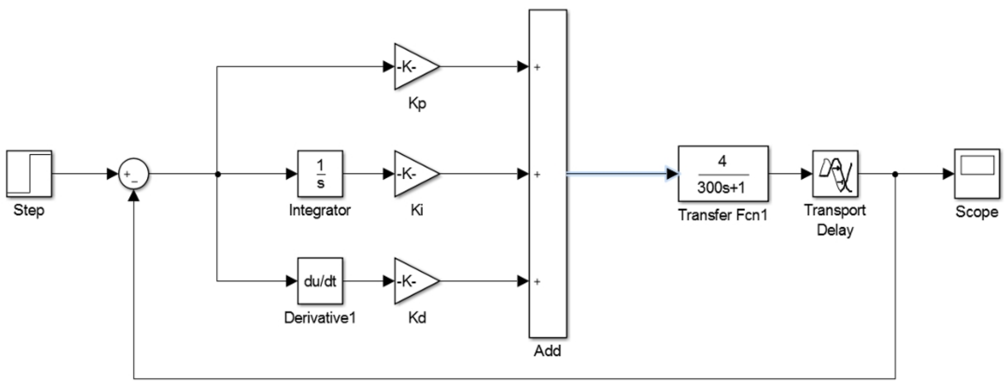

Fig. 8 Configuration diagram of traditional PID controller

By analyzing the PID control system through simulation, the following unit step response characteristic can be obtained.

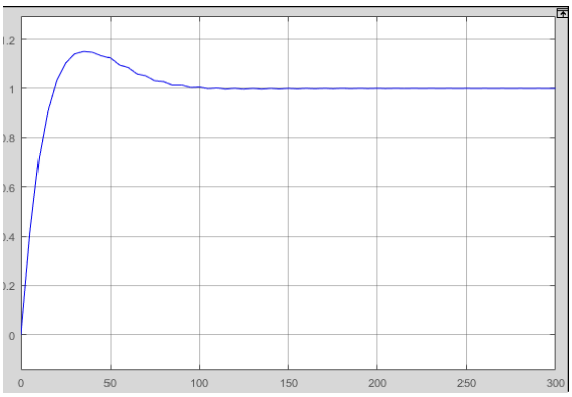

Fig.9 The unit step response characteristic curve of the PID control system

As shown in the figure, the response speed is fast, but the transient value is large, the transient process is high, and the stabilization time is long. If there is perturbation of disturbance in the steering system, the entire system becomes unstable or there is a severe model uncertainty. In order to prove this, the simulation was carried out by applying arbitrary change of disturbance to the system. The disturbance was selected as an arbitrary waveform changing from 0 to 1 at a frequency of 70 Hz.

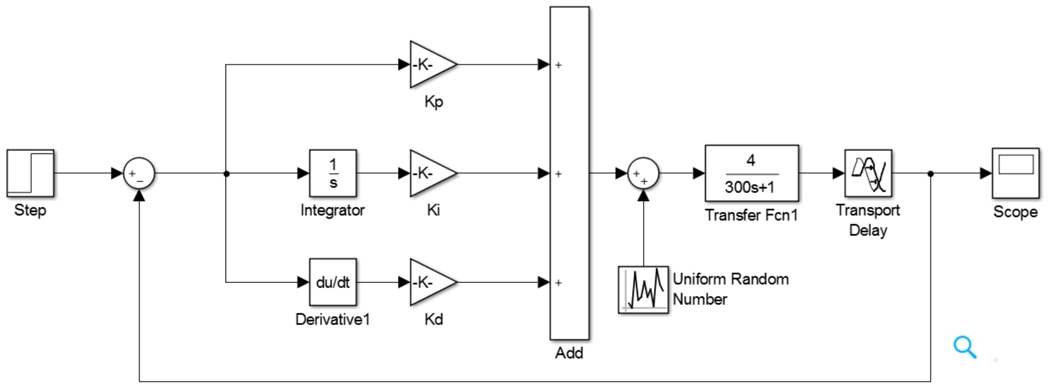

Fig.10 Block diagram of the PID control system with disturbance input

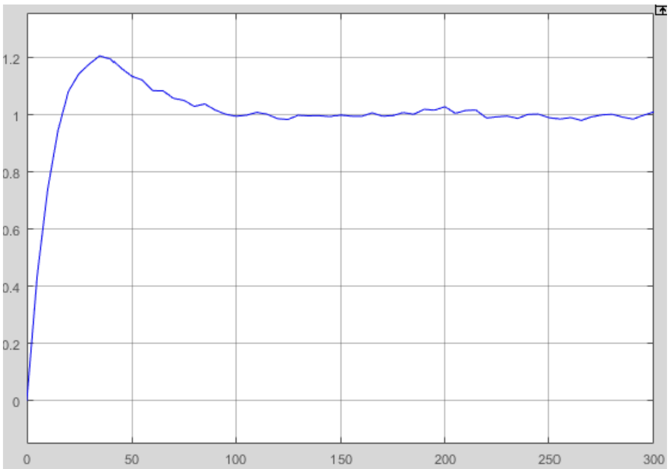

Fig. 11 Response characteristics when disturbance is applied in the system

By comparison, it can be concluded that when adopting conventional PID control, the system has poor stability and good control effect when the time delay is small, the overshoot is small, the stability is good, and the time delay is long.

3.2 The control system of ultra-precision machine tools by ANFIS

The temperature control of the ultra-precision machine tool proposed in the paper is a highly precise monitoring and control system that measures the temperature change at the cutting point in real time and controls the spindle rotation speed and the feed speed of the table. Therefore, it can not be solved by the traditional control method, and the problem of identifying the characteristics of the object also creates complexity. In the preceding studies, it was suggested that self - adaptive neuro — fuzzy inference system was applied to various objects and its effectiveness was obtained.

In this paper, the mathematical model of the object was set as a one number inertia delay segment and the control was realized.

The parameters of fuzzy self-tuning PID controller is to find out the fuzzy relation in different time between PID and three parameters e and e_c, e and e_c in the detection of continuous operation, according to the fuzzy control principle of three parameters are modified online, to meet the different e and e_c control parameters for different requirements, and the accused the object has a good dynamic and static performance. DKp, DKi, DKd are considered from the traditional stability, response speed, overshoot and stability accuracy.

The function of Kd, Kp, Ki three parameters self-tuning requirements are as follows:

1) when the deviation $|e|$ is large, in order to accelerate the response speed of the system, should take a larger Kp; in order to avoid differential since the start of the deviation of e becomes possible supersaturation and the control action is beyond the scope of permission, shall be smaller Kd; in order to prevent the system response of a larger overshoot, produce integral saturation, with integral action limits, usually Ki=0, remove the integral effect.

2) when $|e|$ and $|e_c|$ are in the middle size, in order to make the system response have a small overshoot, Kp should take a little bit, Ki value is appropriate, the value of Kd has a great impact on the system, and the value is moderate to ensure the response speed of the system.

3) when the $|e|$ is smaller, that is, it is close to the set value, in order to make the system have good steady state performance,the value of Kp and Ki should be increased. At the same time, in order to avoid the oscillation of the system in the vicinity of the set value, and considering the anti-interference performance of the system, the value of Kd is very important. The value of Kd should be larger when the average $|e_c|$ is smaller: when the $|e_c|$ is larger, the value of the Kd should be smaller.

4) the size of the variation of $|e_c|$ shows the variation rate of the deviation, the larger the $|e_c|$ value, the smaller the value of Kp, the greater the value of the Ki.

According to the principle of PID parameter setting, the output variables of fuzzy controller are listed on the basis of summarizing the technical knowledge and practical experience of the technical personnel.

The table of control rules for DKp, DKi, and DKd (table 2, table 3, table 4).

Table 2 D*Kp* fuzzy control rule table

ΔK_P				EC			
E	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

Tabe 3 D*Ki* fuzzy control rule table

ΔK_I				EC			
E	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NB	NM	NS	NS	ZO	PS	PS
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PS	PM	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

Tabe 4 D*Kd* fuzzy control rule table

ΔK_D				EC			
E	NB	NM	NS	ZO	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZO
NS	ZO	NS	NM	NM	NS	NS	ZO
ZO	ZO	NS	NS	NS	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

By using MATLAB, it is very convenient and precise to create a mathematical model. MATLAB has a fuzzy editor that can be used to create ambiguous original functions, to create ambiguity rules, to express them in ANFIS, and to create and manipulate mock models while intuitively viewing the existence and distribution of functions.

The following steps are used to create a mathematical model using MATLAB.

1) Select a morphological model (paper: Sugeno model)

2) Select the following membership function (paper: gaussmf)

3) Proceed to place the membership function according to the set interval and create the ambiguity rule. (paper: Write 49 rules)

4) Expressed as ANFIS

5) When the rule creation is completed, it is saved as a * .fis file.

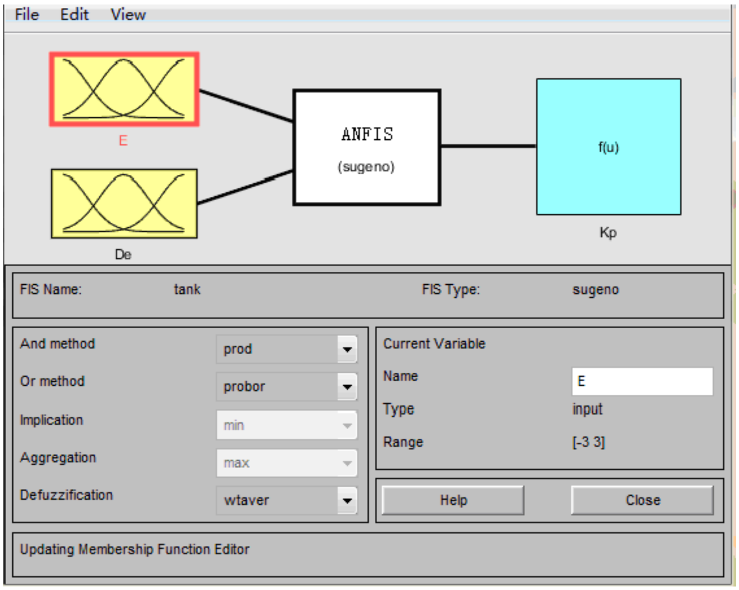

Fig.12 2 input 1 output fuzzy model creation

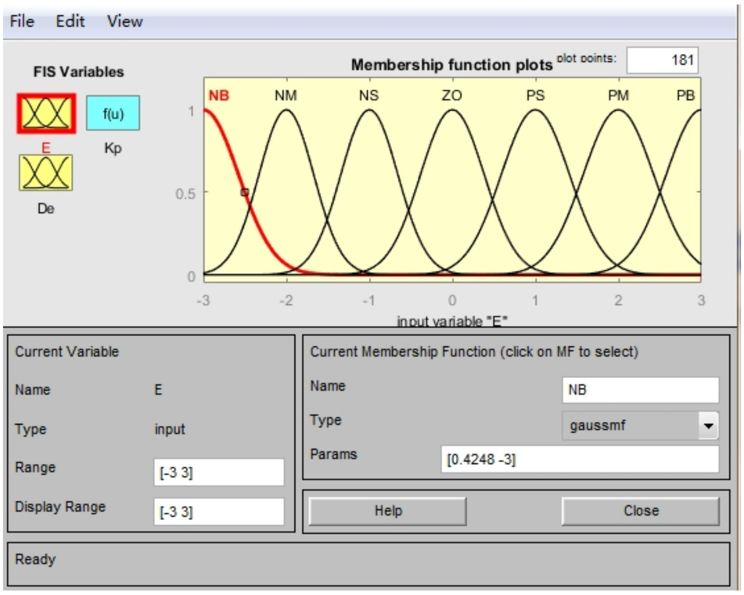

Fig.13 Set membership functions

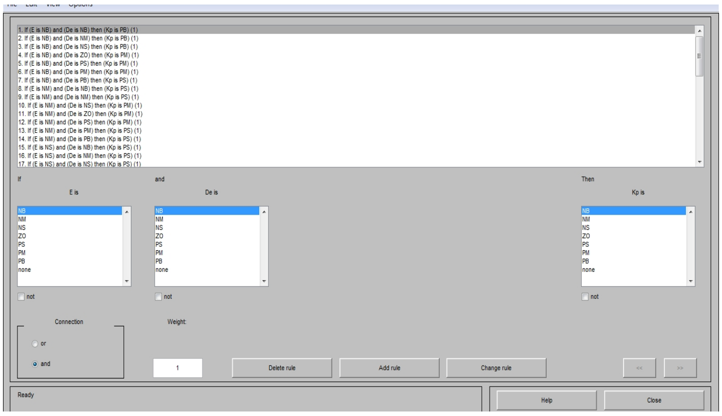

Fig. 14 edit an fuzzy rule

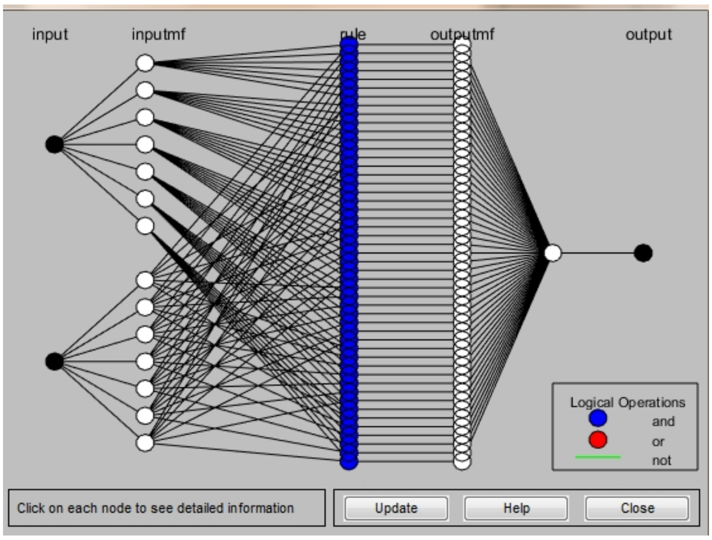

Fig.15 Adaptive neural network form representation of fuzzy rules

The self-adaptive neuro-fuzzy control system that controls the spindle rotation speed and the feed rate of the feed system the ultra-precision machine tool is constructed as follows using the neural-fuzzy control system designed as above.

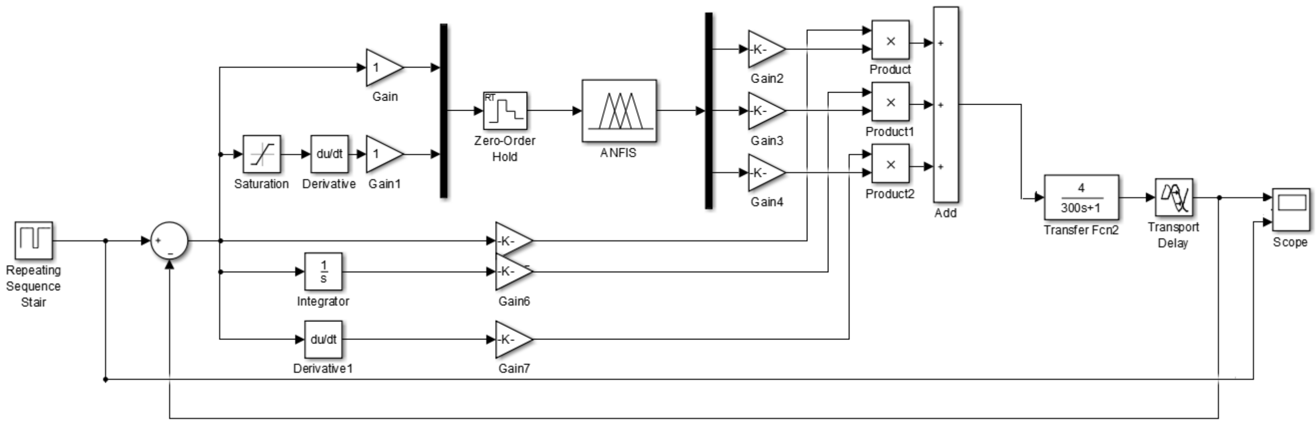

Fig.16 Configuration of Adaptive PID Control System by ANFIS

In order to analyze the characteristics of the maneuvering system, we designed and simulated a control box in the MATLAB/simulink environment. Note that the nerve-ambiguity constructor must be precisely named and saved in the same working folder.

First, we entered the unit step input signal and simulated.

The next PID control system was combined with the simulation.

Next, the characteristics of the proposed control system and the comparison with the already applied PID control system were simulated.

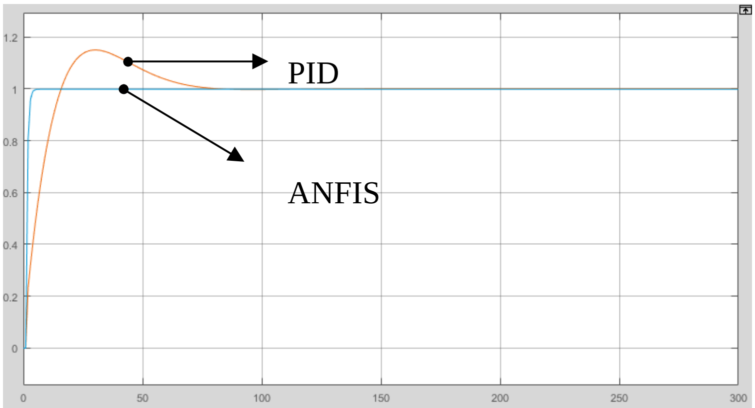

Fig.18 Response characteristic curve of ANFIS control system and PID control system for unit step signal input

As can be seen from the simulation results, it shows that the characteristics of the newly proposed control system far outweigh the previous PID control system.

If we consider the transient time and the transient process, we will give an impulse input signal to investigate the responsiveness.

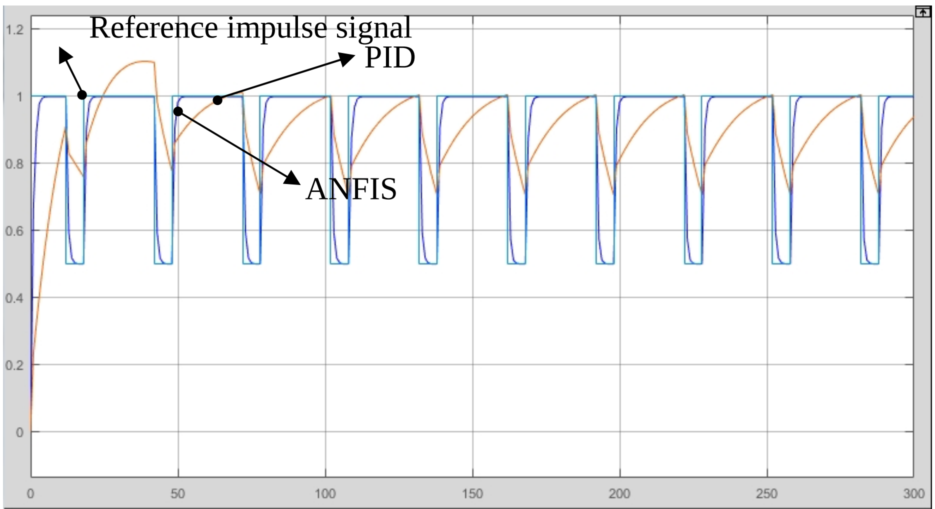

Fig.19 Response characteristic curve of two control systems when implus signal is input

From the simulation results, the characteristics of the proposed control system are that the transient time is short, the over - regulation amount is small, and the quick response is good.

3.3 Technical realization of control system

The control system proposed above is a kind of intelligent control system, and its operating characteristics have real-time characteristics and adaptation characteristics.

The cutting process of ultra-precision machine tools is a highly demanding work process in which various complicated phenomena occurring at the cutting point are monitored in real time and it is necessary to cope with it promptly and accurately.

In particular, the heat phenomenon at the cutting point has a large time constant and a delay time, which requires auxiliary control such as prediction, adaptation, compensation, etc., and there is a guarantee of product precision.

In the paper, a new CNC system was constructed and tested to apply the proposed adaptive control system to the object.

Recently, in the field of computer control system technology, a lot of computer technology and USB control technology have been introduced.

From this, we constructed and simulated a computer control system using one personal computer and PIC18F4550.

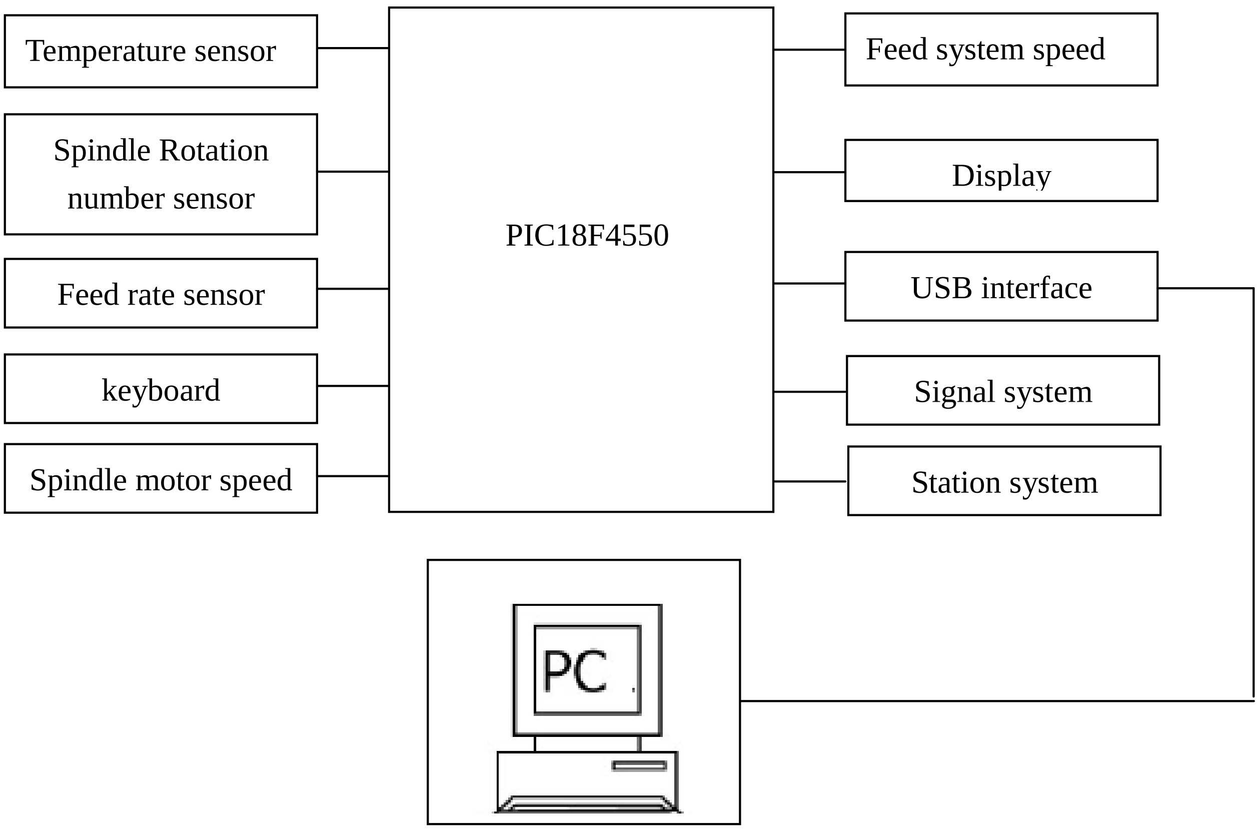

Fig.20 total block diagram of the computer control system

3.4 Cutting of a flat workpiece

Experiments for controlling the cutting temperature were performed using the developed adaptive control system as shown in Figure 12. The temperature and the reference of spindle speed during the cutting are shown in Figure 13, where a depth of cut is 5μm, a feed rate is 15μm/rev, a target temperature change is 7.1° C (the change of the sensor output is 1570m V), and a limit of spindle speed is 5000 rpm. The target temperature change as 7.1° C is an example. At the beginning and ending of the cutting process, the reference of spindle speed is the upper limit of 5000 rpm since the temperature near the cutting point is lower than the target temperature. After the temperature reached the target temperature, the reference of the spindle speed was adjusted to maintain the target temperature by the PID controller. When the spindle speed is decreased, the feed speed of the tool is also decreased to maintain the feed rate of the tool to be constant. Thus, the cutting time with the temperature controller is longer than which without controller. As can be seen in Figure 13, overshoots and fluctuations were seen on initial stage of adaptive controlled process. This reason can be that the setting of PID gain was not turned optimal or the machine tool could not follow the quick change of cutting conditions.

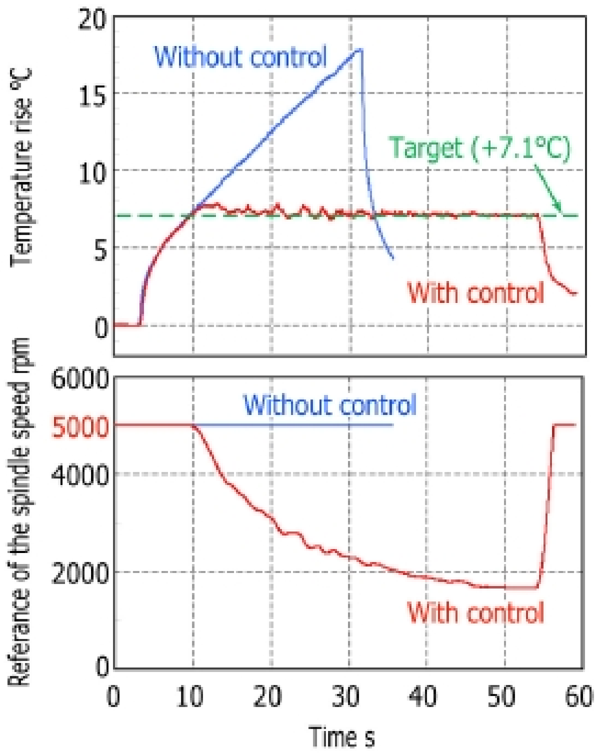

Fig.21 Behavior of the system during the cutting of the flat disk with adaptive control

3.5 Cutting of a stepped workpiece

Face turning experiments were performed by using a workpiece with two steps, as shown in Figure 14. The workpiece has a 2μm step middle of cutting area. The upper limit of spindle speed is 3000rpm, the feed rate is 15μm/rev, the target temperature change is 3.9° C(the change of the sensor output is 860mV) and depths of cut are 3μm and 5μm.

The result of this experiment is shown in Figure 15.

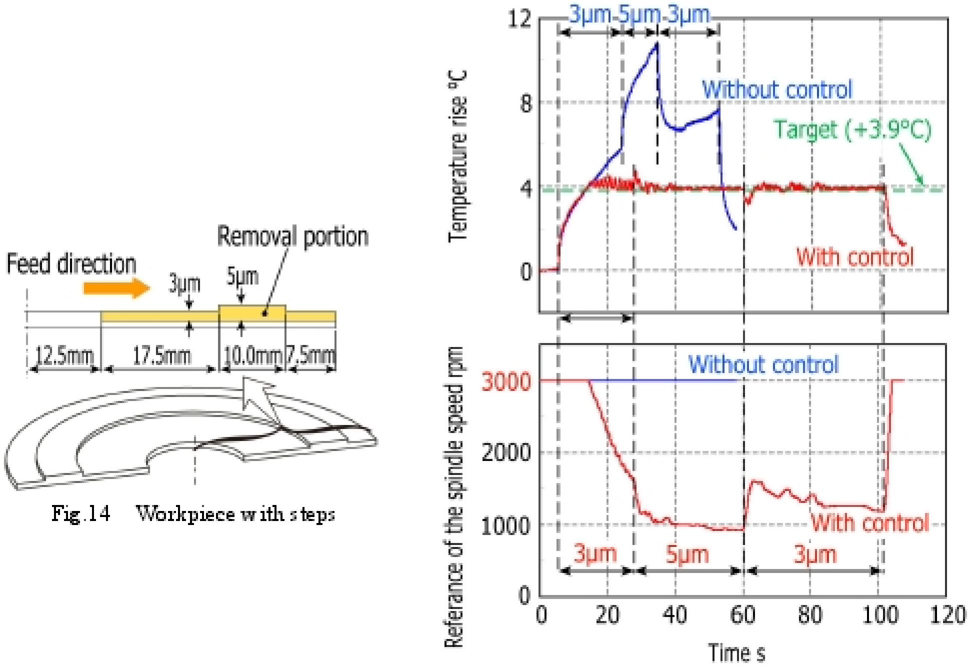

Fig.22 Behavior of the system during the cutting of the stepped disk with adaptive control

The measured temperature without the adaptive control increases according to change in the depth of cut because the spindle speed is constant at an initial condition through the cutting. At the border when the depth of cut changed, slight time delay was seen. However, the time constant of the micro-thermosensor is enough small as already discussed. This delay is the results of not the delay of the sensor but the heat capacity of the workpiece and tool.

When, in contrast, the cutting position passed over the step on the workpiece, the reference of the spindle speed changes quickly with the adaptive control and the temperature near the cutting point is almost maintained to the target temperature. Although temperature fluctuation is also seen, the temperature near the cutting point is maintained almost constant.

4. Conclusions

In order to realize the precision machining of metal cutting engineering monitoring and adaptive control of response characteristics, and the answer should be improved.

We have single crystal diamond tool cutting part of the process to measure the temperature. based on the condition, according to a cutting tool is cutting temperature and cutting depth and the cutting speed, accurate measurement, the new designed ANFIS—PID control system is applicable.

In the lecture, the characteristics of the proposed system were analyzed by various methods. Through field experiments, he confirmed that his characteristics were very good compared to previous control systems.

In the study, the characteristics of the proposed system were analyzed by various methods.

Through field experiments, he confirmed that his characteristics were very good compared to previous control systems.

First, the characteristics of the temperature change at the cutting point were analyzed in detail and a mathematical model was created.

The following ANFIS fuzzy rules were created and expressed in neural network form, then adapted the object control while learning the fuzzy rules.

As a result of simulating the field noise and constructing the multidimensional noises inside the controller, adaptability and responsiveness were improved compared to the general PID controller.

References

(1) Shinno, H., Hashizume, H., Ito, Y., Sato, C., Structural configuration and performances of machining environment-controlled ultra-precision diamond turning machine 'Capsule', Annals of the CIRP, Vol.41, No.1 (1992), pp.425-428.

(2) R. Komanduri, Z.B. Hou, A review of the experimental techniques for the measurement of heat and temperatures generated in some manufacturing processes and tribology, Tribology International, Vol.34 (2001), pp.653—682.

(3) X., Li, A brief review: Acoustic emission method for tool wear monitoring during turning, International Journal of Machine Tools & Manufacture, Vol.42 (2002), pp.157-165.

(4) G.E. D'Errico, An adaptive system for turning process control based on tool temperature feedback, Journal of Materials Processing Technology, Vol.78 (1998), pp.43-47.

(5) Shirase, K., Sawada, A., Wakamatsu, H., Arai, E., Iwata, K., Trial of programless turning based on adaptive force control, Transactions of the Japan Society of Mechanical Engineers, Series C, Vol.66, No.643 (2000), pp.1031-1036.

(6) Yoshioka, H., Hashizume, H., Shinno, H., In-process microsensor for ultra-precision machining, IEE Proceedings Science, Measurement & Technology, Vol. 151, No.2 (2004), pp.121-125.

(7) John A. Thornton, Influence of apparatus geometry and deposition conditions on the structure and topography of thick sputtered coatings, Journal of Vacuum Science and Technology, Vol. 11, No.4 (1974), pp.666-670.

(8) M. N. Ab Malek and M. S. M. Ali, "Evolutionary tuning method for PID controller parameters of a cruise control system using metamodeling," Modelling and Simulation in Engineering, vol. 2009, Article ID 234529, 8 pages, 2009.

(9) T.Korkobi, M. Djemel, and M. Chtourou, "Stability analysis of neural networks-based system identification," Modelling and Simulation in Engineering, vol. 2008, Article ID 343940, 8pages, 2008.