Cutting Force Monitoring based on the Frequency Analysis of Feed Motor Torques

Ryuta Sato[1], Makoto Hasegawa[1], Keiichi Shirase[1]
[1]Graduate School of Engineering, Kobe University, Japan
E-mail: sato@mech.kobe-u.ac.jp

[Received June 30, 2013; Accepted July 30, 2013]

Abstract

Cutting force monitoring without any additional sensors will be an important technology to achieve autonomous machine tools which can control the cutting conditions and failure detections. The purpose of this study is to develop a cutting force estimation method based on servo information in ball screw drive machine tool. In this method, the cutting force is estimated by frequency analysis of servo motor torque of feed drive systems. A frequency component depended on the cutting force is extracted from the analyzed data, and the cutting force is estimated by inverse transformation from the frequency domain to time domain. The motor torque is strongly influenced by the friction force especially in case of the axis stopped. In the proposed method, the estimated cutting force is calibrated based on the identified friction force when the force is detected along the stopped axis. In order to confirm the effectiveness of the proposed method, actual cutting tests and simulations are carried out. As the results, it is confirmed that the proposed method can estimated cutting forces accurately in case of the cutting force becomes larger than the friction force of stopped axis.

Keywords: Cutting force monitoring, NC machine tool, Frequency analysis, Feed drive system, Motor torque

1 INTRODUCTION

Cutting force is important information to sense the cutting conditions and to achieve higher quality and productivity. Hence many significant research works on the cutting force and condition monitoring had been carried out up to now [1][2]. Sato et al. [3] proposed an extended system framework of intelligent machine tool. The intelligent machine tool includes a process planner and M&P (motion & process) control package. In order to achieve the intelligent machine tool, cutting force has to be measured in real time to control the cutting conditions. Although it is possible to measure the cutting forces by using additional sensors, such as piezo-dynamometers [4], the sensors yield too much cost to apply the machine tools on site.

From this point of view, various cutting force monitoring methods based on the servo signals such as motor torque have been proposed [5]. Shinno et al. [6] applied a disturbance observer to detect the cutting force during the ultra-precision machining. Kurihara et al. [7] also applied the dual disturbance observers to detect the cutting forces. These research works successfully monitored the cutting forces based on the servo signals but the axes are driven by linear motors. Typical NC machine tools are driven by servo motors and ball-screws. Choi et al. [8] tried to detect the drill failures based on the frequency analysis of motor current. This research works only focused onto the drilling process.

The purpose of this study is to develop a cutting force estimation method based on servo information in ball screw drive machine tool. In this method, the cutting force is estimated by frequency analysis of servo motor torque of feed drive systems. A frequency component depends on the cutting force is extracted from the analyzed data, and the cutting force is estimated through the inverse transformation from the frequency domain to time domain. The validity of the proposed method is confirmed by comparing the measured and estimated cutting forces of the milling process using square end-mill.

2 MACHINE TOOL CONFIGURATION AND ITS FEED DRYVE SYSTEM MODEL

Figure 1 illustrates the structural configuration of the machine tool used in this study. Although the machine tool is a five-axis controlled machine tool with B- and C-axis on the table side, only X- and Y-axis are controlled in the cutting tests., rotary axes are mechanically clumped in the cutting tests. All translational axes are located on the spindle side, and driven by pairs of AC servomotor and ball-screw. Both of Y- and Z-axis are driven by a couple of motor and ball-screw each other, and X-axis is driven by a pair of motor and bal-screw.

Translational axes are controlled by semi-closed loop control systems based on the rotational angle of motor detected by rotary encoders. Servo signals; motor torque, rotational velocity of motor and positional command for

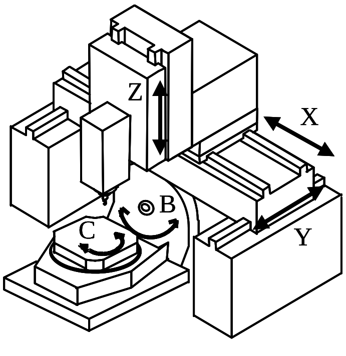
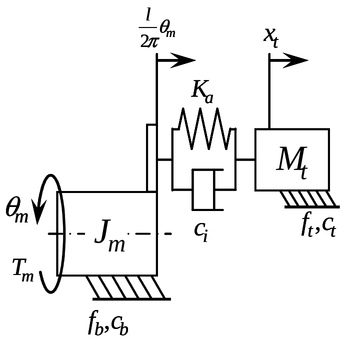
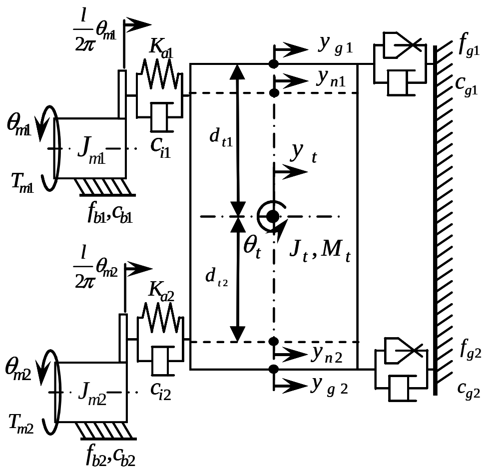


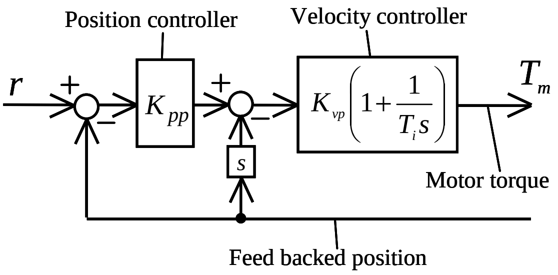
Figure 1: Structural configuration of a five-axis machining center



(a) Vibration model of X-axis



(b) Vibration model of Y- and Z-axis



(c) Block diagram of controller

Figure 2: Model of feed drive systems

each axis can be monitored by a monitoring function of the NC controller of machine tool. The monitored motor torque of X- and Y-axis is used for cutting force estimation in this study. Whole motor torque of Y- and Z-axis can be obtained as a sum of the motor torques of each motor.

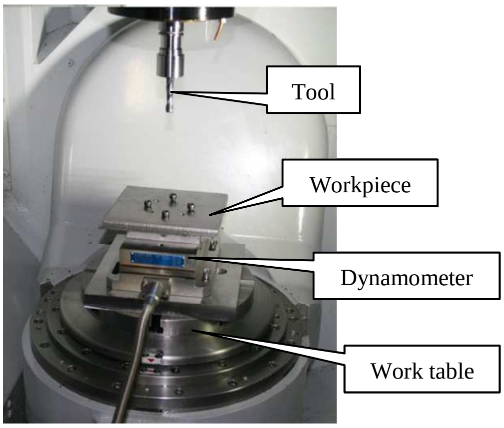
In order to confirm the correctness of the proposed estimation method by both of experiment and simulation, feed drive system mode shown in Figure 2 [9] is applied to the simulations. Figure (a) shows the vibration model of X-axis which is driven by a pair of motor and ball-screw. The model of X-axis has two degrees of freedom. Where, J_m is moment of inertia of motor rotor and ball-screw [kgm^2], M_t is mass of driven components [kg], K_a is axial stiffness of the mechanism [N/m], c_i is internal dumping coefficient of the mechanism [Ns/m], f_t and f_b are Coulomb's friction force and torque, and c_t and c_b are viscous friction coefficient. Figure (b) shows the vibration model of Y- and Z-axis which driven by a couple of motors and ball-screws. The model of Y-and Z-axis has four degrees of freedom with the rotational angle of two motors, translational and rotary movements of driven components. J_t is the moment of inertia of the driven component around Z-axis (around Y-axis for the Z-axis model). It had already confirmed that the models can adequately simulate the dynamic behaviors of the machine tool [9].

Figure 2 (c) shows block diagram of the controller of each servo motor. The controller has two control loops; position and velocity control loops. Position controller is P (Proportional) controller, and velocity controller is PI (Proportional-Integral) controller, respectively. This control system is a typical system for the machine tool feed drive systems. Although in fact that the current control loop exists in the control system, the current control loop can be ignored because the response of current control is much faster than other control loops. From this point of view, it is assumed that the output from the velocity controller is equal to the motor torque T_m.

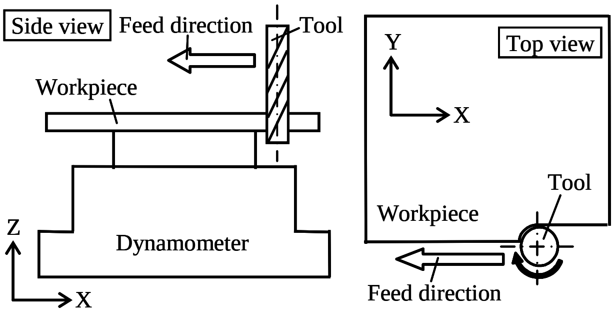
There is no additional control loops or compensators; such as disturbance observer required into the control system. This is one of the important advantages of the proposed estimation method because the proposed method can easily be applied to general machine tools without any changes of the machines.

3 CUTTING TEST

Figure 3 describes the experimental set-up and cutting method for the tests. Figure (a) shows the experimental set-up and figure (b) shows the schematic diagram of the



(a) Experimental set-up



(b) Cutting method

Figure 3: Experimental set-up and cutting method

cutting method. Cutting force during peripheral milling process with square end-mill is estimated in this study.

A dynamometer (KISTLER 9257B) is attached between the table and workpiece as shown in the figure. The X-axis is moved to minus direction and a side of the workpiece is cut by peripheral cutting edges of a square end-mill. Cutting conditions are listed in Table 1. Several tests with several feed rates are carried out in this study.

Table 1: Cutting condition

Workpiece material	S45C
Tool type	Square end-mill
Helix angle	30°
Tool diameter	10 mm
Number of flute	2
Spindle speed	600 rpm
Radial depth of cut	3 mm
Axial depth of cut	5 mm

4 CUTTING FORTH ESTIMATION METHOD

4.1 Relationships between Cutting Force and Motor Torque

Although motor torque of feed drive systems are strongly influenced by the cutting force, the motor torque and cutting force is not identical each other. Because of the motor torque is also influenced by the other factors such as friction and inertial forces.

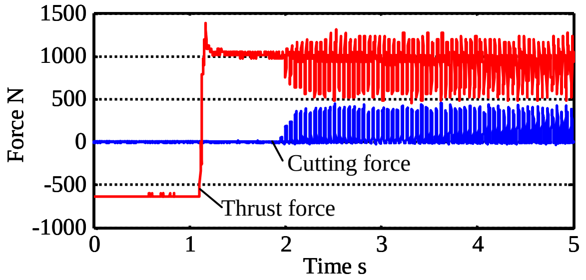
Figure 4 shows an example of measure cutting force and thrust force during the cutting. Figures (a) and (b) show the cutting force along X-, Y-axis and the thrust force of X-, Y-axis motors, respectively. X-axis starts the feed motion at 1 s and the cutting starts at 2 s. Thrust force of the motor F [N] can be obtained from the motor torque T_m [Nm] and lead of ball-screw l [N] as follows:

$$F = \frac{2\pi}{l} T_m \qquad (1)$$

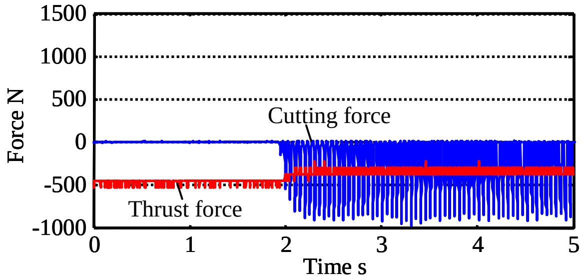
It can be seen from Figure 4 (a), the thrust force stepwise changes when the feed motion starts at 1 s. This change is caused from the frictions and inertial forces. During the feed motion without cutting, the thrust force keeps around 1000 N and this force consists of the friction force of linear guides and friction torque of bearings and ball-screw. The identified total friction forces of linear guides in the other study [9] are 316 N (X-axis) and 560 N (Y-axis). Also the identified total friction torques are 0.8 Nm (X-axis) and 1.42 Nm (Y-axis), respectively.

It also can be seen from Figure 4 (a) that the thrust force vibrates after the cutting stars at 2 s. Unfortunately, however, the amplitude of the vibration of thrust force is bigger than the amplitude of the cutting force. This difference is caused from the frequency characteristics of the feed drive system.

Figure 4 (b) shows the cutting force along Y-axis and the thrust force of Y-axis motor. The Y-axis is not moved in the cutting test. It can be seen from the figure that although large cutting force exists after the cutting starts at 2s, the thrust force does not vibrate, just a small stepwise changes. This behavior is quite different from the thrust force of X-axis shown in figure (a), and the difference is caused from the friction characteristics.



(a) X-axis (moving axis) direction



(b) Y-axis (stopping axis) direction

Figure 4: Comparison of cutting force and thrust force (Feed rate: 72 mm/min)

4.2 Influence of Frequency Response and Friction Characteristics of Feed Drive System

Figure 5 shows the simulated frequency transfer functions of feed drive systems between cutting force to thrust force of motor. This frequency response decides the relationship between the amplitude of cutting force and amplitude of thrust force. If the gain is zero, the amplitude of thrust force becomes identical with the amplitude of cutting force.

It can be seen from the figure that the gain becomes larger than zero when the frequency is higher than 10 Hz. This frequency means the cutting force frequency. It is clear from the results that the vibration amplitude of thrust force becomes larger when the cutting force frequency becomes higher. In addition the relationship between the amplitudes of the cutting and thrust forces depend on the cutting force frequency and the frequency characteristics of the feed drive systems.

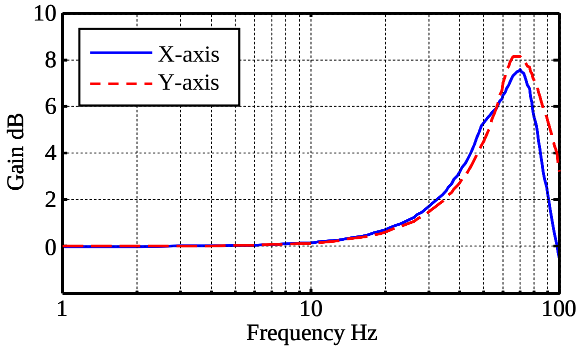
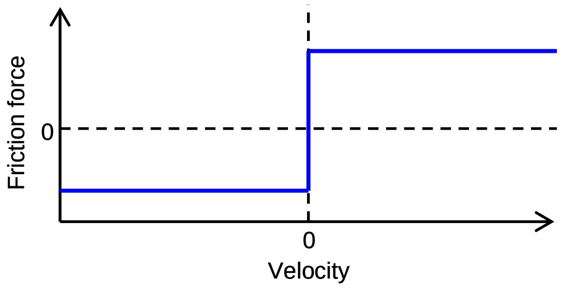
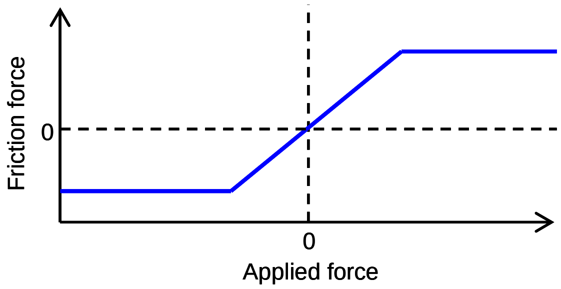


Figure 5: Frequency transfer function between cutting force and thrust force



(a) Relationship between velocity and friction force



(b) Relationship between applied force and friction force

Figure 6: Friction characteristics model

Figure 6 illustrates the simplified friction characteristics model. Figure (a) shows the relationship between velocity and friction force, figure (b) shows the relationship between applied force and friction force. It is generally known that the direction of the friction force depends on the motion direction, and the friction force is balanced with applied force in case the applied force is smaller than the friction force. In addition, the friction force becomes constant in the constant feed speed motion. These characteristics are known as Coulmb's friction.

The friction characteristics mentioned above strongly influences the thrust force during the cutting operation. On the thrust force of the moving axis, since the friction force becomes substantially constant during the motion, the thrust force can detect the changing of cutting force as shown in Figure 4 (a). In this case, the zero point of cutting force on the detected thrust force becomes the friction force.

On the other hand, on the thrust force of the stopping axis, the friction force cannot be constant because the moving velocity is zero. In this case, the friction force is balanced with the cutting force in case of the cutting force is smaller than the friction force, and the axis is moved by the cutting force in case of the cutting force is larger than the friction force. As the result, the control system cannot detect the influence of cutting force in case of the force is smaller than the friction force because the axis position is kept by the friction force. It is clear from the block diagram shown in Figure 2 (c), the control system can only detect the force disturbance when the axial velocity or position is changed by the disturbance.

4.3 Flow Chart of Cutting Force Estimation Method

Figure 7 shows an example of the power spectrum density of thrust force with and without cutting operation. There are no remarkable frequency components on the power spectrum density of thrust force without cutting motion as shown in the figure. The cutting force frequency can easily be predicted as the product of rotational frequency of spindle and number of flutes. As shown in Figure 7 (b), remarkable frequency components can be observed at the predicted cutting frequency (20 Hz in this case) and its harmonics. From the results, it is expected that the cutting force van be estimated by the extract the frequency component of predicted cutting force frequency from the thrust force signal.

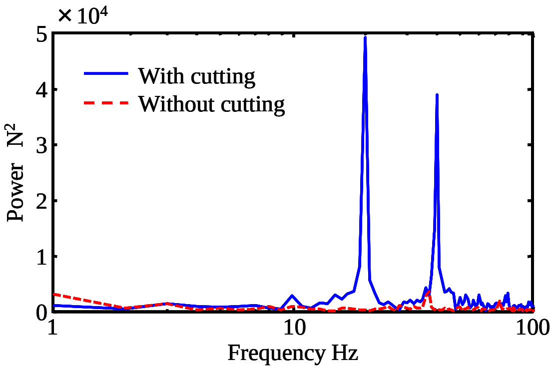


Figure 7: Power spectrum density of thrust force

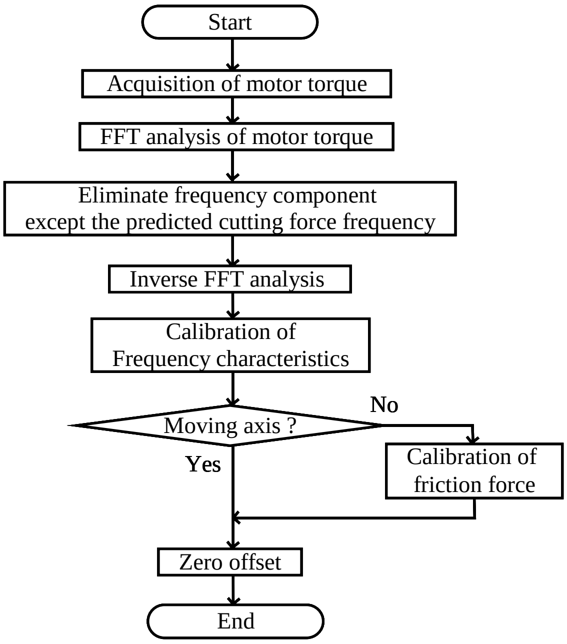


Figure 8: Flowchart of proposed cutting force estimation method

Figure 8 shows the flowchart of the proposed cutting force estimation method. In the proposed method, as the first step, frequency analysis is applied to the acquisitioned motor torque signal of each axis. The cutting force frequency also can easily be predicted from the rotational speed of spindle and the number of flutes of the end-mill.

Frequency component of the motor torque due to the cutting force can be obtained from the analyzed data by eliminating the frequency component except the predicted cutting force frequency. The motor torque changing due to the cutting force in the time domain can also be obtained as the results of the inverse Fourier transformation of the analyzed data.

The frequency characteristics of the feed drive system influences the motor torque as mentioned above. Hence the influence of the frequency characteristics on the amplitude of the motor torque changing is calibrated based on the simulated frequency characteristics of the system as shown in Figure 5.

Since the motor torque changing of stopping axis is strongly influenced by the friction characteristics, the amplitude of the estimated cutting force is calibrated based on the identified friction force of the feed drive system. The amplitude of cutting force changing along the stopping axis can be estimated as the sum of the results of frequency analysis and the friction force.

In addition, finally, the zero position of the estimated cutting force can be decided based on the predicted cutting force changing based on the cutting force model [10]. The zero offset step might be not required in case of the monitoring function is applied to the control of the amplitude of cutting force changing.

5 CUTTING FORCE ESTIMATION TEST

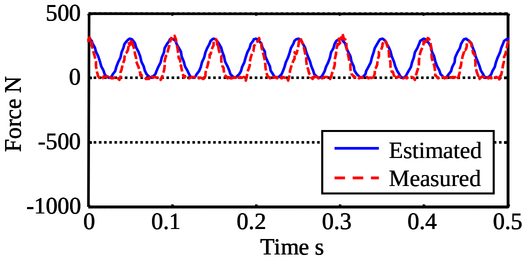
In order to confirm the validity of the proposed cutting force estimation method, measure and estimated cutting forces are compared. Figures 9 and 10 show the measured and estimated cutting forces. Figure 9 shows the experimental results and Figure 10 shows the simulation results. In the simulation, actual measured cutting force is inputted to the models as the force disturbances. Figures (a) show the measured and estimated cutting forces along X-axis, and figures (b) shows the forces along Y-axis, respectively.

It can be seen from the figures that the proposed cutting force estimation method can adequately estimate the amplitude of cutting force changes in both of experiment and simulation results. The estimated cutting force is expressed as a simple sinusoidal wave because the frequency components expect the cutting force frequency are ignored in the proposed estimation method. However, it might be enough to control the cutting condition and failure detection. In order to detect more detailed cutting force changes, the proposed estimation method should be improved in the future works.

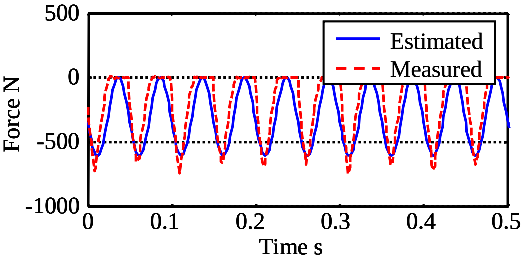
Calibration step of friction force plays a key role to estimate the cutting force along the stopping axis. Figure 11 shows the measured and estimated cutting force along Y-axis without the friction force calibration step. The amplitude of the estimated cutting force is quite smaller than the actual cutting force because of the friction force and thrust force of the motor is balanced when the cutting force is smaller than the friction force in the stopping axis.

If the cutting force is smaller then the friction force, it is impossible to detect the cutting force along stopping axis from the motor torque signal because the control system cannot detect the velocity of position changes. Figure 12 shows the measured and estimated cutting forces in condition of smaller feed rate (20 mm/min). Figure (a) shows the cutting force along X-axis direction, and figure (b) shows the force along Y-axis direction.

In this condition, cutting forces becomes much smaller than the condition of higher feed rate. It can be seen from the figure that the cutting force along moving axis (X-axis) can be adequately estimated by the proposed method

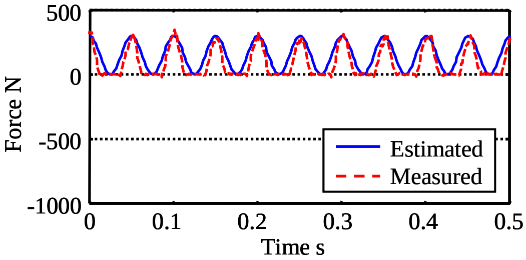


(a) X-axis direction (moving axis)

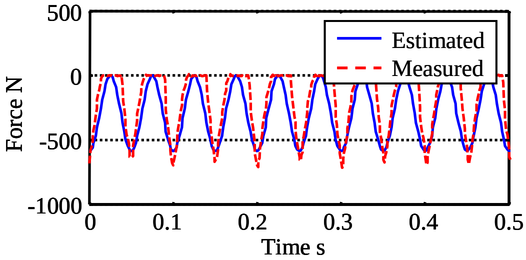


(b) Y-axis direction (stopping axis)

Figure 9: Comparison of measured and estimated cutting forces (experiment, 72 mm/min)



(a) X-axis direction (moving axis)



(b) Y-axis direction (stopping axis)

Figure 10:Comparison of measured and estimated cutting forces (simulation, 72 mm/min)

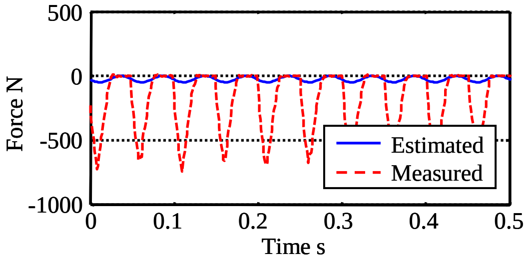
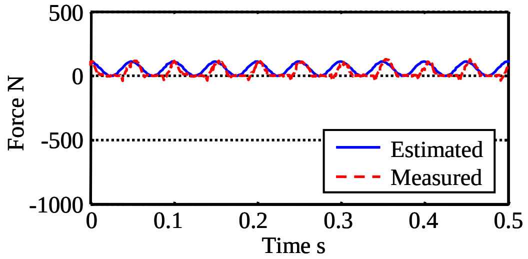
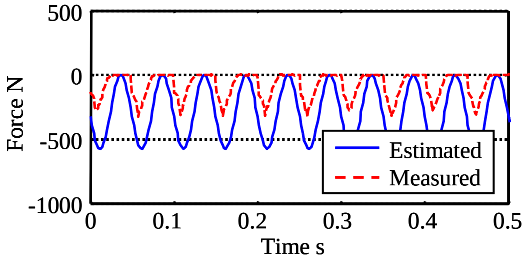


Figure 11:Comparison of measured and estimated cutting forces along Y-axis without friction force calibration (experiment, 72 mm/min)



(a) X-axis direction (moving axis)



(b) Y-axis direction (stopping axis)

Figure 12:Comparison of measured and estimated cutting forces (experiment, 20 mm/min)

even though the cutting force is smaller than the friction force. On the other hand, the cutting force along stopping axis (Y-axis) cannot be estimated by the proposed method in case of the cutting force is smaller than the friction force. In this case, the estimated cutting force amplitude based on the frequency analysis becomes zero, and the estimated amplitude of the cutting force after the friction force calibration step becomes 560 N, same with the coulmb's friction force of linear guides.

It is clarified from the results that the proposed cutting force estimation method can adequately estimate the amplitude of cutting force changes even if the axis does not moves in case of the cutting force is larger than the friction force. It is also clarified, however, the proposed method cannot estimated the amplitude of cutting force changes along stopping axis in case of the cutting force is smaller than the friction force.

6 CONCLUSIONS

In this study a cutting force estimation method based on the frequency analysis of servo motor torque of feed drive systems is proposed. The proposed method can be applied to the feed drive systems driven by ball-screw. The validity of the proposed method is confirmed by comparing the measured and estimated cutting forces of the milling process using square end-mill.

As the results, It is clarified that the proposed cutting force estimation method can adequately estimate the amplitude of cutting force changes even if the axis does not moves in case of the cutting force is larger than the friction force, but it is impossible to estimated the amplitude of cutting force changes along stopping axis in case of the cutting force is smaller than the friction force.

ACKNOWLEDGEMENT

This work was financially supported by JKA foundation. The authors would like to sincerely acknowledge all support from MTTRF (the Machine Tool Technology Research Foundation).

REFERENCES

[1] Byrne, G., Dornfeld, D., Inasaki, I., Ketteler, G., Koning, W. and Teti, R., 1995, Tool Condition Monitoring (TCM) -The Status of Research and Industrial Application, CIRP Annals -Manufacturing Technology, 44/2, pp.541-567.

[2] Teti, R., Jemielniak, K., O'Donnell, G. and Dornfeld, D., 2010, Advanced Monitoring of Machining Operations, CIRP Annals -Manufacturing Technology, 59, pp.717-739.

[3] Sato, T., Kakino, Y, Matsubara, A., Ibaraki, S. and Saraie, H., 2002, Proposal of the Extended System Framework of Intelligent Machine Tool, Proceedings of the 2002 Japan-USA Symposium on Flexible Automation, pp.15-20.

[4] http://www.kistler.com/

[5] Matsubara, A. and Ibaraki, S., 2009, Monitoring and Control of Cutting Force in Machining Processes: A Review, International Journal of Automation Technology, Vol.3, No.4, pp.445-456.

[6] Shinno, H., Hashizumi, H. and Yoshioka, H., 2003, Sensor-less Monitoring of Cutting Force during Ultraprecision Machining, CIRP Annals -Manufacturing Technology, 52/1, pp.303-306.

[7] Kurihara, D., Kakinuma, Y. and Katsura, S., 2009, Sensorless Cutting Force Monitoring Using Parallel Disturbance Observer, International Journal of Automation Technology, Vol.3, No.4, pp.415-421.

[8] Choi, Y.J., Park, M.S. and Chu, C.N., 2008, Prediction of Drill Failure Using Features Extraction in Time and Frequency Domains of Feed Motor Current, International Journal of Machine Tools and Manufacture, 48, pp.29-39.

[9] Nishio, K., Sato, R. and Shirase, K., 2012, Influence of Motion Error of Feed Drive Sytems on Machined Surface, Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol.6, No.6, pp.781-791.

[10] Altintas, Y., 2000, Manufacturing Automation -Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design, Cambridge University Press.