Experimental Verification of Chatter Suppression in End Milling Process Using Cooperative Control of Spindle and Stage Motors

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***Abstract*—Chatter vibration is well known as an undesirable phenomenon, so various methods for chatter suppression have been proposed. Spindle speed variation as a triangular trajectory in the cutting process is one of the methods for chatter suppression. However, this method cannot suppress chatter vibration completely. Moreover, the triangular spindle speed variation requires large torque and a good response of the spindle motor. To solve these problems, this paper proposes a cooperative control of spindle and stage motors. The proposed methods are evaluated by simulations and experiments.**

I. Introduction

A. Background

Machining is an exceedingly important process to produce any products because it is adaptive for various materials, highly precise and very effective. Until today, a considerable amount of research has been conducted on NC machine tools to attain higher accuracy and higher efficiently in machining. Chatter vibration is one of the causes to worsen the quality of products. Particularly, tools and work materials with low stiffness and low damping induce chatter vibration. Chatter vibration is classified as self–excited chatter vibration or forced chatter vibration.

Especially, self–excited chatter vibration, caused by the interaction between tools and work materials, is the most undesirable because, large self–excited chatter vibration strongly reduces control robustness. Methods to suppress self–excited chatter vibrations are divided into four types[1]. Two of these method types analyze the cutting conditions so that self–excited chatter vibration does not occur[2]. However, these approaches require parameters for tools, and measurement of these parameters requires labor and specified skills of machine tool operators. Furthermore, due to changes in the tools' parameters caused by wear and deformation, accurately analyzing the control system models is difficult.

The third type of method is passive chatter suppression by using of dampers on spindles and jigs[3]. However, these methods do not offer sufficient robustness for parameter variations. The fourth type of method is active self–excited chatter suppression by using variable helix end mills[4], [5] and varying spindle motor velocity in cutting process[6], [7].

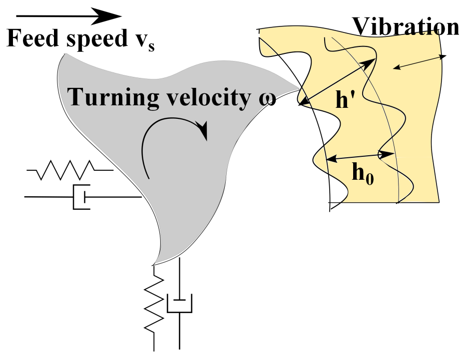

Fig. 1. Schematic view of the cutting process.

B. Purpose of Study

In [7], a method is proposed to suppress chatter vibration using higher amplitude of the spindle speed variation. In contrast, the author's research group has proposed a high frequency spindle speed variation to suppress self–excited chatter vibration and demonstrated its effectiveness. Especially, a triangular spindle speed trajectory was proposed for suppression of self–excited chatter vibration[8]. However, this method has the following two problems:

1) Chatter vibration occurs at the peaks of the triangular spindle speed trajectory, because the spindle speed cannot follow the triangular spindle speed trajectory at the tops of the reference.
2) Triangular spindle speed trajectory requires large motor torque due to the triangular spindle speed trajectory.

Therefore in addition to variable spindle speed control, cooperative variable feed speed control is implemented in this paper to solve the problems mentioned above. The following methods are proposed:

Proposed Method 1
At the tops of the triangular spindle speed trajectory where the spindle speed cannot follow the reference, the feed speed is also changed to

TABLE I. THE SPINDLE AND THE STAGE PARAMETERS.

	Only spindle variation (previous)	Triangle cooperation (proposed 1)	Sinusoidal cooperation (proposed 2)
Chatter suppression	Good	Very good	Good
Spindle motor torque	Not small	Not small	Small

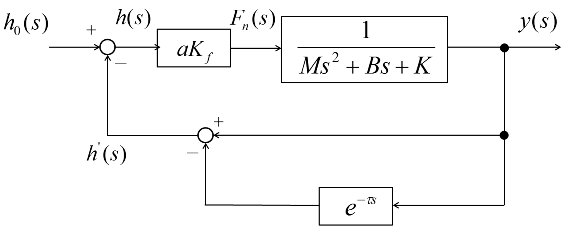

Fig. 2. Block diagram of self–excited chatter vibration.

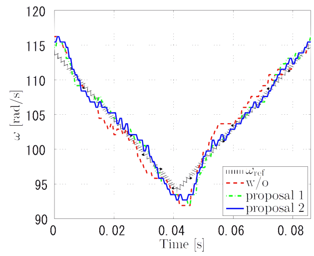

Fig. 3. The experimental spindle speed response in[8].

suppress chatter vibration more effectively then with only spindle speed variation.

Proposed Method 2
: The speed trajectory of the spindle and the feed are sinusoidal waves phase shifted relatively to each other. This method archives to suppress chatter vibration and decreases maximum motor torque of the spindle.

Characteristics of the proposed methods are shown in Table I. The proposed methods are evaluated by simulations and experiments.

II. The Mechanism of Self–Excited Chatter Vibration

Fig. 1 shows the schematic overview of an end milling cutting process[9]. Here, the variation in relative position of the work and the tool induces variation in cutting depth. This variation in cutting thickness deteriorates the quality of the cutting surface. Moreover, the cutting thickness is different between the end mill cutting edges, so that the variation in previous cutting thickness affects the present cutting thickness. This phenomenon is called "regeneration." A change in cutting force, which is determined by the cutting thickness is induced by regeneration and excites the machine tool structure. This process is called self–excited chatter vibration and consists of an unstable closed loop.

Fig. 2 shows the block diagram of self–excited chatter vibration[9]. Here, a is the width of the tool, K_f is the cutting force coefficient, and the second order lag system $1/(Ms^2 + Bs + K)$ is the transfer function describing how the machine frame vibrate. This transfer function is defined as $G(s)$. The nominal cutting thickness h_0 is described as:

$$h_0 = v_{st}\frac{2\pi}{\omega_{sp}} \tag{1}$$

where, ω_{sp} is the spindle speed. Then, as Fig. 2 shows, the actual cutting thickness $h(s)$ is described as

$$h(s) = h_0(s) - (1 - e^{-\tau s})y(s), \tag{2}$$

where, τ is the period between the previous tooth and the present tooth. Then, the thrust cutting force F_n is the proportional to the cutting force coefficient K_f is described as

$$F_n = aK_f h(s). \tag{3}$$

This cutting force excites a displacement $y(s)$. From the equations above, the transfer function from the nominal cutting thickness to the actual cutting thickness is

$$\frac{h(s)}{h_0(s)} = \frac{1}{1 + (1 - e^{-\tau s})K_f aG(s)}. \tag{4}$$

III. Methods of Chatter Suppression

As shown in the previous section, the mechanism of self–excited chatter vibration can be received as a periodic change of cutting thickness inducing a periodic change of cutting force. In previous studies, variable spindle speed control for chatter suppression was proposed[7], [6]. Moreover, in the authors' research group, the method of high frequency spindle speed variation was proposed and achieving notable reduction of chatter vibration [8]. This method is defined as the previous method in this paper. In this section, the previous method is mentioned and then two types of proposed method are explained in detail.

A. High Frequency Spindle Speed Variation (Previous Method)

To define the amplitude and frequency of spindle speed variation, the parameters A_{RVA} and B_{RVF} were introduced as follows

$$A_{RVA} = \frac{\omega_A}{\omega_{av}}, \tag{5}$$

$$B_{RVF} = \frac{2\pi/T}{\omega_{av}}. \tag{6}$$

Here, T is the period of variation in the spindle speed, N_{av} is the average of the spindle speed, and N_A is the maximum value of the spindle speed. The variation in the spindle speed changes the wave–number on the cutting surface generated by the vibration of the tool. Accordingly, the periodic variation in cutting thickness, which induces chatter vibration, is disturbed by the change in the spindle speed. Moreover, it was demonstrated that especially the triangular spindle speed trajectory was effective for chatter suppression in [8].

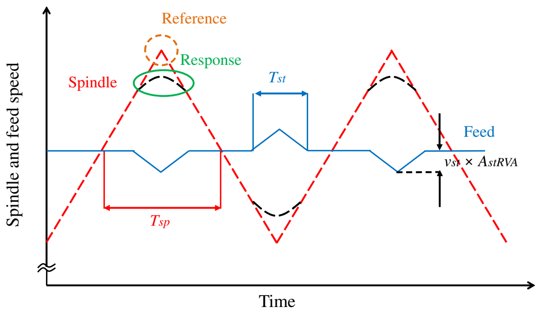

Fig. 4. Triangular speed trajectory cooperative control (Proposed Method 1).

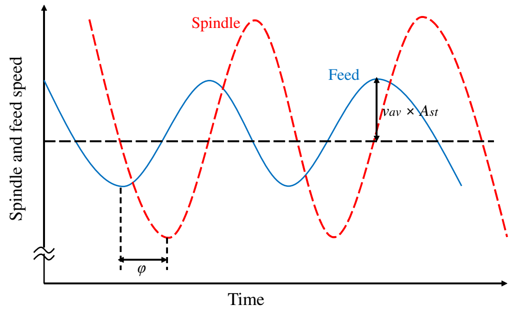

Fig. 5. Sinusoidal speed trajectory cooperative control (Proposed Method 2).

Although the previous method decreased chatter vibration to some degree, the chatter vibration was not completely suppressed. At the tops of the triangular spindle speed trajectory, chatter vibration still occurs. The experimental reference and the response of the spindle speed are shown in Fig. 3. At the top of the triangular wave, the rate of change in the spindle speed is zero, so that the wave–number on cutting surface did not vary in each cut, inducing that induces periodic vibration in cutting thickness. Thus chatter vibration occurred.

B. Triangular Speed Trajectory Cooperative Control (Proposed Method 1)

In the previous method, it is important to change the wave–number on cutting surface in each cutting and the cutting thickness in each cutting. Varying the cutting thickness constantly is important to suppress chatter vibration. Hence the first proposed method is a form of cooperative control, where the feed speed is varied, while the rate of change in spindle speed is near zero. A conceptual diagram is shown in Fig. 4. Here, the red dashed line shows the spindle speed and the blue line shows the feed speed. As shown in Fig. 4, the feed speed is changed when the rate of variation in the spindle speed is zero. This proposed method aims to prevent the periodic change in cutting thickness. In other words, the aim of this method is to guarantee the continuous change in cutting thickness during the cutting process. Therefore, chatter vibration is suppressed.

C. Sinusoidal Speed Trajectory Cooperative Control (Proposed Method 2)

The triangular spindle speed trajectory[8] needs large motor torque at the tops, so a larger motor is required. Larger motors increase cost, size and thermal deformation of machine tools. Therefore, the second proposed method is the cooperative control of spindle speed and the feed speed with sinusoidal reference trajectories. Fig. 5 shows the conceptual diagram. Both reference are phase shifted by ϕ. Although at the tops of the spindle speed sinusoidal trajectory, where the rate of spindle speed is zero and chatter vibration occurs, the feed speed is changed to maintain a varying cutting thickness. Moreover, Proposed Method 2 does not require a large spindle motor torque due to the rate of variation in spindle speed being near zero at the peaks.

IV. Simulation of Chatter Suppression

To simulate the suppression of chatter vibration, controllable parameters are defined. At first, the variable spindle speed $\omega_{sp}(t)$ is defined as

TABLE II. Reference parameter for simulation.

Parameter	Value
ω_{av}	262 rad/s
A_{spRVA}	0.100
B_{spRVF}	0.700
v_{av}	200 mm/s
A_{stRVA}	0.100
T_{sp}	0.171 s
T_{st}	0.0342 s

TABLE III. Model parameter for simulation.

Parameter	Value
Width of cut a	5.00 mm
Specific cutting force K_f	300 Mpa
Dynamic mass M	10.0 Ns^2/m
Mechanical impedance B	200 Ns/m
Dynamic rigidity K	5.00×10^5N/m

$$\omega_{sp}(t) = \omega_{av} + A_{spRVA}\omega_{sp}S_{sp}(B_{spRVF}, t), \tag{7}$$

and then the feed speed $v_{st}(t)$ is defined as

$$v_{st}(t) = v_{av} + A_{stRVA}v_{av}S_{st}(B_{stRVF}, t). \tag{8}$$

Here, ω_{av} is the mean value of the spindle speed, A_{spRVA} is the amplitude coefficient of the spindle speed variation defined in eq. (5), $S_{sp}(B_{spRVF}, t)$ is the shape function of spindle speed trajectory and B_{spRVF} is the frequency coefficient of spindle speed variation defined in eq. (6). $S_{sp}(B_{spRVF}, t)$ in eq. (6) is a trigonometric function or a triangular wave. In the same way, v_{av} is the feed speed average, A_{stRVA} is the amplitude coefficient of the feed speed variation, $S_{st}(B_{spRVF}, t)$ is the shape function of feed speed trajectory and B_{stRVF} is the frequency coefficient of the feed speed variation. Consequently, eq. (7) and eq. (8) fix the nominal cutting thickness $h_0(t)$ as below:

$$h_0(t) = v_{st}(t)\frac{2\pi}{\omega_{sp}(t)}. \tag{9}$$

The simulation is based on the plant block shown in Fig. 2. Equation (7) is used to compute τ, where τ is the period of the spindle rotation depending on time. Therefore $e^{\tau s}$ is used for an approximate model for time delay by changing τ in the simulation depending on the time in Fig. 2. τ is defined as below:

$$\tau(t) = \frac{2\pi}{\omega_{sp}(t)}. \tag{10}$$

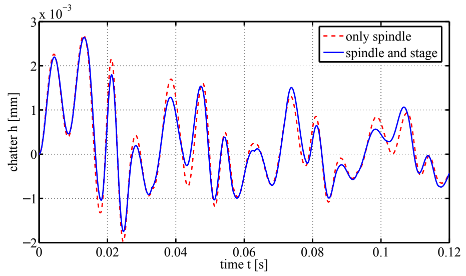

Fig. 6. Triangular trajectory simulation of chatter vibration.

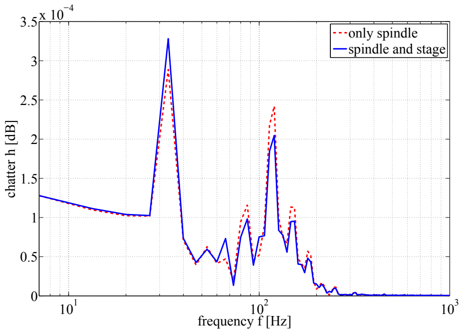

Fig. 7. Triangular trajectory simulation FFT of chatter vibration.

A. Simulation by Triangular Speed Trajectory Cooperative Control (Proposed Method 1)

The simulation model is shown in Fig. 2. Reference parameters are shown in Table II and Table III.

Fig. 6 shows the simulation result of chatter suppression by the triangular velocity trajectory. The dashed red line shows the depth variation h with the variation only considering spindle speed variation. The blue line is with the variation in both the spindle speed and the feed speed. Now, the resonant frequency of the plant model used for the simulation is about 112 Hz. It is known that the frequency of chatter vibration appears around resonant frequency of the plant model[9]. As shown in Fig. 7, which is the FFT graph of Fig. 6, the chatter vibrations around 112 Hz are more suppressed Proposed Method 1.

B. Simulation by Sinusoidal Speed Trajectory Cooperative Control (Proposed Method 2)

This proposed method used a sinusoidal speed trajectory. The spindle and the feed speeds are defined as below:

$$\omega_{\mathrm{sp}}(t) = \omega_{\mathrm{av}} + A_{\mathrm{spRVA}}\omega_{av} \sin(B_{\mathrm{spRVF}}\omega_{\mathrm{av}}t), \tag{11}$$

$$v_{\mathrm{st}}(t) = v_{\mathrm{av}} + A_{\mathrm{stRVA}}v_{\mathrm{av}} \sin(B_{\mathrm{stRVF}}\omega_{\mathrm{av}}t - \phi). \tag{12}$$

Here, ϕ is the phase difference between the spindle speed and the feed speed. The simulation parameters are in Table II. The optimal B_{stRVF} and ϕ are obtained by varying each parameter value. Values over the range [0 1], [0 2π] respectively. This simulation for optimal parameters uses Fig. 2. Average of h is plotted and generate the 3D map. The 3D map shows the effects of B_{stRVF} and ϕ for chatter suppression given by the simulation. This result shows that the chatter vibration tends to be suppressed when $B_{\mathrm{stRVF}} = 0.7$, which is same value of

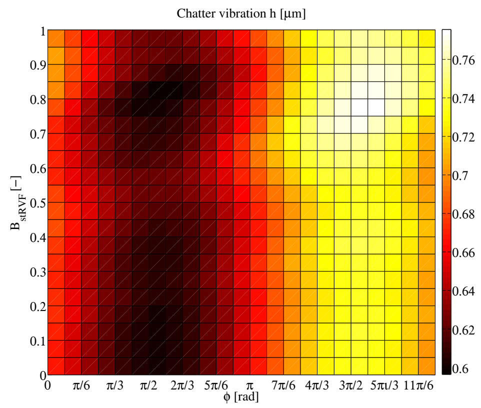

Fig. 8. Dependence of B_{stRVF} and phase shift by sinusoidal trajectory.

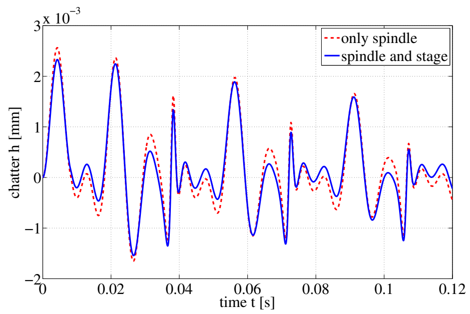

Fig. 9. Sinusoidal trajectory simulation of chatter vibration.

B_{spRVF}, $\phi = \pi/2$, when the rate of variation in spindle speed is zero and the rate of variation in feed speed is maximum, and the variation in cutting thickness is not periodic.

Moreover, using the optimal $\phi = \pi/2$ and $f_{stage} = 0.7$, the time dependent simulation and FFT results are shown in Fig 9, 10. The reference parameters of this simulation are shown in Table II without T_{sp} and T_{st}. Table III are the model parameters used in this simulation. In Fig. 10, the vibrations around 30 Hz are caused by the variation in the speeds of the spindle and the feed. The chatter vibration frequency around 112 Hz is suppressed by Proposed Method 2.

V. Control System

Figure 11 shows the experimental equipment. In this paper, the spindle and the stage are driven by a velocity controller. The spindle and the stage models are described by the transfer function below

$$G(s) = \frac{K_t}{Js + D}. \tag{13}$$

The parameters of the spindle and the stage are shown in Table IV. Here, the subscript "sp" figures the parameters of the spindle and "st" signifies the parameters of the stage. PI speed compensators are used in both systems with pole assignment 80 and 40 Hz for spindle and stage respectively. Both the stage and spindle are controlled in semi–closed loops using high precision, 20 bit absolute encoders.

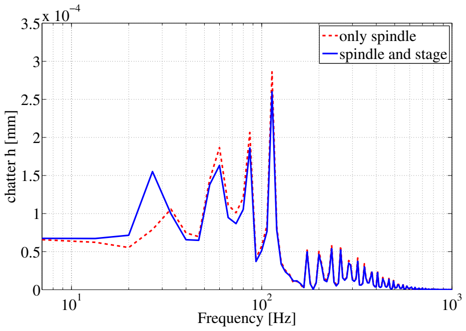

Fig. 10. Sinusoidal trajectory simulation FFT of chatter vibration.

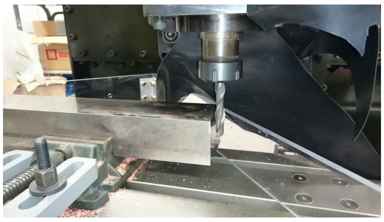

Fig. 11. Experimental setup.

TABLE IV. The spindle and the stage parameters.

Parameter	Value
J_{sp}	6.80×10^{-3} kg · m^2
D_{sp}	7.80×10^{-3} Nm · s
K_{tsp}	0.47 NmA
J_{st}	8.50×10^{-3} kg · m^2
D_{st}	1.40 Nm · s
K_{tst}	0.715 Nm/A

TABLE V. Cutting condition.

Parameter	Value
End mill flutes	2
End mill ϕ	20.0 mm
Radial depth of cut	5.00 mm
Axial depth of cut	20.0 mm
Work piece	C1100

TABLE VI. The reference parameters for Proposed Method 1 experiment.

Parameter	Value
ω_{av}	147 rad/s
A_{spRVA}	0.100
B_{spRVF}	0.500
v_{av}	0.500 mm/s
A_{stRVA}	0.100
B_{st}	0.500
T_{st}	0.0100 s

TABLE VII. The reference parameters for Proposed Method 2 experiment.

Parameter	Value
ω_{av}	147 rad/s
A_{spRVA}	0.100
B_{spRVF}	0.500
v_{av}	0.500 mm/s
A_{stRVA}	0.100
B_{stRVF}	0.500
ϕ	$\pi/2$ rad/s

VI. Experimental Results

In this section, the two proposed methods are evaluated by cutting experiments. Chatter was observed by acceleration sensors attached on the work piece and the spindle, then the measured acceleration was analyzed in the frequency domain. The average of the analyzed data at each frequency band is used for evaluation. Both cutting experiments used the cutting conditions in Table V.

A. Experiment by Triangular Speed Trajectory Cooperative Control (Proposed Method 1)

The reference parameters are shown in Table VI. The result of the cutting experiment is shown in Fig. 12. In Fig. 13, the graph shows the FFT of the work piece vibration. The blue bar is where there is only triangular spindle speed variation and the red bar is Proposed Method 1. As shown in Fig. 12, the chatter vibration mainly appears from 700 Hz to 800 Hz. It is measured that the resonant frequency of the work piece is around 750 Hz, so that chatter appears around 750 Hz. As Fig. 12, the chatter vibration is suppressed with Proposed Method 1.

B. Experiment by Sinusoidal Speed Trajectory Cooperative Control (Proposed Method 2)

The reference parameters are shown in Table VII. The result of the cutting experiment is shown in Fig. 13. In Fig. 13, the graph shows the FFT of the chatter vibration of the work piece. The blue bar is where there is only triangular spindle speed variation and the red bar is Proposed Method 2. As shown in Fig. 12, the chatter vibration mainly appears from 700 Hz to 800 Hz. The chatter vibration is more suppressed by Proposed Method 2 than by the previous method.

VII. Comparison of Proposed Methods

From given chatter suppression results, each proposed method is superior to the previous method of only varying the spindle speed. Keeping this in mind, in this section, the proposed methods are compared each other from the viewpoints of chatter suppression and motor torque.

A. Comparison of Chatter Suppression

At first, the previous methods, where there is only spindle speed variation, are compared. The triangular trajectory of the previous method in Fig. 12 is much smaller than the sinusoidal trajectory in Fig. 13. This result was mentioned already in [8]. Next, a comparison of the proposed methods show that Proposed Method 1 is smaller than Proposed Method 2. However, the decrease in the chatter vibration from the previous method shows Proposed Method 2 gets more benefits from cooperative control of the spindle speed and the feed speed than Proposed Method 1.

B. Comparison of Spindle Motor Torque

Figure 14 and Fig. 14 shows the torque of the spindle motor in the cutting process of constant feed speed and variable spindle speed. Figure 14 shows the triangular spindle speed, which is the red line and spindle motor torque, witch is the blue line. At the tops of the triangular spindle speed, the spindle motor was outputting maximum torque. On the other hand,

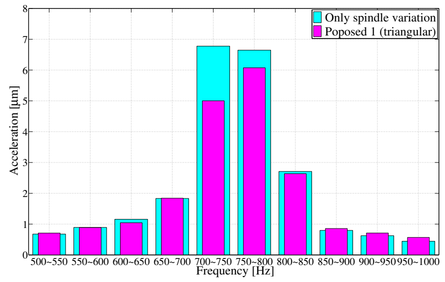

Fig. 12. FFT of the workpiece acceleration by Proposed Method 1.

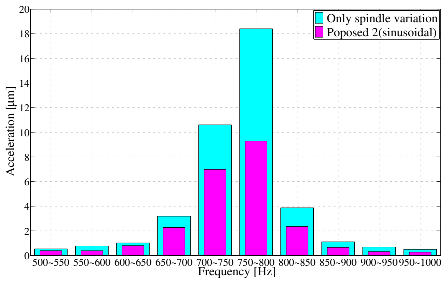

Fig. 13. FFT of the workpiece acceleration by Proposed Method 2.

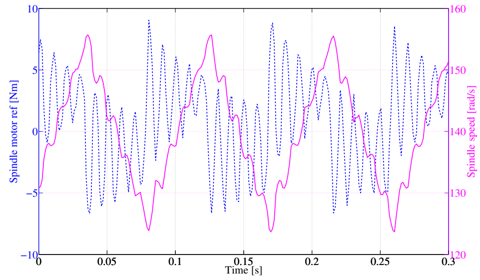

Fig. 14. The spindle speed and the spindle motor torque with Proposed Method 1.

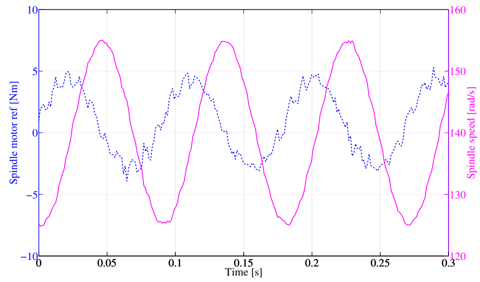

Fig. 15. The spindle speed and the spindle motor torque with Proposed Method 2.

Fig. 14, which is the sinusoidal spindle speed, measured of the motor torque shows that the maximum motor torque is smaller than Proposed Method 1. These graphs show thet Proposed Method 2 has an advantage in the motor torque of the spindle speed.

VIII. Conclusion

In this paper, two types of the cooperative controls between the spindle speed and the feed speed for self–excited chatter suppression were proposed. Both proposed methods were evaluated by simulations and experiments. Proposed Method 1 using triangular speed trajectory is more effective to suppress chatter vibration than the previous method using only spindle speed variation as triangular speed trajectory. Proposed Method 2 using sinusoidal speed trajectory was also more effective to suppress the chatter vibration than the previous method. Compared to Proposed Method 2, Proposed Method 1 showed better chatter suppression. Compared to Proposed Method 1, Proposed Method 2 showed to e slightly less effective in suppression but with a smaller spindle motor torque. These features are shown in Table I. The operator can choose the better trajectory depending on the circumstances. On the other hand, makers also can make low cost and high precision machine tools using small motors with Proposed Method 2, and more high precision machine tools at the same cost using their usual motor with Proposed Method 1.

In future works, it is necessary to optimize the spindle speed and the feed speed trajectory. In optimization of the spindle and feed speeds, there is a possibility for more chatter suppression.

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