High Frequency Variation Speed Control of Spindle Motor for Chatter Vibration Suppression in NC Machine Tools

Teruaki Ishibashi, Hiroshi Fujimoto, Shinji Ishii, Kouji Yamamoto, and Yuki Terada

Abstract— **This paper proposes a spindle motor control method for self-excited chatter vibration suppression in numerical control (NC) machine tools. In conventional NC machine tools, spindle speed is set to constant value during machining, and the spindle speed is determined according to analysis or operator's experience. The proposed method reduces self-excited chatter vibration by varying spindle speed with high frequency during machining. This method can also suppress the disturbance derived from cutting resistance by repetitive control, and achieve spindle speed variation with high frequency by perfect tracking control. Finally, we show the advantages of the proposed method by simulations and experiments.**

I. Introduction

Recently, NC machine tools play an important role as mother machine in industry. A considerable amount of study has been done on the NC machine tools to realize high accuracy and high speed of machining[1], [2]. Cutting resistance, chatter vibration and thermal expansion have negative effect on cutting accuracy. Chatter vibration is the vibration of tool exited by certain factors. Chatter vibration is divided into forced chatter vibration and self-excited chatter vibration.

Forced chatter vibration is caused by large cutting resistance or resonance phenomenon. It is easily suppressed by decreasing cutting resistance or keeping the frequency of cutting resistance from resonant frequency. Many methods have been proposed to analyze and control the cutting resistance[3], [4], [5], [6].

Self-exited chatter vibration is caused by regenerative effect. A lot of previous research have tried to suppress this vibration by analytical technique[7], [8], [9]. Analytical method needs parameters of tools which are difficult to obtain. Furthermore, they are changed during the machining because of temperature swing and tool wear.

Spindle speed variation has been widely used to suppress self-exited vibration[10], [11], [12]. This technique focuses on the amplitude of the spindle speed variation and succeeds in suppressing the vibration by high amplitude of spindle speed variation. However, the frequency has not been mentioned in the literature. From the point of view of the surface roughness, smaller amplitude is desirable.

This paper focuses on suppressing the vibration by high frequency spindle speed variation. high frequency speed variation needs high response of speed control and suppression of disturbance derived from cutting resistance. In the field of hard disc, repetitive control is proposed for suppression of repetitive disturbance[13], [14], [15].

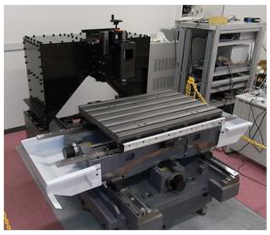


Fig. 1. Experimental equipment.

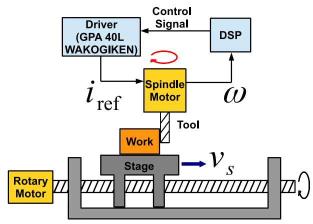


Fig. 2. Schematic diagram of plant

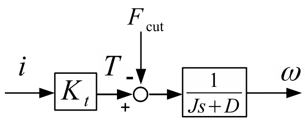


Fig. 3. Block diagram of plant.

The remainder of this paper is organized as follows. Section II describes the experimental equipment. Section III introduces the chatter vibration and conventional techniques. Section IV shows the analysis results of chatter vibration suppression utilizing spindle speed variation and basic experimental results. Section V, VI, VII introduce the spindle speed control system designed to realize the cutting resistance compensation and the spindle speed variation with high frequency.

II. Controlled System

Fig. 1 shows experimental equipment. Machining is performed by feeding stage and pressing a work against tools. The feed rate is set to constant value during machining. Fig. 2 shows the schematic diagram of plant during machining. Here, v_s, i, and K_t are feed rate, current, and torque coefficient, respectively. Cutting resistance is generated during machining. The torque is acquired by

$$T = K_t i. \tag{1}$$

Cutting resistance is considered as a disturbance torque to spindle and denoted as $F_{\rm cut}$. Other disturbance factors are not taken into account because they are quite smaller than cutting resistance. Spindle speed is acquired by

$$\omega = \frac{1}{Js+D}(T - F_{\rm cut}). \tag{2}$$

Here, J, D, and ω are inertia of spindle including tools, friction coefficient of spindle, and spindle speed, respectively. Table I shows parameters of spindle and driver.

TABLE I

PARAMETERS OF SPINDLE.

Driver	GPA40L(WAKOGIKEN)
Inertia J	6.8×10^{-3} kg $\cdot$ m^2
Friction coefficient D	7.8×10^{-3} Nm $\cdot$ s
Torque coefficient K_t	0.47 Nm/A

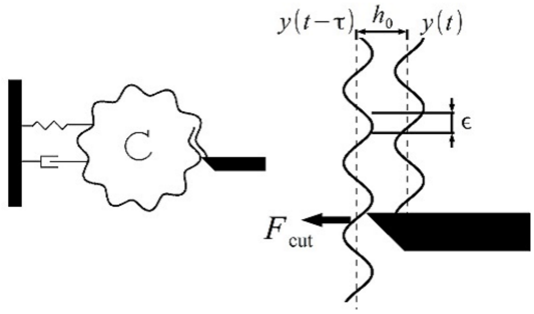


Fig. 4. Cutting off processing

III. CHATTER VIBRATION

Chatter vibration is roughly divided into forced chatter vibration and self-exited chatter vibration. This section introduces the mechanism of each vibration.

A. Forced chatter vibration

Forced chatter vibration is excited by external force. Displacement of tool Y is acquired by

$$Y(\omega) = G(\omega)F(\omega). \tag{3}$$

Here, G and F are frequency response function of tool and periodic external force. Forced chatter vibration is excited when the external force is overmuch or the frequency of the force synchronizes with resonance frequency of tool.

B. Self-excited chatter vibration[16]

Assuming that the vibration is one direction, vibration model of end milling is same as that of cutting off processing. Fig. 4 shows the schematic view of the cutting-off processing. Fig. 5 shows the block diagram of self-excited chatter vibration. Here, a is the width of tool. Nominal chip thickness h_0 is described as

$$h_0 = v_s \left(\frac{2\pi}{\omega}\right). \tag{4}$$

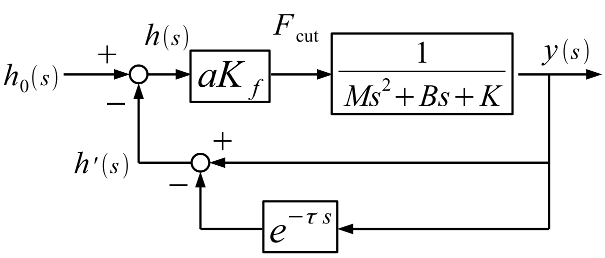


Fig. 5. Block diagram of self-excited chatter vibration.

Here, ω is the spindle speed. Displacement of tool $y(t)$ is excited by cutting resistance. If vibration occurs during cutting, waveform is formed on the cut surface and chip thickness changes. The dynamic chip thickness h' is described as

$$h' = y(t-\tau) - y(t). \tag{5}$$

Here, τ is the period which spindle motor takes to make one rotation. Actual chip thickness h is the sum of the nominal and dynamic chip thickness.

Cutting resistance is proportional to chip volume and describes as

$$F_{\text{cut}} = aK_f h. \tag{6}$$

Here, K_f is cutting resistance coefficient. Assuming that transfer function from cutting resistance to displacement of tool is a secondary system, the vibration model is shown in Fig. 5. Here, M, D, and K are dynamic mass, mechanical impedance, and dynamic rigidity, respectively. Transfer function from nominal chip thickness to actual chip thickness is

$$\frac{h(s)}{h_0} = \frac{1}{1 + (1 - e^{-s\tau})aK_f G}. \tag{7}$$

When the cutting is under critical condition, the vibration continues without attenuation and denominator of (7) is

$$1 + (1 - e^{-j\omega_c\tau})a_{\text{lim}}K_f(\Phi + jH) = 0. \tag{8}$$

Here, a_{lim} is width of tool in critical condition. Φ and H are real and imaginary part of transfer function G. From the condition that the real part and the imaginary part are zero,

$$1 + a_{\text{lim}}K_f[\Phi(1 - \cos\omega_c\tau) - H\sin\omega_c\tau] = 0. \tag{9}$$

$$\Phi\sin\omega_c\tau + H(1 - \cos\omega_c\tau) = 0. \tag{10}$$

is obtained. From (9) and (10), width of tool in critical condition is

$$a_{\text{lim}} \left|\frac{1}{2K_f\Phi(\omega_c)}\right|. \tag{11}$$

In the case that spindle speed is constant, self-excited chatter vibration occurs when a is larger than a_{lim}.

IV. PROPOSAL METHOD FOR SELF-EXCITED CHATTER VIBRATION SUPPRESSION

Self-excited chatter vibration occurs when periodic variation of cutting resistance and chip thickness excite each other. Self-excited chatter vibration can be suppressed by breaking the periodicity. Wavelength of the wave of cutting surface changes according to spindle speed because frequency of the vibration ranges around resonant frequency of tool. This section introduces the self-excited chatter vibration suppression by spindle speed variation method.

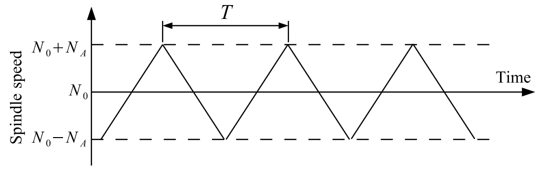


Fig. 6. Reference of spindle speed.

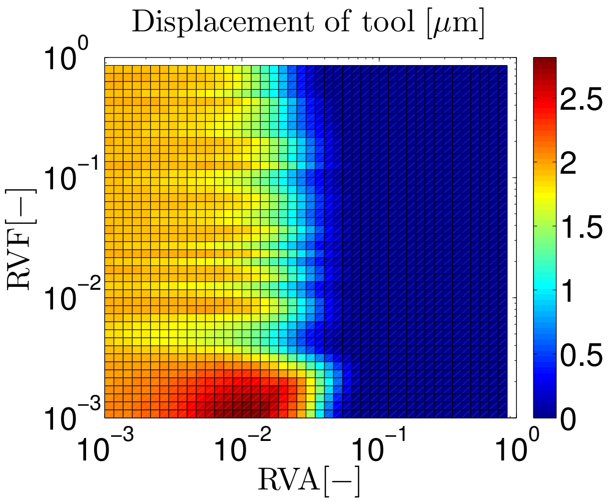


Fig. 7. Dependence of RVA, RVF ($N_0 = 262$ rad/s).

A. Spindle speed variation control

To simplify the simulation, triangular wave is chosen as spindle speed reference with the cycle of T like Fig. 6. Here, N_0 and N_a are average and amplitude of spindle speed. To generalize amplitude and frequency of spindle speed variation, the parameters RVA and RVF are introduced as follows:

$$\mathrm{RVA} = \frac{N_A}{N_0}. \quad (12)$$

$$\mathrm{RVF} = \frac{2\pi}{N_0 T}. \quad (13)$$

B. Simulation of chatter vibration suppression

TABLE II
PARAMETERS OF CHATTER VIBRATION.

Feed rate v_s	2×10^{-3} m/s
Width of cut a	5×10^{-3} m
Specific cutting force K_t	300 MPa
Dynamic mass M	10 $\mathrm{Ns^2/m}$
Mechanical impedance B	200 Ns/m
Dynamic rigidity K	5×10^5 N/m

Fig. 7 shows a simulation result of chatter vibration suppression by spindle speed variation and Table II shows the simulation condition. 262 rad/s with which the chatter vibration occurs is chosen as N_0. RVA and RVF are changed from 10^{-3} to 1.

Chatter vibration is suppressed dramatically around RVA is 0.05. Fig. 8 shows the RVF dependence with constant RVA.

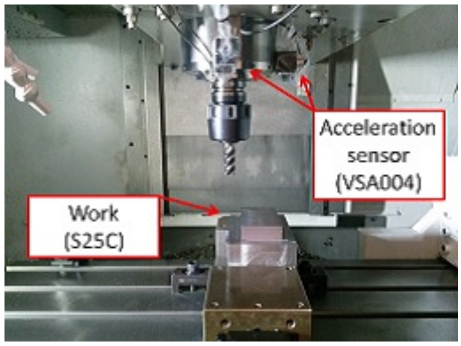


Fig. 9. Experimental equipment 2.

Fig. 8(b), Fig. 8(c), and Fig. 8(d) show chatter vibration with RVF $= 0.2, 0, 4$ and 0.8 in the time domain. In the case of RVF $= 0.2$ and 0.4, chatter vibration is increasing. However, chatter vibration decays when RVF $= 0.8$, which means chatter vibration can be suppressed by increasing RVF.

C. Experiment of chatter vibration suppression

TABLE III
CUTTING CONDITION.

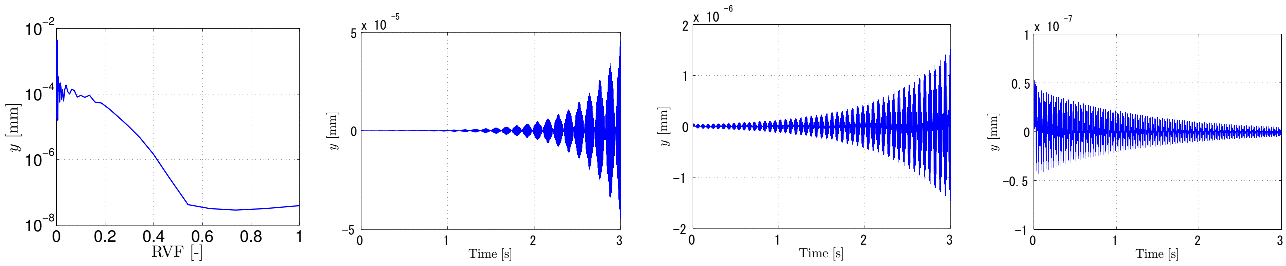
End mill flutes	4
End mill ϕ	20 mm
Radial depth of cut	20 mm
Axial depth of cut	2 mm
Work piece	S25C
Feed rate	643 $\mathrm{mm/min^{-1}}$

This subsection introduces the experimental result of chatter vibration by spindle speed variation. Fig. 9 shows the experimental equipment for metal machining. Chatter vibration is detected by acceleration sensor attached to spindle motor. Table III shows cutting condition.

Experiment is done with the spindle speed shown in Fig. 10(a) and Fig. 11(a). Fig. 10 is experimental result with RVA $= 0.3$ and RVF $= 0.01$, and Fig. 11 is with RVA $= 0.4$ and RVF $= 0.02$. When the spindle speed is constant, chatter vibration occurs. The spectrum of vibration with constant spindle speed is shown in Fig. 10(c) and Fig. 11(c). Chatter vibration is known to range around resonant frequency of tool. Therefore, resonant frequency of tool is around 800 Hz. This vibration is self-exited chatter because forced chatter vibration does not occur in this cutting condition. Vibration is suppressed by spindle speed variation. The spectrum of vibration with variable speed is shown Fig. 10(d) and Fig. 11(d). Vibrations around resonant frequency decrease comparing to constant spindle speed. These result shows effectivity of spindle speed variation.

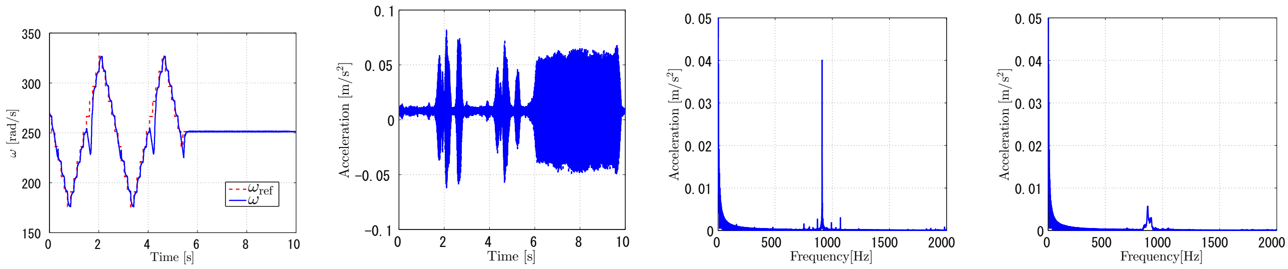
V. CUTTING RESISTANCE COMPENSATION FOR HIGH RVF

To achieve large RVF, high frequency speed control and cutting resistance compensation are needed. This section introduces control system to achieve the performance. Cutting resistance is proportional to chip thickness. Therefore, cutting



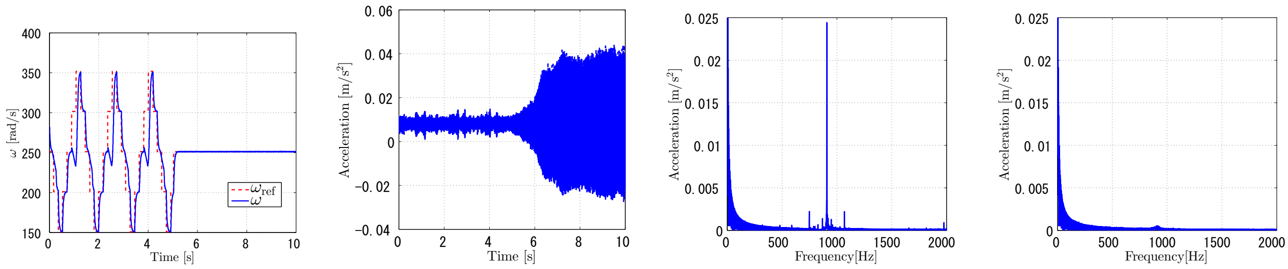
(a) Dependence of RVF. (b) RVF = 0.2 . (c) RVF = 0.4 . (d) RVF = 0.8 .

Fig. 8. Dependence of RVF （$N_0 = 262$ rad/s, RVA = 0.1） .



(a) Spindle speed. (b) Vibration of tool. (c) Vibration of tool (constant speed). (d) Vibration of tool (variable speed) .

Fig. 10. Experimental result of chatter vibration （RVA = 0.3, RVF = 0.01） .



(a) Spindle speed. (b) Vibration of tool. (c) Vibration of tool (constant speed). (d) Vibration of tool (variable speed).

Fig. 11. Experimental result of chatter vibration （RVA = 0.4, RVF = 0.02） .

resistance is depend on the angle of spindle motor θ. Fig. 12 shows proposal control system. Feedback controller C_{PI} is designed with the pole ω_p of 100 rad/s.

A. Perfect tracking control

Perfect tracking control (PTC) is two degrees of freedom control. PTC can achieve tracking to reference value with no error and delay by changing input value N times during sampling period. Here, N is set to be equal with the order of nominal plant n. In this paper, the order of plant is 1. The disturbance and plant variation are suppressed by feedback controller. The discrete-time state equation of plant is described as

$$x[k+1] = Ax[k] + Bu[k]. \quad (14)$$

$$\omega[k] = Cx[k]. \quad (15)$$

From (14) and (15), the inverse model and nominal output is

$$u_0[k] = B^{-1}(1 - z^{-1}A)x_d[k+1]. \quad (16)$$

$$\omega_0[k] = z^{-1}Cx_d[k+1]. \quad (17)$$

B. Disturbance compensation

Disturbance is estimated by following process. Spindle speed and speed error e are described as

$$\omega = \omega_0 - \frac{P(s)}{1 + C_{\mathrm{PI}}(s)P(s)} F_{\mathrm{cut}}(t). \quad (18)$$

$$e(t) = \omega_0(t) - \omega(t). \quad (19)$$

from (18) and (19), cutting resistance F_{cut} can be described as

$$\hat{F}_{\mathrm{cut}}(t) = \frac{1 + C_{\mathrm{PI}}(s)P(s)}{P(s)} e(t). \quad (20)$$

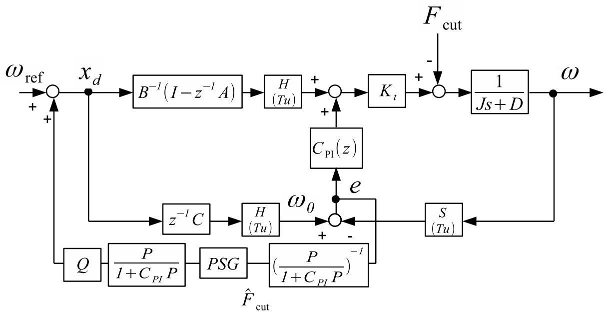


Fig. 12. Repetitive Perfect tracking controller (RPTC).

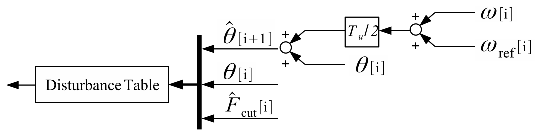


Fig. 13. Periodic signal generator (PSG).

Therefore, cutting resistance can be calculated by (20). Cutting resistance can be duplicated by saving to memory and recovered according to angle of spindle motor like Fig. 13 and Fig. 14. Compensation signal is generated by duplicated cutting resistance which is calculated by $P/(1+CP)$. This system needs information about angle of spindle motor of 1 sample ahead. It is estimated by

$$\hat{\theta}[\mathrm{i}+1]=\theta[\mathrm{i}]+\frac{\omega[\mathrm{i}]+\omega_{\mathrm{ref}}[\mathrm{i}]}{2}T_u. \tag{21}$$

Cutting resistance have non-periodic spectrum because machining is discrete phenomena. Repetitive control has bad influence for non-periodic disturbance derived from water bet effect. To deal with the problem, Q-filter is applied to compensation signal. Q-filter is described as

$$Q[z]=\frac{1+\gamma z^{-1}+z^{-2}}{\gamma+2}. \tag{22}$$

Here, γ is 2 in this paper.

VI. Simulation of Repetitive Control

This section shows simulation result of proposal repetitive control. In this simulation, cutting resistance is supposed to be

$$F_{\mathrm{cut}}=\sum_{l=0}^{4}\sin l\theta. \tag{23}$$

And number of memory is 10000. Fig. 15(a) shows the simulation result with constant speed reference. Compensation starts at 0.5 s, and error caused by cutting resistance decrease. Error after 0.5 s attributes to 1 sample delay of Q-filter. In Fig. 15(c), spindle speed reference is variable with RVA $=0.1$ and RVF $=1$. Speed error decrease by repetitive control even when the spindle speed is not constant.

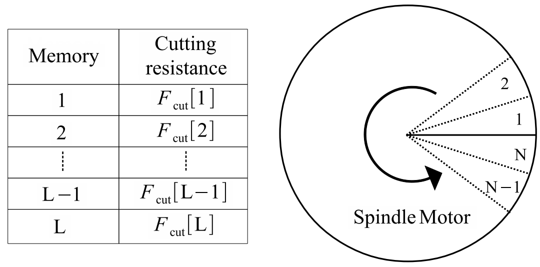


Fig. 14. Disturbance table.

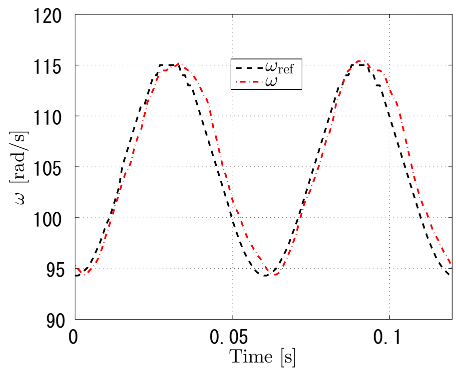


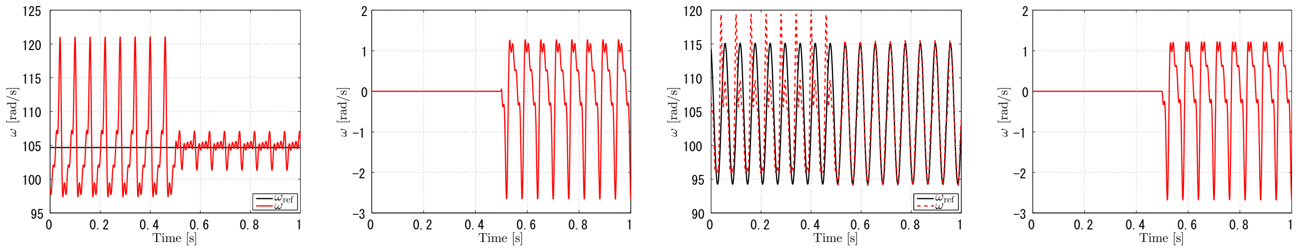
Fig. 17. Spindle speed (RVA $=0.1$, RVF $=1.15$).

VII. Experiment of Repetitive Control

This section shows experimental result of proposal repetitive control system. Cutting is done using experimental equipment 1 and chemical wood. The number of memory is 2000. Fig. 16 shows experimental result with constant spindle speed reference. Fig. 16(a) and Fig. 16(b) show speed error and the spectrum of speed error without compensation. The errors at 16.7 Hz and 4×16.7 Hz attribute to cutting resistance and torque ripple. Fig. 16(c) and Fig. 16(d) show speed error and the spectrum of speed error with compensation. Errors at 16.7 Hz and 4×16.7 Hz decrease by compensation. In Fig. 17, spindle speed reference varies like sinusoidal wave with RVA $=0.1$ and RVF $=1.15$. Compensation is applied in latter cycle. Table IV shows averaged speed error. These experimental results represent the effectiveness of repetitive control.

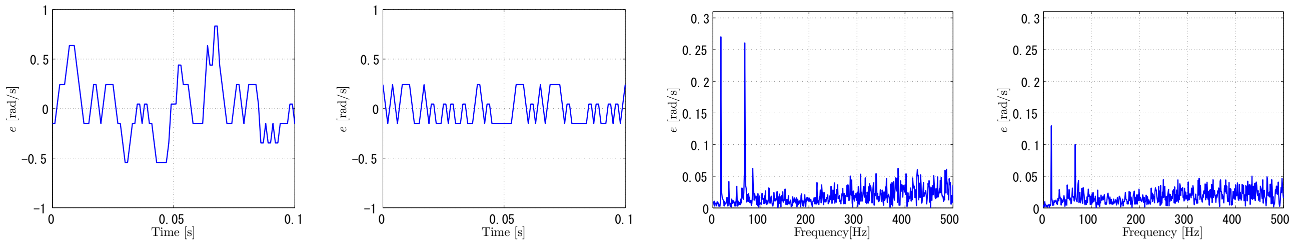
VIII. Conclusion

In this paper, spindle speed variation control method for chatter vibration suppression is proposed. In addition, repetitive control system for high frequency variation is proposed. Simulation results and experimental results show the effectiveness of chatter vibration suppression by high RVA and RVF. Effectiveness Repetitive control is verified by simulation and experiment. In the future, chatter vibration suppression by high RVF is verified by metal machining.



(a) Spindle speed (constant speed).
(b) Compensation signal (constant speed).
(c) Spindle speed (variable speed).
(d) Compensation signal (variable speed).

Fig. 15. Simulation result of RPTC.



(a) Speed error (without compensation).
(b) Speed error (with compensation).
(c) Frequency analysis (with compensation).
(d) Frequency analysis (without compensation)

Fig. 16. Experimental result (constant speed).

TABLE IV

AVERAGE OF THE ERROR.

Without compensation	with compensation
1.74	1.38

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