A Noise-Free Servo-Spindle for High-Speed NC Gear Grinding Machines

Takashi Emura, Lei Wang, Hisashi Nakamura, Masashi Yamanaka and Yasushi Teshigawara
Department of Mechatronics and Precision Engineering, Tohoku University
Aoba, Aramaki, Aobaku, Sendai, 980-77 Japan

Abstract— **The authors developed a productive type NC (Numerically Controlled) gear grinding machine for automobile plants. This NC machine requires high-accuracy synchronization between the grinding spindle and workspindle. We must use high-power servomotors and servo-amplifiers to satisfy the specification required for high-speed grinding. However, since the high-power servo-amplifier causes very large ripple of motor current at PWM (Pulse-Width Modulation) frequency and induces strong noise, it becomes difficult to get the stable synchronous rotation among spindles. Therefore, the authors tried to use two-phase type PLL to achieve noise-free high-speed synchronous spindles and to reduce the noise caused by the current ripple with a kind of current filter. In this paper, an approach for suppressing the noise and experimental results are described.**

I. Introduction

Gear grinding takes extremely long grinding time and it prevents increasing the productivity in mass production of gears. Thus, the authors developed a productive type NC gear grinding machine for automobile plants, which are the most productive plants of gears. This machine requires two large-power servo-spindles for its grinding-spindle and workspindle. These servo-spindles also have to be synchronously controlled with high precision even rotating at a high speed. The authors used high-power and high-speed servomotors to drive the spindles. For example, the servomotor for grinding-spindle has a rated power of 22 kW, rated output torque of 22 N·m and maximum rotary speed of 10 000 r/min. The servomotor for workspindle has a rated power of 16 kW, rated output torque of 82 N·m and maximum rotary speed of 2000 r/min.

These servomotors are driven by PWM (Pulse-Width Modulation) type servo-amplifiers, and the PWM type amplifier of large power causes a very large ripple in motor current which appears at PWM frequency. Since this large current ripple induces a strong noise which causes trouble to control systems, it is difficult to realize synchronous control of high accuracy. Therefore, the authors tried to use two-phase type PLL (Phase-Locked Loop) to get noise-free high-speed synchronous spindles and tried to use a kind of current filter to reduce the ripple of motor current. Experiments were carried out to confirm the effectiveness of the noise-free systems. In this paper, an approach for suppressing the noise and getting the high-speed and high-precision synchronous spindles is described with experimental results.

II. Noise Caused by PWM

Problems of noise of the grinding-spindle is more severe than that of the workspindle because the rated power of the grinding-spindle is larger than that of the workspindle. Thus we mainly describe about the case of grinding-spindle in the followings. The grinding-spindle is driven by a high-power brushless servomotor. Since the maximum output voltage of the servo-amplifier is limited to 200 V and the rated power of the servomotor is 22 kW, the current of field coil has to be more than 200 A at a peak load. For this large current, a wire diameter of field coil became large, and the number of turns became a few because of the limitation of winding space. Thus inductance of the field coil was constrained to a very small value. The measured inductance of one phase is about 30 μH at 1 kHz and it is reduced to very small value of less than 1.5 μH at 25 kHz of PWM frequency. Since the coil inductance is extremely small like this, its electrical time constant is very small. This means that we can get a good control characteristics. However, the extremely short time constant causes very large current ripple at PWM frequency, and this current ripple induces the strong noise. The strong noise gives serious problems to control systems.

In order to analyze the ripple current, numerical simulation of motor current was carried out. Fig. 1(a) is simplified model of synchronous motor for simulation, where coil inductance L is 1.44 μH, coil resistance R is 0.15 Ω and voltage of DC line E is 200 V. PWM output voltage E_U, E_V and E_W of servo-amplifier are supplied on terminal of three phases U, V, W. PWM pattern shown in Fig. 1(b) are generated by comparing reference voltage e_U, e_V and e_W with triangle wave e_b of which frequency is 25 kHz.

Fig. 2(a) is an example of simulated results, where the output frequency of the servo-amplifier is 300 Hz. As shown in Fig. 2(a), motor current is overlapped by large noise. Fig. 2(b) gives the detail situation by comparing simulated and measured results of coil current, where simulated results agreed with the measured results. Thus the simulated results shows that the motor current has very large current ripple at PWM frequency.

This simulation shows clearly that the servomotor and power amplifier generate very strong noises for the sake of smallness of coil inductance. The coil inductance decreases sharply at high switching frequency in such large power motor because of the magnetic characteristic of field core. The noises caused by switching is a very severe problem in this NC machine and has to be overcome in order to achieve the high precision synchronous control.

Therefore, the following sections describe two different approaches for overcoming switching noise problem. Section III presents a synchronous control method of two-phase type PLL which enables the system engage a high-precision and high-

0-7803-3026-9/95 $4.00

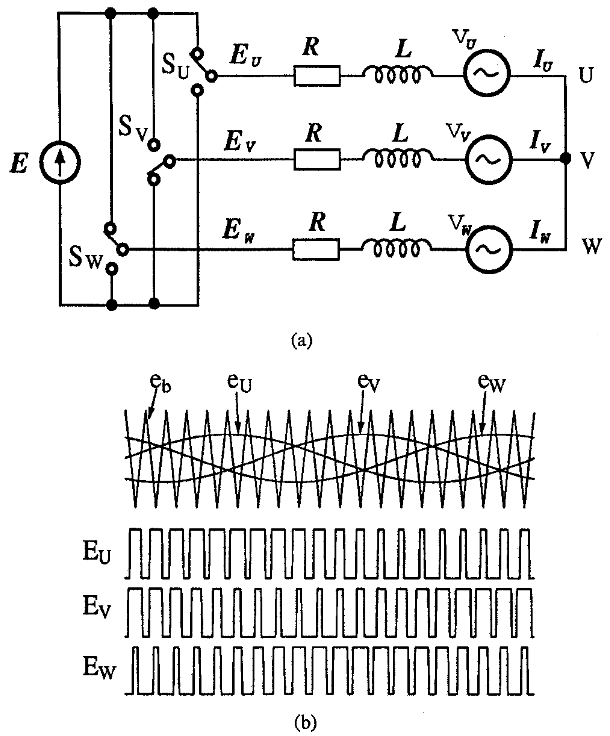
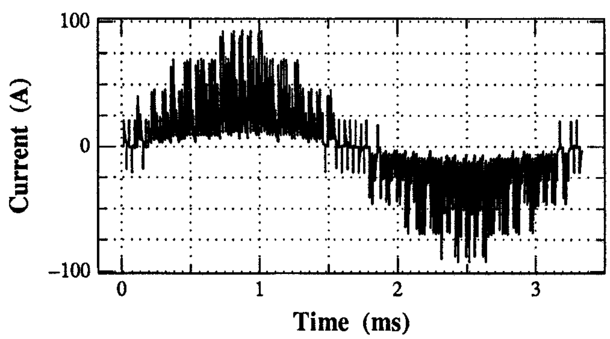
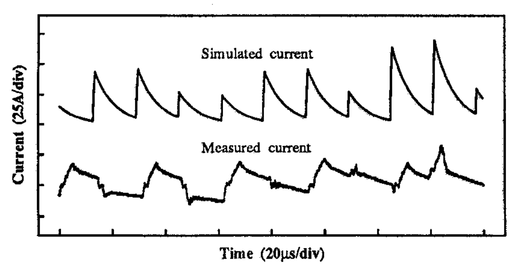


Fig. 1. Motor model for numerical simulation. I_u, I_v, I_w are line current and V_u, V_v, V_w are back EMF (electromotive force)



(a) Simulated motor current.



(b) Comparison of simulated and measured results.

Fig. 2. Ripple of motor current.

speed synchronous control under strong noise situation. Section IV gives discussion of using large power filter to suppress switching noise and the experimental results.

III. Synchronous System by Two-Phase Type PLL

The developed gear grinding machine requires high-speed synchronous control with high accuracy. The high-speed and high-precision synchronous control systems are realized usually by using a high-resolution and high-speed encoder whose output is two-phase sinusoidal wave. However, the voltage of the sinusoidal waves is usually very small, and it is difficult to detect this small voltage without problems of the noise under the strong noise surroundings. This means that we cannot use the conventional control method of high-precision synchronization. Therefore, the authors used two-phase type PLL in this synchronous system. The two-phase type PLL was first proposed by Emura [1] and its noise rejection ability was already verified [2]–[4].

Fig. 3 is blockdiagram of the high-speed synchronous system between grinding spindle and workspindle of the NC gear grinding machine. Both of the servo-spindles were controlled by two-phase type PLL. A command pulse generator generates two pulse trains whose frequency ratio is the velocity ratio of grinding-spindle to workspindle. Position controllers of two-phase type PLL control the spindles so as for them to follow each command pulse accurately. By using two-phase type PLL, high-speed and high-precision synchronous control was realized. Two interpolators of two-phase type PLL interpolate encoder signal with high resolution and the interpolated output pulses of rotational angle are sent to servo-amplifiers.

A. *High-resolution detection of rotary angle with interpolator of two-phase type PLL*

The servo-amplifiers which we used this time require a two-phase rectangular signal for generating the three-phase field current that synchronizes with rotor angle. However, we could not use the conventional interpolators of comparator type because of the noise induced by the ripple current. Therefore, the authors designed special interpolators which use two-phase type PLL as shown in Fig. 4 to detect rotary angles of spindles. Circuits of this interpolator was designed mainly according to the description in [3], and so they are only briefly described in the following.

Input signal is a two-phase sinusoidal wave ($\sin\theta_i$, $\cos\theta_i$) obtained from encoder. A tracking signal of two-phase sinusoidal wave ($\sin\theta_o$, $\cos\theta_o$) is generated by a voltage controlled oscillator (VCO). This VCO is controlled so as to track the input signal. Phase difference of input signal and tracking signal is calculated by phase detector (PD). Loop filter (LF) removes high-frequency components of output of PD and output to VCO. V/F converter contained in VCO generates pulse train

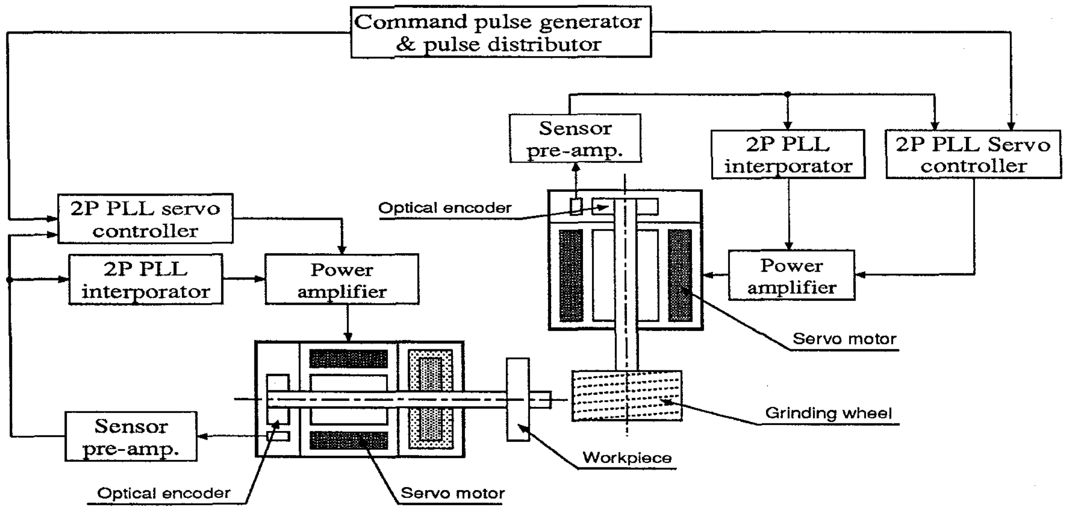


Fig. 3. A high-speed synchronous system for NC gear grinding machines.

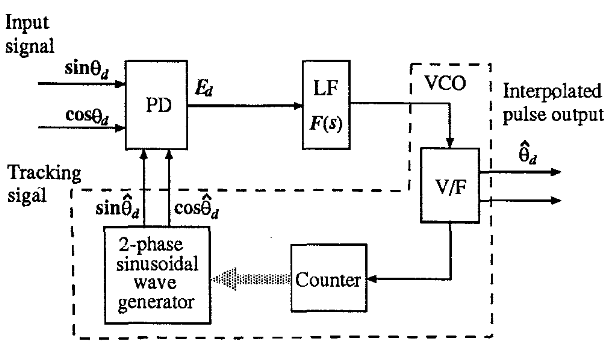


Fig. 4. Blockdiagram of interpolator using two-phase type PLL.

with the frequency proportional to input voltage. The pulse trains is counted with a binary counter, and the output of counter is fed to a ROM. Two-phase sinusoidal wave in digital value is written in the ROM and it is output when addressed. D/A converters convert the ROM output to analog voltage. The sinusoidal wave is controlled so as to track input of two phase sinusoidal signal by controlling the phase difference to 0, this means that PLL is in locked state. Under the locked state, pulse from V/F becomes to the interpolated pulse of input signal which is the rotary angle of encoder.

The most significant difference of two-phase type PLL from conventional PLL is that we can always obtain the true 2-phase sinusoidal wave which tracks input signal. This means that it has excellent noise suppression characteristics and wide range of input frequency. This circuit can also lock when motor changes its rotary direction.

Optical encoders of very high precision are used to detect rotary angle of shaft. Number of optical slits is 1800 for grinding-spindle and 9000 for workspindle. We can get 2-phase sinusoidal waves from the encoders. The developed interpolator divides them by 128 times and output 2-phase rectangular pulse signal. Hence the resolution is 5.6″ and 1.1″ respectively, and the maximum frequency becomes up to 38.4 MHz. The pulses are fed to power amplifiers and as well used to monitor synchronous control. In [3], a magnetic scale with induction type head was used as the rotary sensor. Because induction type head can not work at low speed, the interpolator could not work at rotary speed below 300 r/min. However, the newly developed system can work at any speed below 10 000 r/m for grinding spindle and below 2000 r/min for workspindle. Of course, we can give reversible rotations to the spindles.

In general, detection with so high accuracy and high frequency is critically affected by noises and it is very difficult to realize stable control. However, the new interpolators can detect the rotor angles without misoperation. Fig. 5 illustrates an example of experimental results. In Fig. 5, input signal means signal obtained from encoder and tracking signal means the sinusoidal wave of VCO. As shown in Fig. 5, signal from encoder is distorted by strong noise. However, the sinusoidal wave which is precisely tracking the input signal has no distortion, because it is generated by VCO whose output waveform is true sinusoidal wave. We can get the interpolated pulses from the output pulses of V/F converter, by which the tracking sinusoidal waves were constructed.

B. Servo-Controller with Two-Phase Type PLL

Servo-controller uses the two-phase type PLL method as well. The schematic is shown in Fig. 6. A servo-error de-

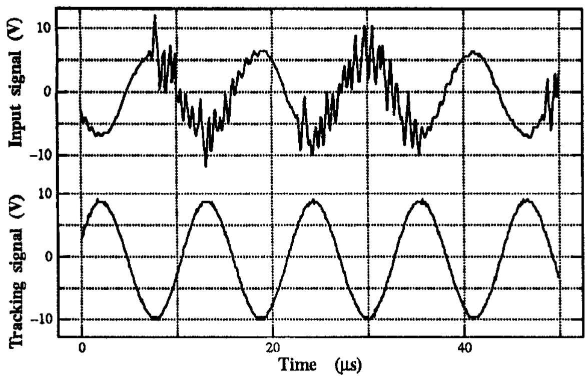


Fig. 5. Experimental results of interpolator of two-phase type PLL. (Workspindle , 500 r/min)

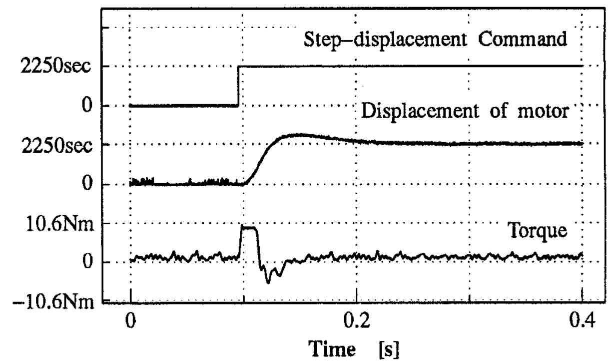


Fig. 7. Step response of grinding-spindle

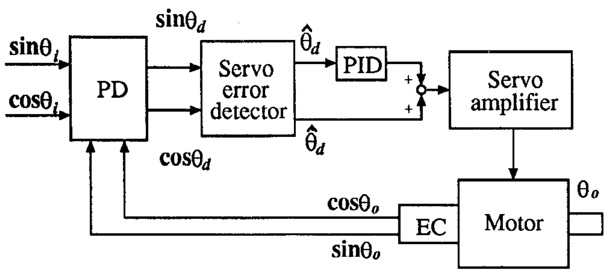


Fig. 6. Schematic of servomechanism of two-phase type PLL.

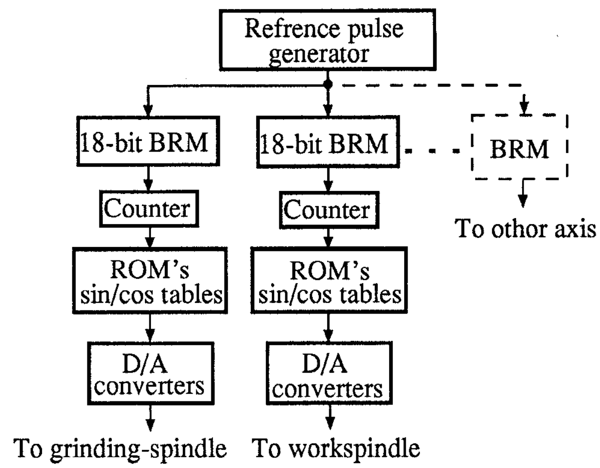


Fig. 8. Reference signal generator for synchronous control system of two-phase type PLL

tector of two-phase type PLL is used to detect servo-error with very high precision. PID controller controls the motor torque to make the servo-error to 0. Reference signal of this loop is a pair of two-phase sinusoidal waves ($\sin\theta_i, \cos\theta_i$), and their phase is compared with the two-phase sinusoidal waves obtained from encoder by the following vector phase operation.

$$\left.\begin{array}{r}\cos\theta_i\cos\theta_o - \sin\theta_i\sin\theta_o = \cos\theta_d\\ -\cos\theta_i\sin\theta_o + \sin\theta_i\cos\theta_o = \sin\theta_d\end{array}\right\}. \quad (1)$$

Hence we can get a pair of two-phase sinusoidal waves of which argument is phase difference $\theta_d = \theta_i - \theta_o$. Since we can detect the phase difference θ_d with the same principle as the interpolator mentioned previously, the servo-error detector of two-phase type PLL detects the servo-error with high resolution and high accuracy.

Another feature of this loop is that the servo-error detector is able to detect angular velocity error with high accuracy. This is based on the excellent capability of PLL in frequency detection as known. By feedback of the angular velocity error obtained from the phase detector, we could realize the servo-controller whose D gain is high enough and consequently whose stability is significantly high. The resolution and maximum speed are 11.25″ and 10 000 r/min for grinding spindle and 1.125″ and 2000 r/min for workspindle respectively. These values are extremely excellent values that have never been realized.

Fig. 7(a) shows a step response of grinding-spindle. From Fig. 7, it is known that the grinding-spindle tracks command pluses precisely even under the existence of strong noise.

C. Reference Signal Generator

Both of workspindle and grinding-spindle controlled by the above mentioned two-phase type PLL is positioning servomechanism. Their positioning command is given consequently two-phase sinusoidal wave of which angular frequency is decided by the specifications of work piece and tool. The structure of reference signal generator is simple as shown in Fig. 8.

As shown in Fig. 8, the output pulse frequency of a reference pulse generator is decreased by BRM (Binary Rate Multiplier), of which decreasing rate is decided by the rotary speed of each axis. Since bit length of BRM's is 18, the accuracy of synchronous rotation is 2^{18}. The output pulse of each BRM is counted by binary counter and transformed into two-phase sinusoidal wave by two ROM's in which look-up tables are written, and after that it is converted to analog two-phase signal by two D/A converters.

IV. Reduction of Ripple Current by Large-Current Filter

As mentioned previously, the ripple of motor current generates very strong noise. Even the synchronous control system can work well under such circumstance, other detectors required for servo-controller are interfered by the switching noise and they did not work without misoperation. Therefore, the ripple of motor current is necessary to be reduced to a tolerable level. As the mean current of motor is about 100 A and the frequency of current ripple is 25 kHz, the authors tried to decrease this current ripple by using a large-current filter whose frequency characteristics is high enough.

A. Large-Current Filter

This filter consists of 6 choke coils L_0 and L_1, 3 capacitors C and 3 resistors R as illustrated in Fig. 9(a). I_0 is current of servo-amplifier, I_1 is current of motor and I_2 is current dissipated by RC circuits. Because the purpose of this filter is to reduce the ripple of switching frequency, choke coils of ferrite core are used to obtain good characteristics at PWM frequency. The rated current of the coils is 110 A.

B. Frequency-Domain Analysis

One phase of the filter can be simplified as Fig. 9(b), where winding inductance of motor is omitted because it is very small compared with that of filter. If output current of servo-amplifier is I_0 and output voltage is E, impedance of one phase $Z_0 = E/I_0$ is given by

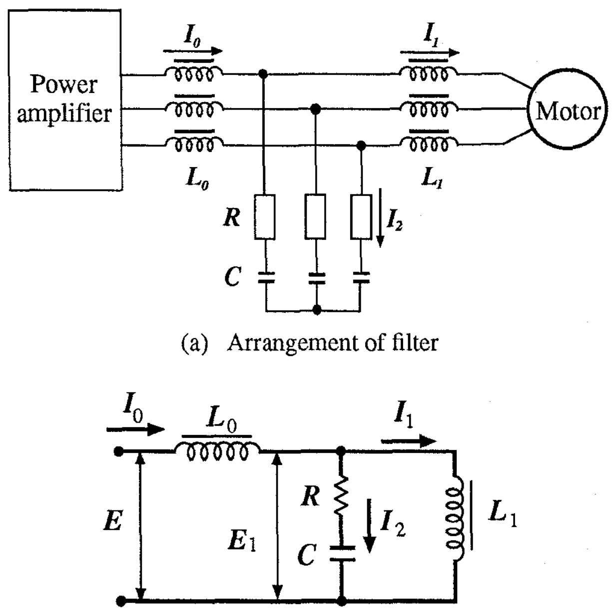
$$Z_0 = \frac{s(L_0 + L_1) + s^2RC(L_0 + L_1) + s^3CL_0L_1}{1 + sRC + s^2CL_1}. \quad (2)$$

If field current of motor is I_1, we can use impedance $Z_1 = E/I_1$ for expressing suppression ability of current ripple of motor. Z_1 is given by

$$Z_1 = \frac{s(L_0 + L_1) + s^2RC(L_0 + L_1) + s^3CL_0L_1}{1 + sRC}. \quad (3)$$

Frequency characteristics of Z_0 and Z_1 are shown in Fig. 10. In Fig. 10, a_1, a_2, a_3 and a_4 are constants defined by the following equations.

$$\left.\begin{aligned} a_1 &= L_0 + L_1, & a_2 &= \frac{1}{2\pi}\sqrt{\frac{1}{CL_1}}, \\ a_3 &= \frac{1}{2\pi}\sqrt{\frac{L_0 + L_1}{CL_0L_1}}, & a_4 &= \frac{1}{2}R\sqrt{\frac{C(L_0 + L_1)}{L_0L_1}}, \end{aligned}\right\} \quad (4)$$



(a) Arrangement of filter

(b) Model of one phase of filter

Fig. 9. Structure of filter used for reducing ripple of motor current

where a_1 is the overall inductance of the network. As shown in Fig. 10(a), we can obtain good ripple suppression ability overall frequency range by increasing a_1. However, since large a_1 lowers response frequency of motor current, the authors used $a_1 = 100\mu$H. We must use large-size inductors because of large motor current and its large ripple. a_2 means the undamped resonant frequency of loop $R - C - L_1$ and it has no effect on Z_1. a_3 is the characteristic frequency of the filter. Fig. 10(c) shows that a small a_3 gives good suppression ability of ripple, but this requests to increase C, L_0 and L_1. Thus, for a certain sum of L_0 and L_1, $L_0 = L_1$ was used. As seen in Fig. 10(d), a_4 is the damping ratio and kept below 0.7. By choosing the parameters properly, we could effectively reduce the current ripple in high-frequency range more than 25 kHz of PWM frequency.

C. Experiments

Fig. 11 is the experimental results. The effectiveness can be confirmed by the comparison of motor current with and without the filter. Fig. 11(a) gives a sharp contrast of motor current, where $L_0 = L_1 = 50\mu$H, $R = 1\Omega$ and $C = 20\mu$F. Rotary speed of motor is 3000 rpm, and spectrum of motor current shown in Fig. 11(b) shows that the induced noise nearby of 25 kHz was significantly reduced by the filter.

V. Conclusions

The authors used two high-power servomotors for getting a productive type NC gear grinding machine. Since inductance of

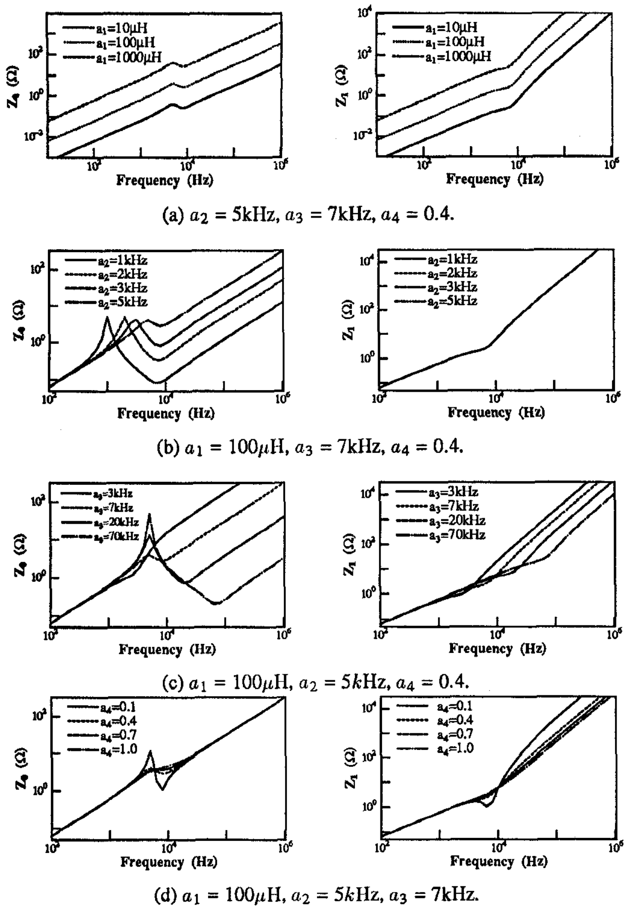


Fig. 10. Numeral results of impedance of Z_0, Z_1.

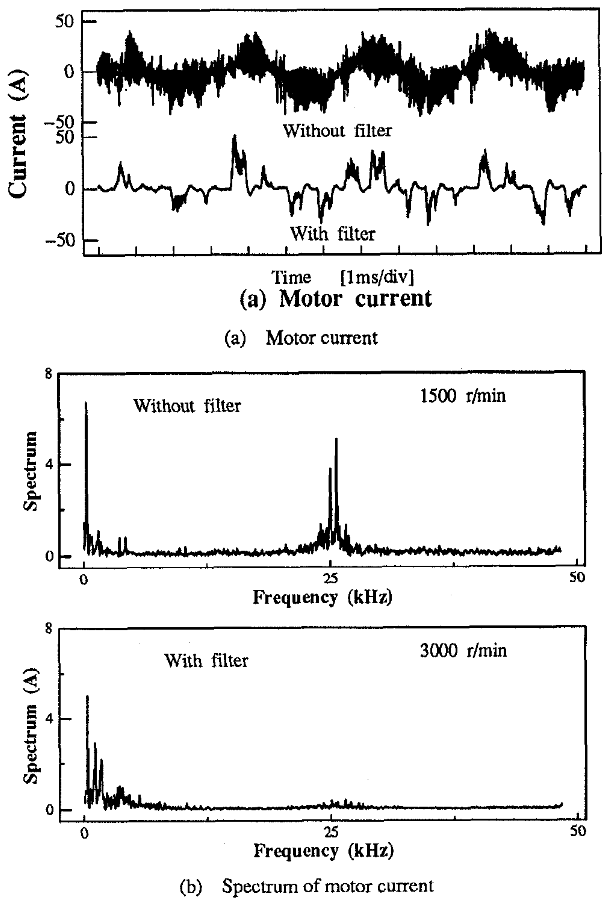


Fig. 11. Experimental results.

field coil of these motors is extremely small at PWM frequency, the ripple current of field coil became very large and large ripple current induced strong noise. The induced noise caused misoperation of control systems. Therefore, the authors used two-phase type PLL to realize high-precision control of spindles under the strong noise surroundings. Moreover, a large-current filter was used to reduce ripple of motor current. From simulation and experiments, the following conclusions were obtained.

(1) From simulation, it became clear that large ripple of motor current is caused by extremely low inductance at PWM frequency of the field coil. Simulated results were coincident with experimental results.
(2) The two-phase type PLL is useful for getting the high-speed and high-precision synchronous spindles. It rotates the spindles stably without misoperation under strong noise surroundings.
(3) The proposed large-current filter is effective for reducing the ripple of motor current.

VI. Acknowledgements

The authors thank Mr. T. Sakaguchi (NEC) for his cooperation making control circuits of spindles. A part of this work was supported by the Grant-in-Aid for Scientific Reseach of the Ministry of Education of Japan and the Grant of Toyoda Machinery Co. Ltd.

References

[1] T. Emura, "A study of a servomechanism for NC machines using 90 degrees phase difference method," Prog. Rep. of JSPE, pp. 419-421, 1982.

[2] T. Emura, A. Arakawa, and M. Hashitani "A study of high precision servo-spindle for hard gear finishing machines," The Inter. Conf. on Advanced Mechatronics, pp.427-432, 1989

[3] T. Emura, L. Wang and A. Arakawa,"A high-resolution interpolator for incremental encoders by two-phase type PLL method," in ***Proc. IEEE*** IECON'93, 1993, pp 1540-1545

[4] T. Emura, L. Wang and A. Arakawa, "A Study on A High-Speed NC Gear Grinding Machine Using Screw-Shaped CBN Wheel," ASME Journal of Mechanical Design, Vol.116, No.4, pp.1163-1168, Dec. 1994.