Industrial Paper

High-performance Synchronized Control between Spindle and Servo Motors for CNC Equipment

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Abstract -
In recent CNC machine tools, it is necessary to control the spindle and the servo axis in synchronization with each other, for example thread cutting or synchronous tapping, which has become more important.

Conventionally, position and speed loops are generally controlled on the CNC side, and the configuration of the master-slave follow-up control is adopted in which the servo motor follows the less responsive spindle motor. However, this method has three limitations: the command response due to the feedback of the spindle motor, the characteristic variation of the Induction Motor (IM motor), and the influence of the network dead time.

In this paper, we propose the high-performance synchronized control method between spindle and servo. This method consists of mainly three components. First, to improve the characteristic of IM motor control, we develop a unique multi-core system which minimize the dead time in the position/speed/current control loop for the spindle motor. Second, we propose a control method to improve the characteristics of IM motor, whose characteristics tend to change with temperature. Finally, we propose a compensation method using a high-speed network to minimize synchronization errors caused by differences in responsiveness.

By the proposed method, we achieved much higher productivity of machining process especially for the synchronized cutting process such as Thread cutting and Synchronous Tapping. Compared with the conventional control, productivity was improved by 20%. Besides, the system became robust to power supply environment.

1 INTRODUCTION

The CNC system is roughly composed of four components. The first is a CNC controller that configures machine coordinates according to the machining program generated by the user and generates the position and speed commands for the feed axis and spindle (tool). The second is actuators such as servo motors mainly for position control of table on which work is mounted and spindle head on which rotating tool is mounted. And one of the other actuators is the spindle motor mainly for speed control by rotating tool at high speed in the machining center, or rotating a workpiece itself in the lathe. Third is the servo amplifiers and spindle amplifier which are power converters that supply power to the actuator. Finally, there are detectors such as encoders and linear scales that feedback the position and speed of the operating part of the machine or motor.

The brain for the whole control of the machine tool is a CNC. This controller mainly generates the movement amount of each feed axis per unit time by analyzing sequentially the machining programs called G-code which describes the machining path of the tool, the feed speed of the tool and the number of revolutions of the tool. Further, a command value of the rotation speed of the spindle motor is generated according to the cutting conditions.

Here, the spindle motor must perform a milling process that requires an ultra-high speed of over 30,000 revolutions per minute. In addition, high power exceeding several tens of kilowatts to withstand heavy cutting is required. Therefore, the induction motor (IM motor) that does not use the permanent magnets is used for the spindle motor, instead of the synchronous motor (SM motor) with the permanent magnets that is generally used for a servo motor.

Therefore, in the spindle motor control, it is difficult to realize high-response control at the same level as the servo. This means that it is difficult to completely synchronize the rotational position of the spindle and the position of the servo feed, such as thread cutting and synchronous tapping.

In the conventional threading process, CNC generates the feed axis position command as a master based on the rotational position of the spindle that response slowly and a relatively responsive servo axis follows the position of the slow spindle. In this method, it is necessary to limit that the processing speed is slow and acceleration is small.

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Further, in the case of synchronous tapping, since the cutting load is relatively small and the inertia of the cutting tool (Tapper) itself is small, unlike in the case of thread cutting in which the workpiece itself is rotated, position commands to the spindle and the servo are given independently in some cases. However, even in this case, if there is a slight difference in synchronization due to the effect of the biting of the facet, the tapper may be damaged, and a screw conforming to the standard cannot be processed.

In this paper, section 3.1 of chapter 3 proposes a method for constructing a high-response, high-precision feedback loop that increases the responsiveness of the servo and the spindle itself and prevents the fluctuating in position and speed due to high-speed machining and cutting disturbances.

The most important point in constructing a high response feedback loop is minimizing the dead time and the processing cycle time in the loop.

Therefore, we have implemented position, speed, and current loop control in servo amplifiers and spindle amplifiers in order to minimize the effects of dead time caused by the communication interface outside feedback loop control.

In addition, in order to minimize the time delay and processing time in the servo and the spindle amplifier and to implement the function to improve the motor control performance in a specialized method, a multi-core design was proposed, and the feasibility of high-speed and high-precision control of the spindle and the servo was verified in section 4.1.

Next, in section 3.2, we proposed a control method that improves the characteristics of the IM motor, whose characteristics tend to change in the temperature environment, and stably achieves the performance of the spindle motor, and verified its effectiveness in section 4.2.

Finally, section 3.3 proposes the method to realize compensation between amplifiers to compensate for the difference in response between the servo and the spindle that occurs even when the response of the servo and spindle is increased. As for the effect of this, section 4.3 shows the verification results of this compensation. Subsection 4.3.1 describes in threading, and Subsection 4.3.2 and 4.3.3 show the verification results in actual synchronous tapping.

2 RELATED TECHNOLOGIES

Chapter 2 shows the CNC system and the basic control structure of the servo and spindle, and then describes the problems of conventional spindle and servo synchronous control.

2.1 Basic Configuration of CNC Equipment

Multi-tasking machines such as the one shown in Fig. 1

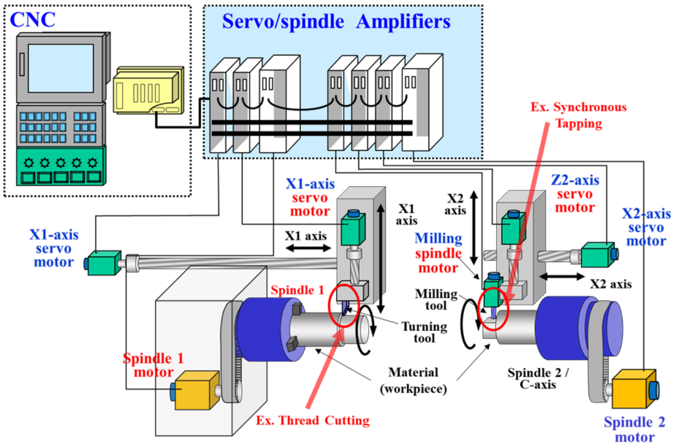

Figure 1: System configuration example of multi-tasking machine

are increasing in recent years.

Each axis is driven by servo motor connected to the ball screw in the machine. The tool used for cutting is attached to the spindle head and driven by the spindle motor. The CNC controller and the amplifiers that are used to control the speed and position in addition to power supply for the servo and the spindle motors are all installed in an electrical enclosure.

In the CNC system, since the path of the cutting tool directly affects the accuracy of the workpiece, it is important to follow the command with a small error against the influence of various load disturbances such as cutting disturbance and machine friction.

It is also important to match the performance of synchronization and response between the X, Y, and Z axes. If the synchronization and response of each axis do not match, the tool path is not able to follow the command from CNC controller. It means that the processing (cutting) accuracy could not satisfy the required quality.

2.2 Basic Servo/Spindle Control Architecture (Distributed Control)

Figure 2 shows a control block diagram at the time of thread cutting in which the rotational position of the main spindle and the position of the servo axes need to be synchronized.

Permanent magnets are used for servo motors that require high-response position control, while induction motors that do not use permanent magnets are generally used for spindle motors. For example, in a machining center or lathe that uses CNC, it is possible to rotate a rotating tool more stably higher speed than a case that requires position control of a spindle motor, or to withstand heavy cutting well. Since it is important to achieve the highest possible output, synchronous motors that are not suitable for high-speed rotation or high-output at high-speed rotation are rarely used.

On the other hand, machining required for machine tools

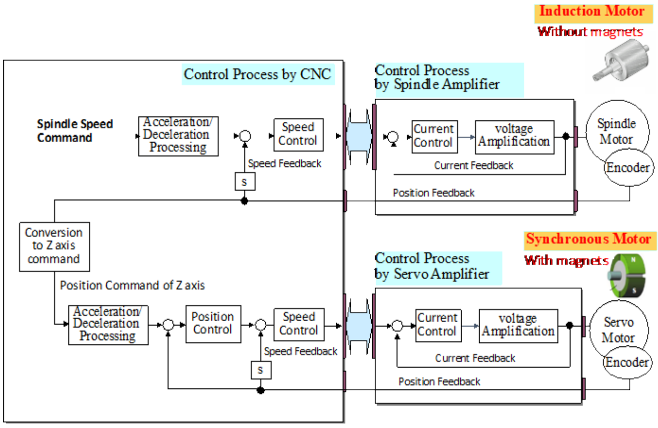

Figure 2: Synchronous control between Spindle and Servo（Thread Cutting）

is becoming more complicated, and machining that requires synchronizing the positions of the spindle motor and the servo motor, such as threading and synchronization taps, must be performed by one machine.

As described above, the response of the spindle motor is low which means that the response frequency is one digit lower than servo motors. Therefore, the method of centralized control as shown in Fig. 2 is common in general. The servo axis uses the position feedback of the spindle motor which is returned to the CNC side as a position command of the servo axis in such thread cutting.

As described above, the servo follows the movement of the spindle having low response, so that the synchronization error between the spindle and the servo can be reduced.

2.3 Issues with Spindle and Servo Synchronous control

In this section, the problems in the conventional synchronous control between spindle and servo are shown by using the example of thread cutting control and synchronous tap machining.

2.3.1 Thread Cutting Control

It is possible to improve the synchronization performance between the spindle and the servo axis by constructing a control method as shown in Fig. 2 and making the servo with relatively quick response follow the position of the spindle motor with low response. Since a spindle with low response is used as a reference, there is a problem that unless the response of the spindle increases, the tact time cannot be improved by increasing the speed of thread cutting.

In addition, the position feedback of the spindle motor is returned to the CNC side once, converted to the servo axis command, and then passed again to the servo amplifier via the network, which increases waste time. Therefore, there was a limit to suppresses synchronization errors eventually.

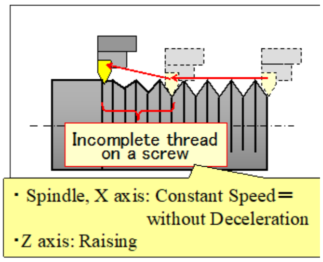

Figure 3: Incomplete thread on a screw

Further, since there is a difference in the acceleration/deceleration time between the spindle and the servo, machining cannot be started until the spindle and the servo reach a constant speed in order to ensure synchronization accuracy. Alternatively, there is also a problem that the speed of the main spindle and the X-axis cannot be reduced until the Z-axis finishes to raise as shown in Fig. 3.

2.3.2 Synchronous Tapping

Also, in synchronous tapping, similar to thread cutting, since it is necessary to control the servo axes in synchronization with the rotational position of the main spindle, centralized control on the CNC side as shown in Fig. 2 is adopted in some cases. On the other hand, compared to the thread cutting, since the drilling is performed after the preliminary hole is formed in advance, the cutting load is relatively small, and unlike the thread cutting which rotates the work itself, the inertia of the cutting tool (tapper) itself is small.

In some cases, as shown in Fig. 4, position commands to the spindle and the servo are given independently of each other, and in many cases, the configuration is aimed at higher-speed machining.

However, if there is a slight deviation in synchronism such as the influence of the bite of a facet, there are problems such as inducing damage to the tapper and making it impossible to process a screw conforming to the standard.

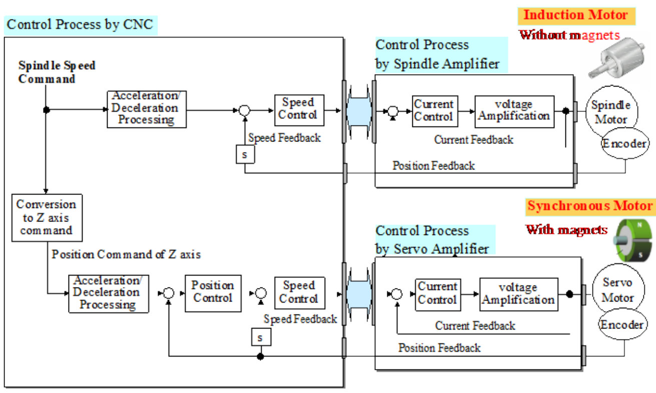

Figure 4: Synchronous control between Spindle and Servo（Synchronous Tapping）

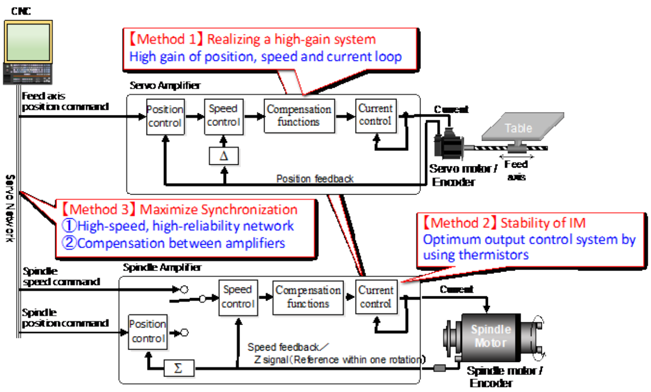

Figure 5: Basic configuration of High-response synchronous control between Spindle and Servo

3 PROPOSED SYSTEM (High-response synchronous control system between Spindle and Servo)

This section describes the proposed methods to realize the synchronous control between the spindle and servo with high response and accuracy. The system is largely composed of the following three methods, the basic structure of which is shown in Fig. 5.

As mentioned above, in the conventional system, there have been many cases in which the controller controls the position and speed loop and switches the control method according to the machining process, especially in the threading and synchronous tapping in which synchronous control between the spindle and servo is required. In this paper, in order to pursue the high-speed command follow-up characteristics and the robustness against disturbance, we propose the distributed control system in which the position and speed loop are executed by the servo and spindle amplifier.

Based on this decentralized control, we could achieve the high-precision synchronous control system between the spindle and the servo by using the following three methods.

[Method 1] High gain of position, speed and current loop

Section 3.1 describes the details of Method 1 for realizing a high-gain system in which each independent spindle and servo follow commands from the controller at high speed and with high response and are not easily affected by cutting disturbances.

[Method 2] Power optimization of IM spindle motor using thermistors

Induction motors (IM motor) used in the spindle are greatly affected by temperature characteristics. That is because it is generated by the motor's own coil and magnetic circuit, which is different from a synchronous motor in which the magnetic field for generating torque can be obtained from a stable permanent magnet.

Therefore, we have developed an optimum output control system using a thermistor, and its effect is described in Section 3.2.

[Method 3] High-speed, high-reliability network and compensation between amplifiers

Section 3.3 describes compensation between amplifiers to maximize synchronization performance by complementing the difference in responsiveness between the spindle and servo, and also describes high-speed, high-reliability networks to realize this.

3.1 PROPOSED METHOD 1 (High gain of position, speed and current loop)

The following items are necessary to achieve high gain performance in the main spindle and servo control loop.

(1) Faster position, speed, and current loop processing
(2) Reduce the dead time in the loops
(3) Higher accuracy and higher resolution of position, speed and current feedback data

In practice, we have implemented all of the initiatives in (1), (2), and (3) to realize the system. In this paper, we describe the initiatives in (1) that are particularly distinctive.

Figure 6 shows a block diagram of the newly developed the current control core unit. Conventionally, the processing of the position, speed, and current loop in the spindle and servo amplifier has been sequentially performed by software processing by a general-purpose CPU.

On the other hand, in order to greatly improve the performance, we have developed a dedicated calculation unit which is called the current control core unit that is the innermost among the control loops and requires the highest gain (high response).

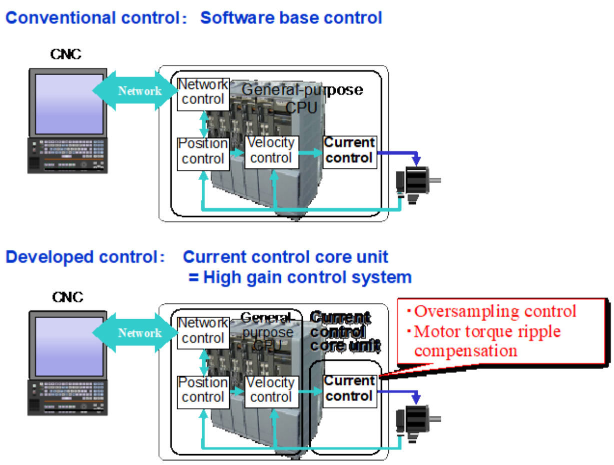

Figure 6: Current control core unit

Thus, oversampling function enables parallel running of position/speed loop processing and current loop processing, so that the PWM switching frequency can be stably increased, and high gain of the position/speed/current loop can be realized.

3.1.1 Oversampling Function

Figure 7 shows a timing chart of the oversampling function mounted on the current control core unit. As a comparison, the timing of the valley sampling which was performed by the conventional control is described. In the conventional control, the position control, speed control and other various processes are performed by one CPU, so that the current loop cannot be always operated. Therefore, the current feedback (current FB) data is AD converted only at the valley timing of the reference triangular wave, which is least affected by the PWM switching. On the other hand, by processing the current loop control in the current control core unit, the current loop can be constantly turned, and at the same time, the ΣΔ + IIR filter is incorporated in the current control core unit instead of the one-time conversion by the AD converter, so that the current can be detected with less ripple and with high accuracy.

Here, we adopted that the resolution of ΣΔ + IIR filter is corresponding with 12bits, the carrier frequency is 9kHz and 5 times oversampling.

3.1.2 Motor Torque Ripple Compensation

Figure 8 is a control block diagram of the current control core unit. As shown in the figure, the compensation of harmonic wave is incorporated in the dq-axis via UVW phase conversion on the current feedback side and the voltage command side. The torque generated by the motor is generated by the product of the linkage magnetic flux of the rotor and stator and the motor current. At this time, the torque ripple is generated by the interlinkage magnetic flux containing many harmonic components. For this reason, a

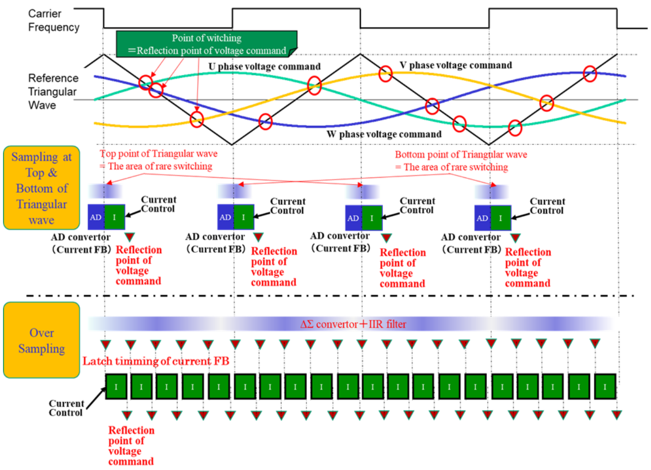

Figure 7: Oversampling for current loop

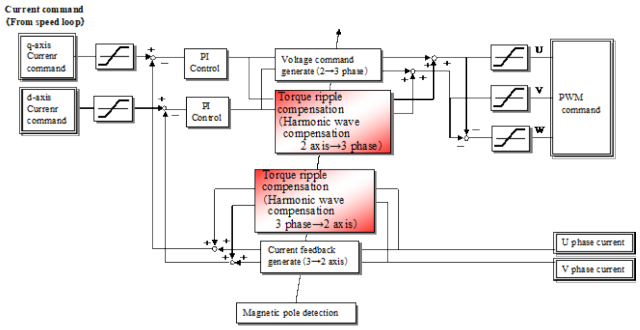

Figure 8: Torque ripple compensation in the current control core unit

function to correct this problem is also built in for the current control core unit.

3.2 PROPOSED METHOD 2 (Output optimization of IM main Spindle motor utilizing thermistor)

The torque τ of an induction motor (IM motor) generally used for a spindle motor is given by the following equation.

$$\tau = \frac{PM}{2L} i_q \psi_d$$

$$\psi_d = M i_d$$

τ : Torque of the induction motor
P: Number of poles
M: Mutual inductance between the stator and rotor
L: Inductance
ψ_d: interlinkage flux
i_q: q-axis current, i_d: d-axis current

Here, since the interlinkage magnetic flux is made of the product of the d-axis current flowing in the motor and the inductance instead of a permanent magnet like a servo motor (Synchronous motor), it is easy to be affected by temperature, and it is difficult to always obtain a stable output.

Therefore, as shown in Fig. 9, we developed the system that a thermistor is built into the coil of the spindle motor, and it enables the spindle amplifier to constantly monitor

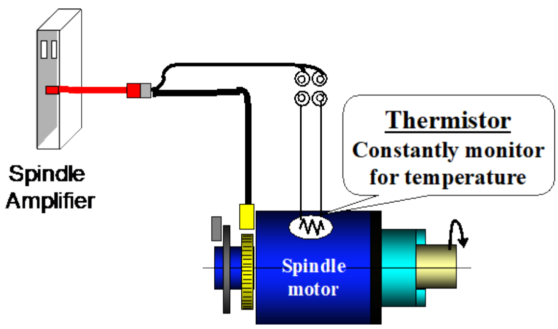

Figure 9: Constant monitor for temperature

the temperature. In this system, stable output characteristics are obtained regardless of temperature by controlling the d-axis current i_d according to temperature conditions.

3.3 PROPOSED METHOD 3 (High-speed, high-reliability network and compensation between amplifiers)

In order to maximize the advantage that the servo and spindle control gain increases, such as the tracking performance in high-speed cutting, it is necessary to improve the cycle of the command output from the CNC controller to the spindle and servo amplifiers. Besides, it is also important to increase the accuracy of command units.

Another advantage of using the distributed control method is that the dead time can be minimized because the network is not interposed in the control loop of the servo or spindle. On the other hand, there is a problem that compensation between the servo amplifiers or between the spindle and the servo cannot be performed.

In this section, we have developed a high-speed, high-reliability network and the compensation between amplifiers.

3.3.1 High-speed, High-reliability Network

We have developed a high-speed optical communication servo network that dramatically improves the network performance between the CNC-servo and the spindle.

The points of this network are as follows.

・Communication baud rate improvement:
5.6 MHz → 50 MHz (Approximately 10 times)
・Improvement of communication cycle:
1.7 msec → 0.2 msec (about eight times)
・Improvement of command resolution: 1 μm → 1 nm
・Protocol that enables data exchange between servos and spindle

3.3.2 Improvement of Synchronous Control between Spindle and Servo by the Compensation between Amplifiers

In section 3.1, we describe how to improve command followability and rigidity against external disturbances by realizing high gain control of each of the servo and spindle.

However, in the spindle control, there are cases where the command follow-up characteristics are inferior to the servo because an induction motor (IM motor) which is difficult to achieve high responsiveness due to the influence of an electrical time constant and high inertia is used and the acceleration/deceleration characteristics are not stable due to voltage saturation (torque saturation) caused by a power source environment or the like. It means that it is sometimes difficult to obtain high synchronization performance between the spindle and the servo axis.

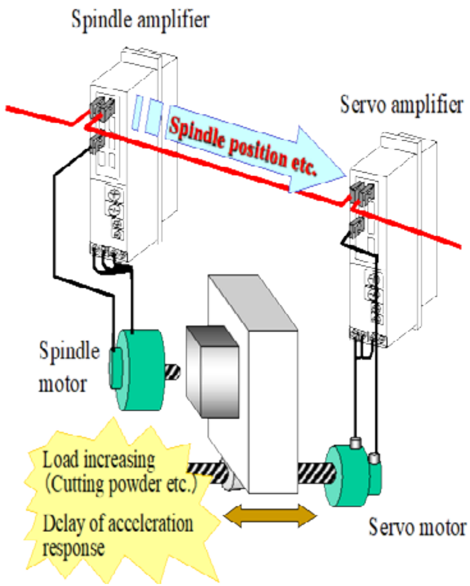

Figure 10: High-speed synchronous tapping function

Therefore, we have developed a high-speed synchronous tap function that utilizes the data communication protocol between amplifiers incorporated in a high-speed optical network and utilizes the amplifier compensation between the spindle and servo as shown in Fig. 10.

Figure 11 shows a block diagram of the high-speed synchronous tap function. A position command synchronized with the spindle and the servo is sent via a network. On the other hand, the spindle amplifier and the servo amplifier perform position loop control to control the motor to follow the command.

If it is possible to ideally follow the command without any cutting disturbance or the like, synchronization accuracy can be guaranteed, but in general, it is difficult to improve the speed frequency response of the spindle motor control more than that of the servo control shaft.

Therefore, in the proposed method, the position deviation and the speed feedback in the spindle amplifier are passed to the servo amplifier using the inter-amplifier data reception protocol provided in the high-speed optical network. On the servo amplifier side, unit conversion is performed using the spindle position sent by the CNC controller and the servo axis conversion coefficient K which means a ball screw pitch, and the spindle position deviation is added to the servo axis position command as a correction position, and the spindle speed feedback is added to the speed command as a correction value. The spindle speed feedback is further differentiated, converted by the inertia J of the servo and the torque constant of the motor, and then added to the current command as a correction current value. Since these correction position commands and current commands are data delayed by the network, they are values fed forward to make up for the dead time Td caused by the network.

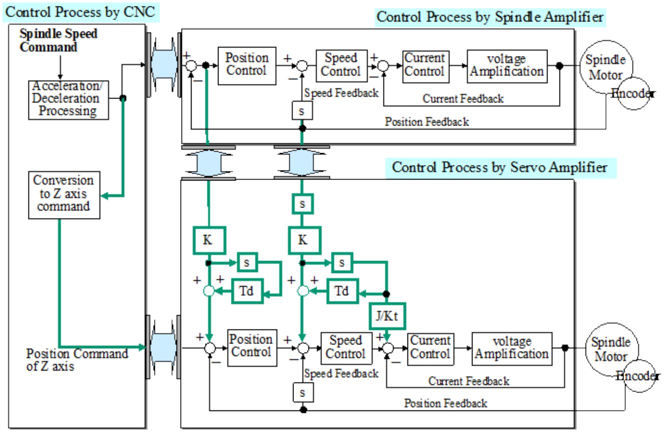

Figure 11: Diagram of High-speed synchronous tapping

As a result, it is possible to achieve high precision and high speed in the servo-to-spindle synchronous control such as the synchronous tapping compare with the conventional control, and this can greatly contribute to the improvement of productivity.

4 EVALUATION

First, the effects of method 1 and 2 which are measures to increase the response of each spindle and servo are shown in Section 4.1 and 4.2. Then, the synchronous control performance of the spindle and servo with high response including the effects of method 3 is shown based on the simulation results of thread cutting and the actual machining results of synchronous tapping in Section 4.3.

4.1 Verification of Effects of High gain system (Method 1)

First, the effect of increasing the control loop gain of the spindle and servo using the current control core unit equipped with an oversampling function and torque ripple compensation is shown.

Figure 12 shows the result of temperature rise of the motor and the result of frequency spectrum analysis of the motor current when the spindle motor is rotated at high speed of 12,000 r/min. The harmonic component superimposed on the current is drastically cut. As a result, the loss called iron loss generated in the motor is reduced. As a result, the temperature is reduced by 10%.

Figure 13 shows the result of roundness measurement in the X-Y plane of a servo-driven machine tool. Under the condition that the accuracy of the circle was 4.0 μm in the conventional control, the accuracy of the circle was improved 1.5 times to 2.5 μm by increasing the gain through the method implemented this time.

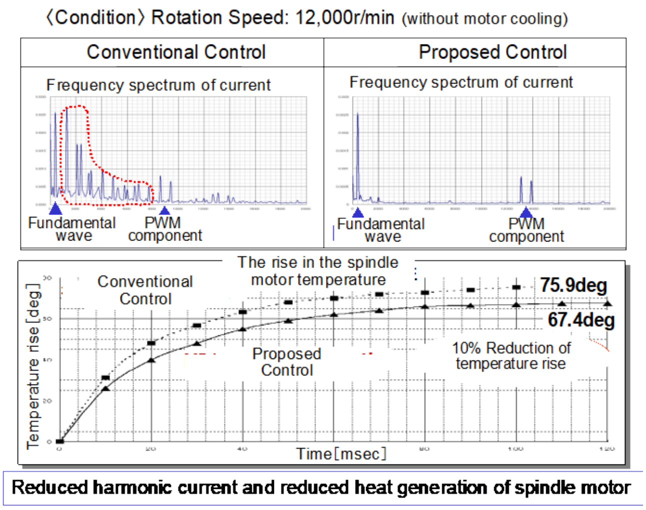

Figure 12: The effect of High-gain control (Spindle)

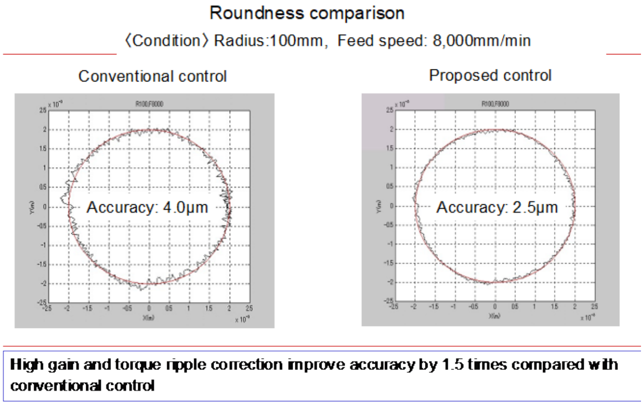

Figure 13: The effect of High-gain control (Servo)

4.2 Effect of Output Optimization Control of IM Spindle Motor (Method 2)

Figure 14 shows the effect of adopting a new control system that controls output characteristics by utilizing information from a thermistor mounted on the spindle motor. The plot on the right shows the acceleration /deceleration

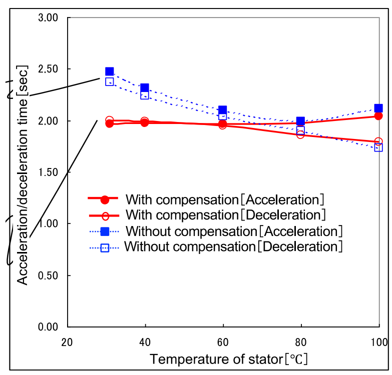

Figure 14: The effect of the Spindle temperature compensation based on thermistor

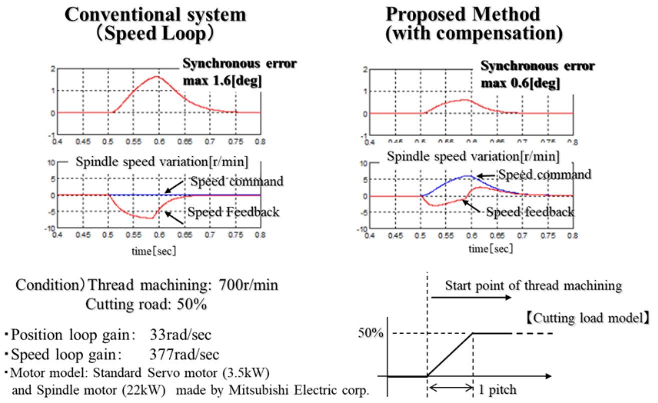

Figure 15: Effect in case of thread machining

time change when the temperature changes after adjusting the parameter under the condition of 80 ℃. The blue dotted line plots the fluctuation during the conventional control without compensation and the red solid line plots the fluctuation when the proposed compensation is performed. The figure shows that the fluctuation due to the temperature change is suppressed.

4.3 Verification of Synchronous control Performance between Spindle and Servo

For the performance improvement of synchronous control, subsection 4.3.1 describes the evaluation by simulation, and subsection 4.3.2 describes the evaluation by real machine.

4.3.1 Thread Machining Improvements: (Simulation Validation)

In this subsection, we simulated the thread machining improvements by using Matlab/Simulink before real machining (cutting) process. Because it is easy to assess the advantage of proposal method by simulation instead of real machining process.

Figure 15 shows the simulation results of threading by synchronous control of the spindle and servo. The simulation condition is follows.

[Simulator] Matlab/Simulink

[Control loop gain]

Position loop gain: 33rad/sec

Speed loop gain: 377rad/sec

[Motor model]

Standard servo motor (3.5kW) and spindle.

Motor (22kw) made by Mitsubishi Electric corp.

[Machining condition]

Speed: 700r/min, Cutting load: 50%

This time, the conventional system in which the servo follows the rotational position feedback of the spindle has been changed to a system in which the spindle and the servo

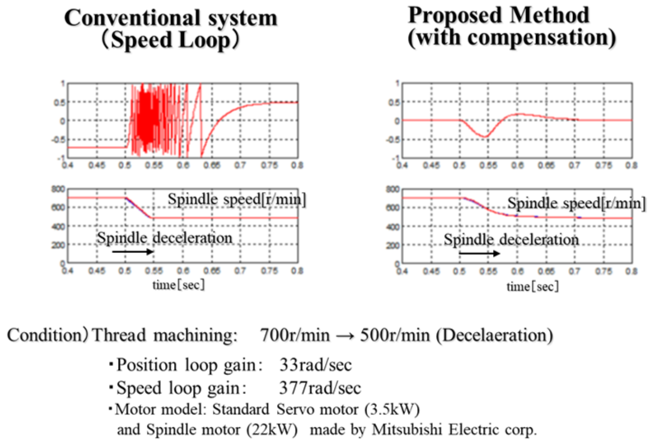

Figure 16: Synchronous accuracy in case of thread machining (Overriding speed conditions)

follow the position command. Synchronization accuracy is improved by performing compensation between the spindle and servo in conjunction with high gain control. The synchronous error became 0.6 degree from 1.6 degree which was the result of conventional method.

As a result, conventionally, in order to ensure synchronization accuracy, machining cannot be started until the spindle and servo reach a constant speed because synchronous error is too much to use, but in the proposed method, the synchronization accuracy can be improved within appropriate level (0.6 degree) even when the spindle speed is changed as shown in Fig. 16 (Overriding speed condition). Here, Fig. 16 case shows the condition when the machining speed was decreased from 700r/min to 500r/min.

As shown in Fig. 17, the spindle can be decelerated (Override) when the Z-axis tool is pulled up, and the length of the incomplete threaded portion can be shortened.

Figure 17 shows the calculation result the condition of which is follows.

[Machining model]

M56 screw (pitch: 5.5mm, depth of cut: 4mm)

[Spindle speed] 1,000r/min

[X axis speed] 5.5m/min, [Ball screw pitch] 10mm

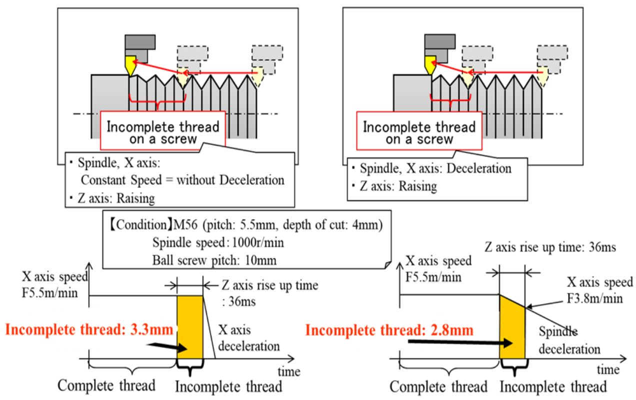

Figure 17: Reduction of incomplete thread

4.3.2 Verification of Synchronous Control Performance between Spindle and Servo (High-speed and high-precision synchronous tapping: Verification of real machine machining)

Figure 18 shows the results of synchronous tapping in an actual machining center. The figure on the left shows the results under the conventional operating conditions in which the compensation function between amplifiers is disabled. Here, since the spindle motor needs to be used in a region where torque saturation does not occur, the motor is operated with an acceleration/deceleration time constant of 560 msec including a margin. On the other hand, the middle figure shows a case in msec. At this time, the torque saturation region of the spindle motor is applied, so that the spindle motor cannot follow the command and the synchronization error with the servo axis increases from 30 pulses to 160 pulses.

On the other hand, the figure on the right shows the result when the compensation between amplifiers is enabled. As shown in the middle figure, the time constant is 350 msec, which indicates that the torque of the spindle motor is saturated. However, the figure shows that the synchronization error between the spindle motor and the servo axis is greatly improved to 8 pulses.

Figure 19 shows a plot of the synchronization error when the tapping of the M6 screw is cut by changing the time constant. In the normal control, the synchronization error increases as the acceleration/deceleration time constant of the spindle decreases, and especially when the time constant is set so as to be small as to enter the torque saturation region, the increase of the synchronization error becomes remarkable. In other words, in actual use, it is necessary to set the time constant with enough margin so that torque saturation does not occur in consideration of changes in the power supply environment. On the other hand, when the

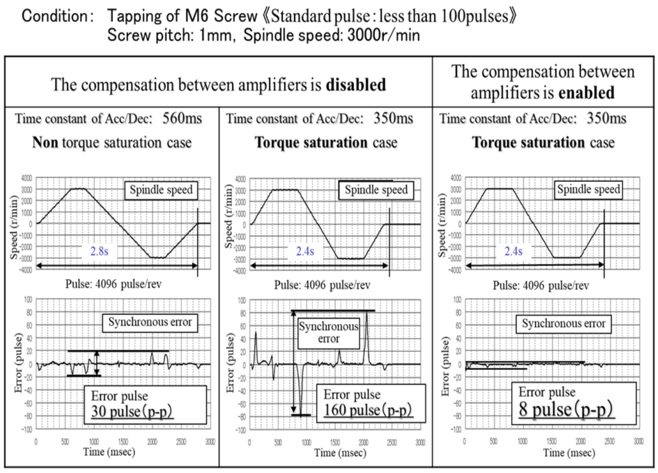

Figure 18: Verification result of synchronous tapping

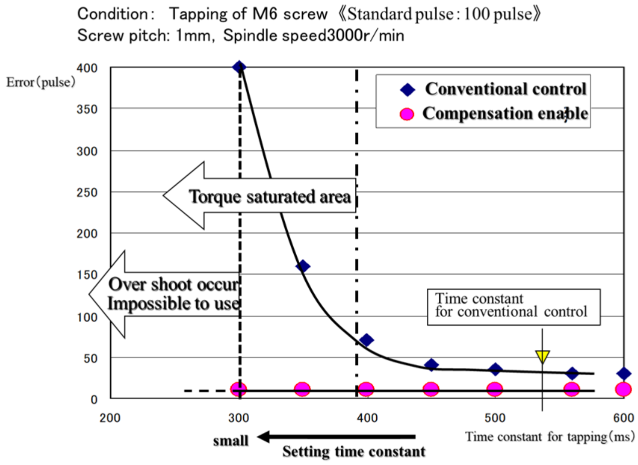

Figure 19: Time constant for tapping and synchronous error

compensation between amplifiers is enabled, the synchronization error is suppressed even if it is applied to the torque saturation region. It means that it is not necessary to set the time constant with enough margin as in the past, and it can greatly contribute to shortening the machining time.

4.3.3 Verification of Synchronous Control Performance between Spindle and Servo (Continuous machining of synchronous tapping: Verification of actual machine machining)

Figure 20 shows the results of continuous machining of synchronous tapping of M5 screws on an actual machining center. Even if the spindle speed and acceleration /deceleration time constant are shortened while securing the screw accuracy under the conventionally set machining conditions without the compensation between amplifiers, the accuracy can be secured by performing the compensation between amplifiers, resulting in productivity improvements of 30 to 36 units and 20% within the same time (75 seconds).

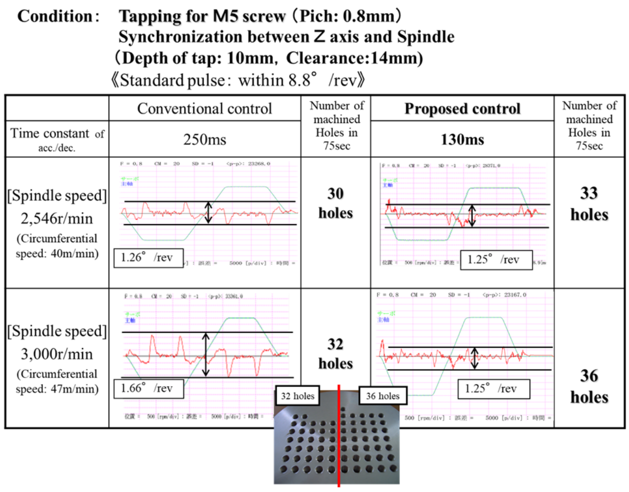

Figure 20: Result of continuous tapping by proposed control

5 CONCLUSION

In recent years, in order to improve productivity, the demand for combined machining corresponding to various machining operations by one machine tool has been increased. Under these circumstances, there has been an increase in the number of cases that the spindle and the servo are used for machining in synchronization. This paper introduces the methods implemented to realize high speed and high precision in the synchronous machining of the spindle and servo.

At first, we proposed a method for constructing a high-response, high-precision feedback loop that increases the responsiveness of the servo and the spindle itself and prevents the fluctuating in position and speed due to high-speed machining and cutting disturbances.

Specifically, in order to minimize the time delay and processing time in the servo and the spindle amplifier and to implement the function to improve the motor control performance in the specialized methods, a multi-core design was proposed, and the feasibility of high-speed and high-precision control of the spindle and the servo was verified by showing below. In the case of the spindle motor control, the effect of reducing heat generation of the spindle motor for suppressing deterioration in accuracy due to thermal expansion of the machine is shown. In the case of the servo control, the effect of improving the accuracy of the feed shaft is shown.

Next, we proposed a control method that improves the characteristics of the IM motor, whose characteristics tend to change in the temperature environment, and stably achieves the performance of the spindle motor, and verified its effectiveness for the fluctuation suppression of acceleration and deceleration time in a real machine.

Finally, we proposed the method to realize compensation using the high-speed and high-reliability network between amplifiers to compensate for the difference in response between the servo and the spindle that occurs even when the response of the servo and spindle is increased. As for the effect of this, we showed the simulation verification results in threading, and showed the verification results in actual synchronous tapping.

As a result, in comparison with the conventional control, for example, under the conditions of the synchronous tap processing shown in this document, productivity improvement of 20% was achieved. Besides, it is able to make a robust system to power supply environment.

This also served as a guideline for making the most of the future evolution of semiconductor processes for spindle and servo control, and at the same time showed the importance of the network between the CNC controller and spindle and servo.

In the future, we plan to continue to optimize the architecture and compensation algorithms to maximize the synchronization performance of the spindle and servo, while also incorporating the evolution of semiconductors and network technologies timely.

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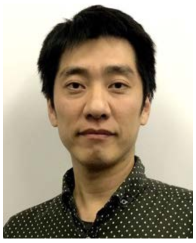

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