Industrial Paper

Optimum Method of Spindle control for Multi-tasking Machine

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Abstract - Recent machine tools control quite an increased number of axes for multiple cutting processes. Furthermore, more advanced functions have become necessary for machine tools: sharing data with the host system or using AI to improve machining accuracy, supporting collaboration with robots, and so forth. Therefore, one of the most critical issues for CNC controllers of machine tools is to enhance the CPU performance.

To address this issue, we have established distributed control of servo/spindle position/speed feedback loops in the power amplifier independently from the CNC controller.

In the past, only speed control was necessary for spindles. However, switching between position control and speed control has become necessary to allow for various machining modes for the increasing number of systems with advanced spindle functions. The time and complexity required for switching control loops are bottlenecks for improvement in productivity of machine tools.

In this research, we propose an approach to perform consecutive position control for spindles.

Keywords: Spindle motor control, Multi-tasking machine, Consecutive position control, Tracking delay compensation

1 INTRODUCTION

CNC equipment consist of the CNC controller, actuators, amplifiers, and detectors. To run the user's machining program, the CNC controller generates position/speed commands sent to the feed axes and spindles (tools) that constitute the machine coordinate system. Actuators such as servo motors and spindle motors are used to drive the feed axes and spindles. Servo amplifiers and spindle amplifiers are used to supply variable power to the actuators. Detectors such as encoders and linear scales are used to feed back the position/speed of operating parts of machines or motors.

The CNC controller, i.e. computerized numerical control controller, is the brain that controls the entire operation of machine tools. The CNC controller sequentially analyzes a G-code program that include description of the machining path, feed speed, and number of rotations of the tool, and generates commands of the travel distance per unit time for each feed axis. The CNC controller also generates speed commands for spindle motors according to the cutting conditions. The CNC controller is the open-loop control in which the control action is not dependent on feedback from the path or position of the actual machine, and the control to ensure correct positions is not performed.

Meanwhile, machine tools are required to have performance to minimize the reaction forces (disturbances) during heavy cutting and the effects of friction and stiffness in machines to achieve micrometer or nanometer level cutting accuracy in as short time as possible. High-speed, high-accuracy tracking of position/speed commands generated by the controller is critical for the actual machines and motors. Hence, high-response feedback loop control is one of the most essential factors in developing CNC equipment.

There are two ways to establish the feedback loop: one is to establish the loop of the system as a whole using the CNC controller, servo/spindle amplifiers, motors, and detectors, and the other is to establish the loop without the CNC controller. The design philosophy differs between the two models because the performance required for each component and the interface between components are different for each model.

While servo/spindle amplifiers are connected one-on-one to motors with power lines, serial communication through one network interface is used between the CNC controller and multiple amplifiers. When the feedback loop control is processed by the CNC controller, the communication cycle time becomes longer in the control loop with increasing difficulty in seeking high-level response performance due to the massive amount of exchanged data. For that reason, we developed CNC equipment in which servo amplifiers perform position/speed feedback loop control for servo motors that move the feed axes.

On the other hand, the spindle motor control has been more complex to achieve high productivity. The servo axes don’t have to change the control mode. It means that the servo axes are controlled by position loop consecutively. On the other hand, spindle motor control is required to use properly the speed loop control and position loop control. Although spindle amplifier is only needed to control the spindle motor speed and output power on the process of turning and milling, it is needed to control the angle position of cutting tool and to synchronize with other servo axes on the process of tapping C-axis mode for multi-tasking machine.

In the former systems, the mechanical angle of spindles had to be adjusted every time when the machining mode was changed. As it was necessary to recalculate a designated position, it was not possible to reduce the machining time.

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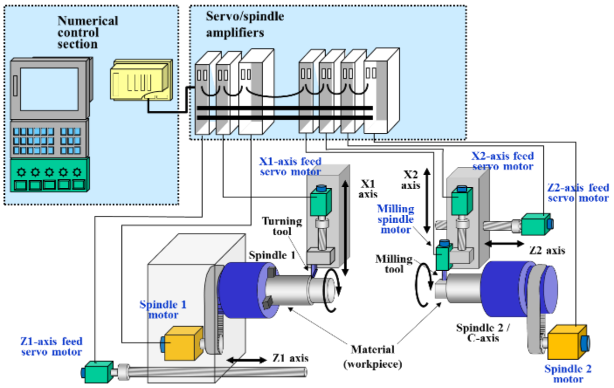

Figure 1: System configuration example of multi-tasking machine

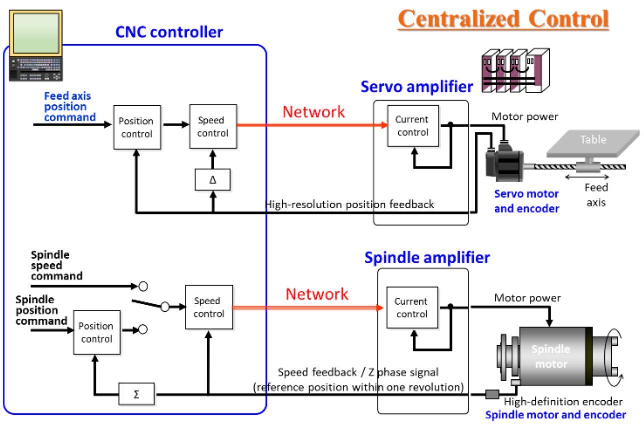

Figure 2: Centralized control of Servo/Spindle.

Besides, speed control operations were more susceptible to disturbances during cutting than position control operations.

Hence, we propose an approach to perform consecutive position control in spindle amplifiers for spindle motors regardless of the machining mode.

This approach reduces extra sequential control to change the machining mode, ensures robustness against disturbances, and enables establishment of the spindle control system for high-accuracy machining.

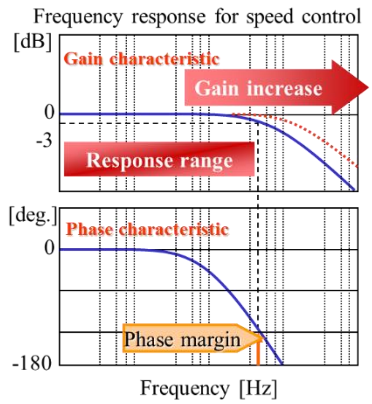

Figure 3: Response level of the speed control loop.

2 RELATED TECHNOLOGIES

2.1 Basic Configuration of CNC Equipment

Multi-tasking machines such as the one shown in Fig. 1 are increasing in recent years.

Each axes are driven by the servo motors 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 which is 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.

The path of the cutting tool affects accuracy of the workpiece directly. Therefore, it is significant for servo motors to ensure robust command tracking for position and feed speed control commands with minimal errors by suppressing load disturbances such as cutting reaction force or friction in machines. It is also important to keep the synchronous accuracy and the same response level for X, Y, and Z axes. Otherwise, the tool may follow the wrong path not intended by the CNC controller, resulting in unsatisfactory machining accuracy.

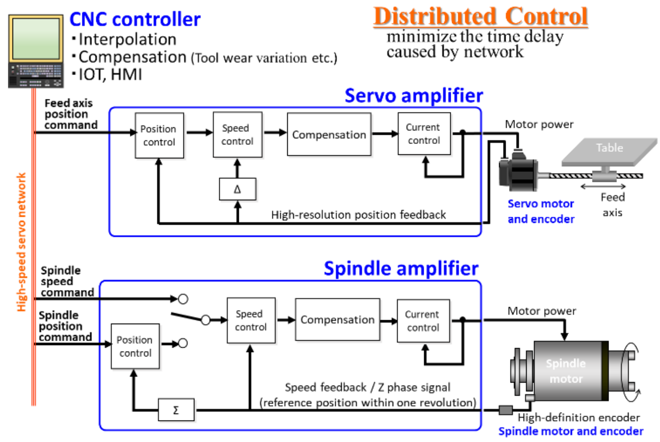

Figure 4: Distributed control of Servo/Spindle

2.2 Basic Servo/Spindle Control Architecture (Distributed Control)

In some cases, positions and speeds of servo/spindle motors are controlled by the CNC controller showed by Fig. 2. By using the CNC controller, it becomes easier to develop equipment with synchronous control of multiple axes or to perform compensation for multiple axes. However, this architecture has a drawback: the controller is connected to the amplifiers over network, and it is not possible to allow high-speed control loops due to the dead time.

Figure 3 shows the frequency response characteristics that affect disturbance suppression and command tracking for servo and spindle speed control. Generally speaking, it is necessary to increase the loop gain and broaden the response range to improve disturbance suppression and command tracking. However, the phase margin is reduced as the dead time increases, and the feedback loop becomes unstable and

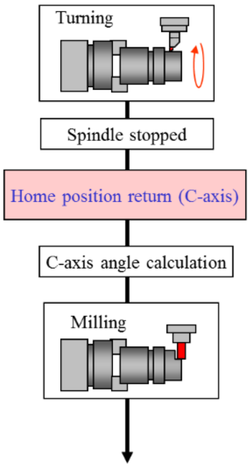

Figure 5: Switching from turning to milling (C-axis).

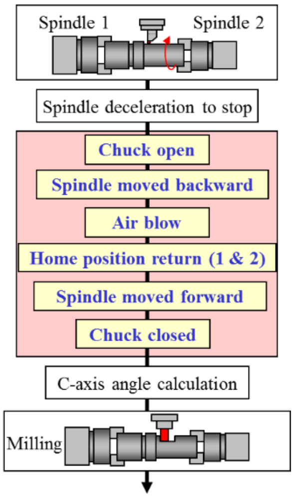

Figure 6: Switching from spindle-linked turning to C-axis-linked milling

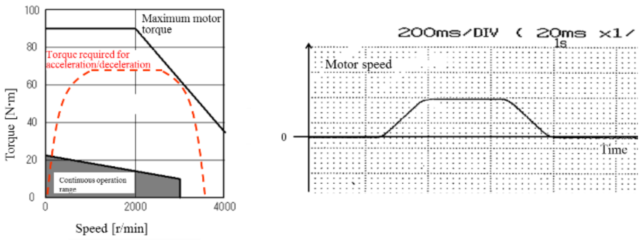

Figure 7: Normal acceleration/deceleration waveform of position loop control.

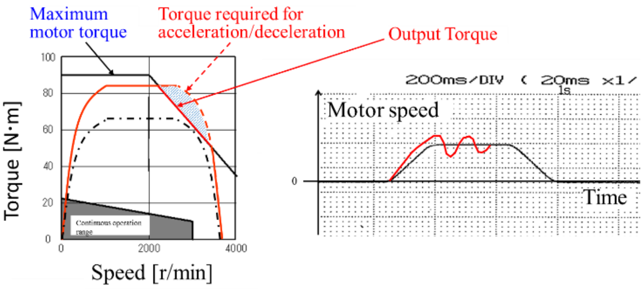

Figure 8: Abnormal acceleration/deceleration waveform of position loop control.

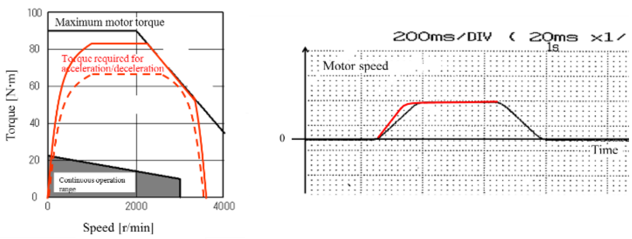

Figure 9: Acceleration/deceleration waveform of speed loop control.

causes oscillation. Furthermore, the load applied to the controller increases along with increase in the total number of control axes in recent machine tools.

In order to address the above-mentioned issues, we adopt the architecture shown in Fig. 4 for servo and spindle control loops. The position feedback and speed loops are implemented inside the amplifiers (distributed control) and the network communication that involves a substantial amount of dead time is established outside of the control loops.

2.3 Issues Identified with Spindle Control

Multi-tasking machines that perform multiple operations prevail in recent years. Position control and speed control for the spindle motors are switched in multi-tasking machines according to the machining program (refer to the spindle amplifier section in Fig. 4). In addition to operations such as turning, milling, or drilling by spindle rotation control, it is necessary for multi-tasking machines to perform operations such as C-axis control or synchronous tapping (C-axis control: synchronous position control with the servo axes).

2.3.1 Time required for switching the control methods

When the spindle requires only speed control in the machining mode such as turning, neither the CNC controller nor the spindle amplifier handles position data such as tool tip angles.

In this case, to change the control mode from turning to milling (C-axis control), it is necessary to stop the spindle once, perform home position return, and detect the tool tip angle as shown in Fig. 5.

Another example is shown in Fig. 6. To change the machining mode from turning one workpiece chucked by two spindles to milling (C-axis control), home position return is required for both spindles. The chuck of each spindle is opened to release the workpiece and home position return is performed one after another for two spindles. Then, the chuck is closed and the workpiece is held by the spindles again, the C-axis angle is calculated, and milling is started. It takes several to tens of seconds each time to switch between two modes. Therefore, repeating switching has significant impact on productivity.

Moreover, the switching process sequence control involves complex programming.

2.3.2 Consecutive position control in spindle amplifier

The following section describes the issues involved with consecutive position control in spindle amplifiers in the same way as in servo amplifiers.

(1) Acceleration and deceleration time

The tool attached to the spindle is frequently changed according to the machining conditions. The spindle motor must be decelerated and stopped once every time the tool is changed, and accelerated back to the maximum speed after the tool change. The number of spindle rotations per minute ranges from several thousands to tens of thousands and it takes several to tens of seconds each time to accelerate or decelerate the spindle. One of the requirements demanded for spindle motor control is to reduce the acceleration and deceleration time as much as possible.

Figure 7 is a diagram to show the maximum motor torque. The horizontal axis of the graph represents the motor speed. In general, the maximum torque generated by motors is reduced due to saturation of the induced voltage in the high-speed region even though the maximum current value of the amplifier is not changed.

Under these circumstances, when acceleration/deceleration is performed with the unchanged position loop, it is necessary to build a program with a time constant that would not allow the required torque to exceed the maximum motor torque as shown by the dashed line in Fig. 7.

If a program is built with a time constant that would require the torque exceeding the maximum motor torque as shown in Fig. 8, position control to follow the command is not achieved. Then, position errors are accumulated to cause overshooting, resulting in vibration or mechanical impact.

On the other hand, acceleration to the maximum speed or deceleration to a stop in a shortest possible time is desirable in the machining mode without position control as mentioned above. Therefore, the utmost motor torque must be applied for acceleration/deceleration.

As shown by the solid line in Fig. 9, in the case of speed loop control, the utmost motor torque can be applied for acceleration/deceleration without overshooting since position deviations are not accumulated even though a program is built with a time constant that would allow the torque require for acceleration/deceleration to exceed the maximum motor torque. However, it is not possible to control the cutting tool's angle position on the spindle since position control is not performed in this case. For that reason, position control and speed control are switched according to the machining mode for spindle control in preceding systems.

(2) Spindle encoder

Spindle motors require speeds exceeding 30,000 r/min (revolutions per minute). Besides, cutting fluid or other liquids may enter from the spindle end. For the reason of durability and speed, optical encoders for servo motors cannot be used for spindle motors. Therefore, magnetic detection type encoders are used in general.

In the preceding systems, it is difficult for magnetic encoders to keep tracking the spindle end angle accurately without deviation in the range over several tens of thousands revolutions per minutes. To switch to position control for C-axis control or the like, installation of an encoder for position control is required in addition to the encoder for speed detection.

However, we modified the spindle encoder which is able to use for both speed control and C-axis control without additional encoder.

We could achieve this new encoder by adopting mainly two attempt.

One is detection method. We adopted high accuracy cutting method of gear and also high resolution Magneto Resistive Sensor inside the encoder.

Another one is data transmission method. We had made the position data in amplifier by interpolating AD convertor data which was converted from analog output signal through the cable from encoder before. But it was limited by the analog output frequency and easily effected by noise. If we wanted to obtain high resolution data in the condition of high speed, analog frequency was far beyond the frequency of AD convertor performance. So we developed the serial communication interface which is able to send the high resolution data without any effect of noise.

By using these technologies, we could create the spindle end position data accurately without deviation even if the number of revolutions exceeds several tens of thousands per minute. The next section describes the control method to achieve consecutive position control with this spindle encoder.

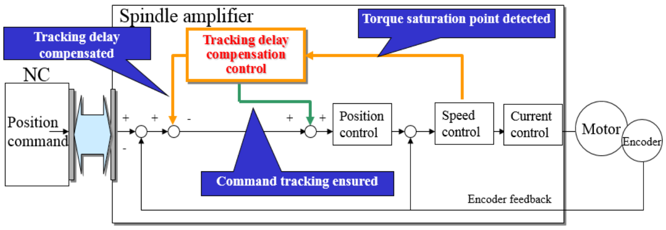

Figure 10: Tracking delay compensation control for consecutive position control.

3 PROPOSED METHOD

3.1 Outline of Tracking Delay Compensation Control

As mentioned above, a major issue for consecutive position control is overshooting. Overshooting occurs when position control to follow the command is not achieved, resulting in position deviation, during acceleration/deceleration with the utmost motor torque. Thus, we propose the use of spindle amplifier with the tracking delay compensation control as shown in Fig. 10.

Thus, consecutive position control can be performed in the spindle amplifier regardless of the machining mode. Consequently, the machining mode switching time can be reduced and disturbances during cutting can be suppressed further more.

3.2 Tracking Delay Compensation Control

Figure 11 is the block diagram to show the details of the control in the spindle amplifier which performs the tracking delay compensation control we propose.

(1) CNC controller

A CNC controller 1 gives speed command signals as output to the spindle during ordinary turning, machining, or milling operations. For tracking delay compensation control, speed command signals are integrated to generate position commands. On the other hand, position command signals are out-

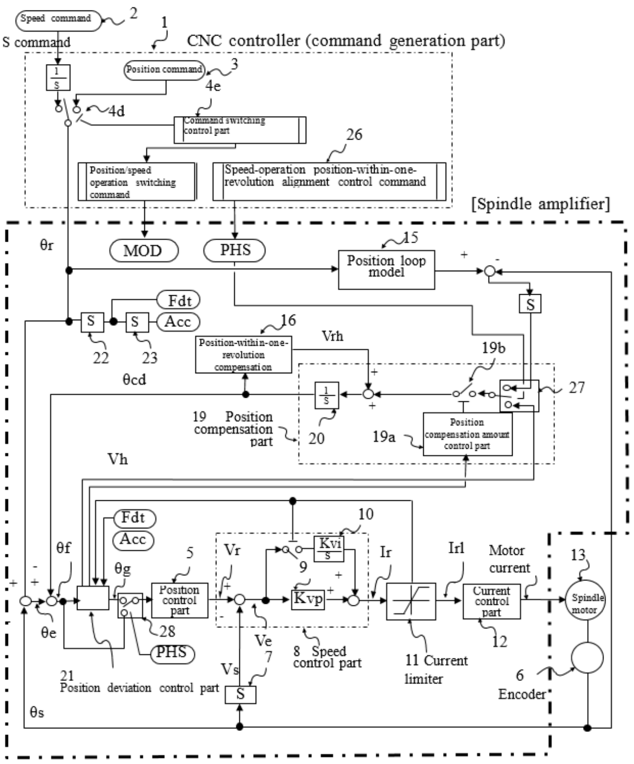

Figure 11: Tracking delay compensation.

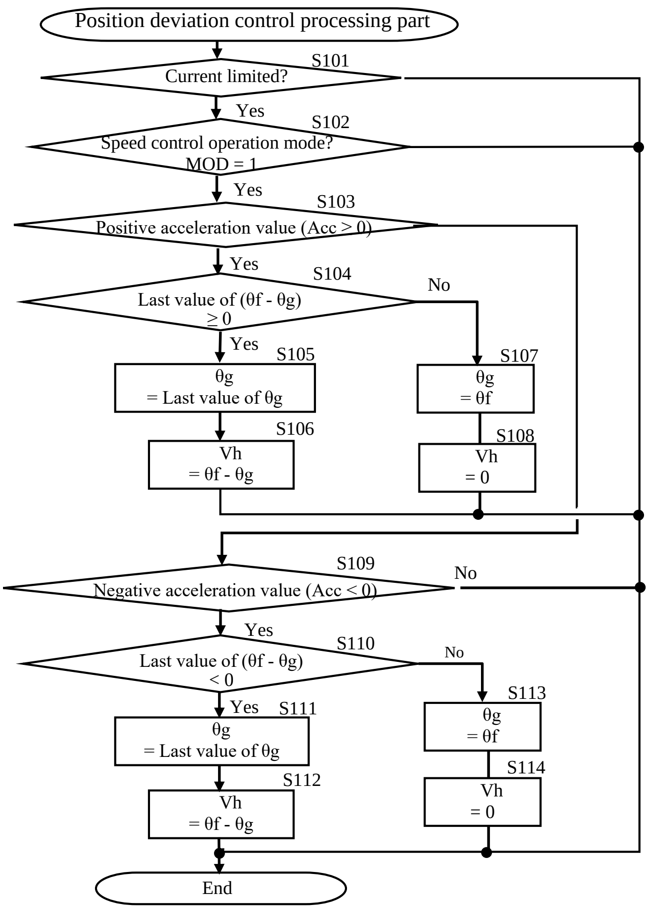

Figure 12: Operation flowchart in the position.

put according to the spindle-end rotation angle during synchronous tapping or C-axis control. In the CNC controller 1, the position of a switch 4d is changed according to the change in the machining mode, and a position command signal θr for the spindle amplifier is generated. Meanwhile, a command switching control part 4e outputs a position/speed operation switching command MOD, which contains data to show whether position control operation or speed control operation is performed at the time of switching.

(2) Position/Speed/Current control part

Position, speed and current control parts are used typical method. However, current limiter rolls as important functions.

The current control part 12 controls a current of a motor 13 based on a current limit value output by the current limiter 11.

While a current is limited by the current limiter 11, the current limiter 11 outputs a current limit command Il to the integral speed controller 10 to stop the integral action. The integral speed controller 10 stops the integral action to avoid unnecessary integral action of the speed deviation signal Ve while the current is limited, and to prevent overshooting from occurring for the speed command value after the current limit is released. The current limiter 11 outputs the current limit command Il also to the position deviation control part 21.

(3) Position deviation control part

A position deviation signal θe represents the difference between the position command signal θr output by the CNC controller and a position signal θs generated by a motor-end or spindle-end encoder. In typical position loop control, θe is input to position control part directly. However, this proposed method uses position deviation control part 21.

This position deviation control part 21 uses below input signals.

- θf: Deviation input signal created by θe and θcd which is generated by command compensation part 19.
- θr: Which is converted to a command speed signal Fdt by a differentiator 22.
- Acc: Command acceleration signal.
- MOD: Position/speed operation switching command.
- Fdt: Command speed signal.

After the predetermined operation is completed, the position deviation control part 21 outputs a deviation limiting output value θg to a position control part 5.

Figure 12 shows the flowchart of the operation carried out by the position deviation control part 21. In the position deviation control part 21, while the current limit command Il is given (S101) and the operation mode is speed control during which the position/speed operation switching command (MOD) does not require absolute position tracking (S102), when the command acceleration signal Acc has a positive value (Acc ≥ 0) (S103) and the deviation input signal θf increases in the positive direction (S104), it is assumed that the position deviation control section output value θg equals to the last value of θg (S105), and that the input/output deviation signal Vh has a (θf - θg) value (S106). Meanwhile, in order to send a command to the position compensation amount control part 19a in the position compensation part 19 to turn on the switch 19b (Fig. 11), the input/output deviation signal Vh output from the position deviation control part 21 is accumulated by the compensation position deviation amount θcd. The compensation position deviation amount θcd is subtracted from the position deviation signal θe to generate the deviation input signal θf.

When the command acceleration signal Acc has a negative value (Acc < 0) (S109) and the deviation input signal θf increases in the negative direction (S110), it is assumed that the output value θg equals to the last value of θg (S111), and that the input/output deviation signal Vh has a (θf - θg) value (S112).

When the input/output deviation signal Vh output from the position deviation control part 21 has a (θf - θg) value, the position deviation amount control part 19a of the position compensation part 19 shown in Fig. 11 turns on the switch 19b. Then, the input/output deviation signal Vh of the position deviation control part 21 is accumulated by the integrator 20 to output the compensation position deviation amount θcd. The compensation position deviation amount θcd is subtracted from the position deviation signal θe. The input/output deviation signal Vh (base of θcd) represents the difference between θcd and the signal θe that represents the difference between the position command signal θr and the motor 13 position signal θs. Therefore, when the current command value reaches the limit in the motor controller due to saturation of the motor output voltage during acceleration/deceleration of the motor, insufficient torque for the commanded acceleration, or other reason, it is possible to prevent the gap between the speed command calculation signal Vr (output from the position control part 5) and the actual motor speed Vs from increasing even if the position command signal θr value (converted from the speed command signal) is too large while the speed command 2 is selected with the switch 4d. Consequently, it is possible to reduce the delay in returning to position control when the current limit is removed.

(4) Position compensation part

A position-within-one-revolution compensation control part 16 is present on the output side of the position compensation part 19. The position-within-one-revolution compensation control part 16 normalizes the compensation position deviation amount θcd output by the position compensation part 19, and calculates a position-within-one-motor-revolution deviation signal Vrh (the data for two or more revolutions are discarded and the motor deviation amount within one revolution (difference between the position command and the actual motor position) is calculated). When it is confirmed that the current command is within the current limit after the current limit is removed, a position-within-one-revolution compensation amount Vrh is calculated so that the position within one motor revolution deviation becomes zero. Vrh is added to the integrator 20 in the position compensation part 19.

Figure 13 (b) shows the acceleration/deceleration slope profiles of the position-within-one-revolution deviation signal Vrh. The horizontal axis represents the speed, the vertical axis the slope (acceleration), the solid line the case 1 profile, the chain line the case 2 profile, and the dash-dotted line the motor torque characteristics.

As shown in Fig. 13 (a), the maximum speed in the Vrh compensation pattern is determined at a certain ratio γ (e.g. 10%) of the speed feedback value at the start point of actual compensation. The slope profile (acceleration) to the maximum speed in the Vrh compensation pattern is determined according to the motor output torque characteristics as shown by the dash-dotted line in Fig. 13 (b). The slope profile line may be straight as shown by the solid line (case 1) in Fig. 13 (b) by leaving a margin for the motor output torque characteristics if the controller's processing time and the memory capacity allow. Otherwise, the profile may be set in stages as shown by the chain line (case 2). Thus, the compensation is performed in a stable and fast way for the position within one revolution after the current limit is removed.

(5) In case of speed control mode

In the CNC controller 1 in Fig. 11, a command PHS, which shows that compensation is not required for the position within one motor revolution, is input to the motor controller from a position-within-one-revolution alignment control part 26 in speed operation mode that does not require absolute position tracking. The command PHS is transmitted to a switch 27 in the position compensation part 19 and a switch 28 between the position deviation control part 21 and the position control part 5. The switch 27 usually connects to the input/output deviation signal Vh input from the position deviation control part 21. However, when the command PHS is input, the switch 27 is switched to connect to the opposite side of the Vh signal. On the opposite side, the switch connects to the differential value input of the deviation of the actual motor 13 position measured by the encoder 6 from the ideal motor 13 position calculated from an equivalent control system model that has the characteristics of the controlled object by a position loop model 15 based on the position command signal θr. Ideally, motor 13 position is controlled to follow the characteristic of position control part 5. So position loop model 15 is designed based on parameters of position control part 5.

When the position/speed operation switching command MOD instructs speed control operation mode, the ideal motor 13 position is calculated and the deviation of the actual motor 13 position measured by the encoder 6 from the ideal position is used for generation. When the command PHS is input, the switch 28 is also switched and the deviation input signal θf is directly input to the position control part 5 by a route passing through the position deviation control part 21.

Thus, when compensation is not required for the position within one motor revolution, acceleration/deceleration time can be minimized according to the motor output torque.

(6) The signal waveform in the proposed control

Figure 13 also shows waveforms of the operation signals when the proposed approach is taken. In the topmost graph, the horizontal axis represents the time, the vertical axis the speed, the chain line the speed command signal Fdt, the dash-dotted line the speed command calculation signal Vr, and the solid line the motor speed Vs. In the second graph from the top, the horizontal axis represents the time, the vertical axis the current, and the solid line the current command value. The

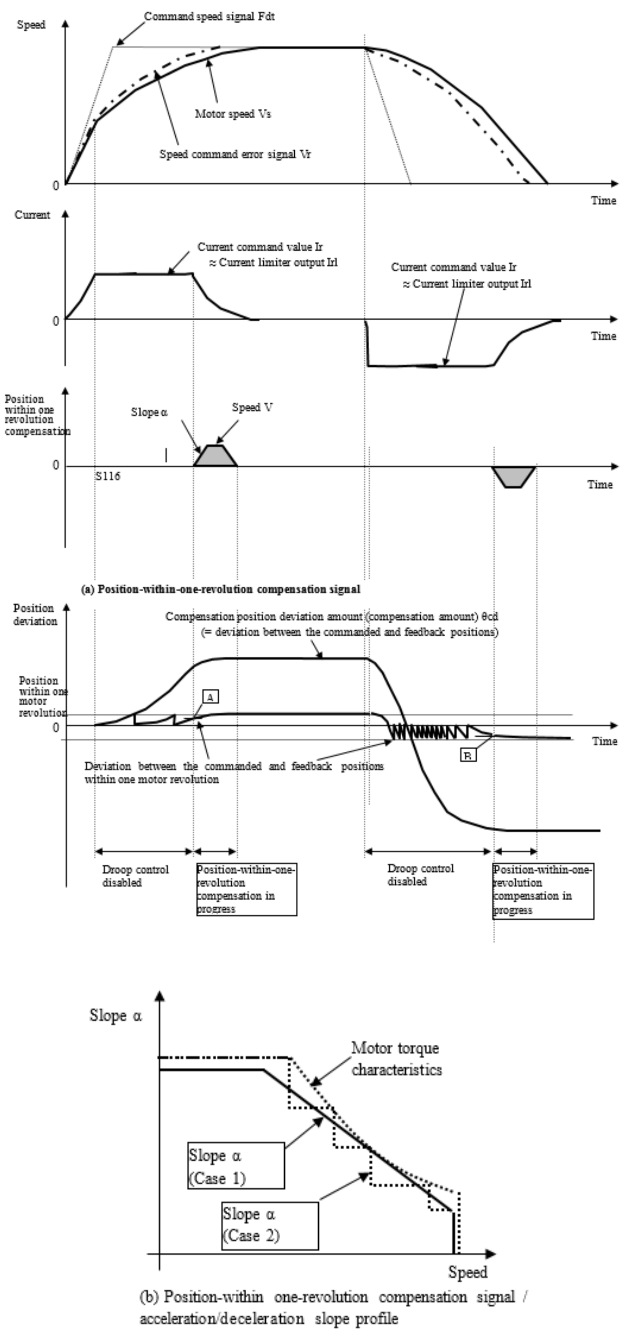

Figure 13: Tracking delay compensation control signal waveform.

third graph shows the position-within-one-revolution compensation signal Vrh. The horizontal axis represents the time, and the vertical axis the compensation amount. In the fourth graph, the horizontal axis represents the time, the vertical axis the position deviation, and the solid lines represent the compensation position deviation amount θcd and the deviation of the position within one motor revolution. In our approach, even if the motor cannot be fully accelerated due to the current limit and the motor speed Vs deviates significantly from a command speed signal Vrv output by the command generation part 1, the position deviation control part 21 limits the position deviation control part output value θg under certain conditions to prevent the speed deviation signal Ve, which represents the gap between the speed command calculation signal Vr output by the position control part 5 and the actual motor speed Vs, from increasing beyond the predetermined level. Thus, transition to position compensation is performed faster when the motor output torque characteristics are restored and the current limit is removed, preventing overshooting from occurring for speed or position control.

Furthermore, after the current limit is removed, the position-within-one-revolution compensation amount Vrh is added to the integrator 20 in the position compensation part 19 to enable consecutive control of the spindle position within one revolution to follow the command. The compensation position deviation amount θcd is reduced during acceleration and increased during deceleration to make the position within one revolution zero. Therefore, it takes less time to determine the compensation amount and perform the compensation for the position within one revolution.

4 VERIFICATION OF THE PROPOSED APPROACH BY SIMULATION

The following shows the result of verification by simulation of the effect of the proposed tracking delay compensation control.

Figure 14 shows the acceleration/deceleration waveform for an ordinary position loop without the tracking delay compensation control we propose. When a program is built with a time constant that would allow the torque to exceed the maximum motor torque, the intended acceleration/ deceleration torque becomes unachievable. Consequently, deviations from position commands are accumulated, and control loop works for recovery, resulting in overshooting.

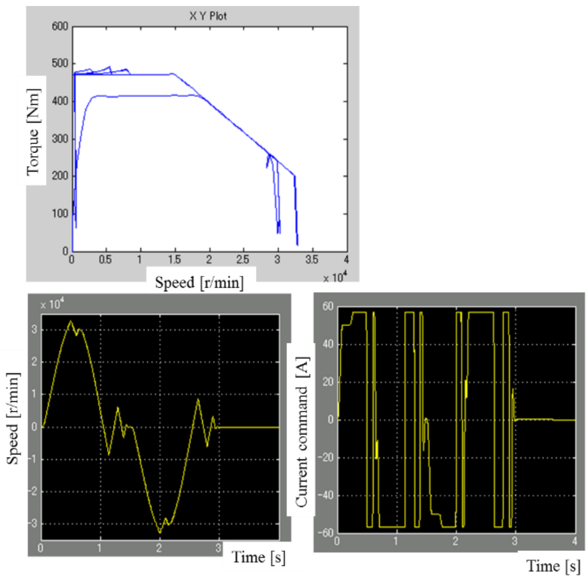

Figure 14: Acceleration/deceleration waveform without tracking delay compensation control.

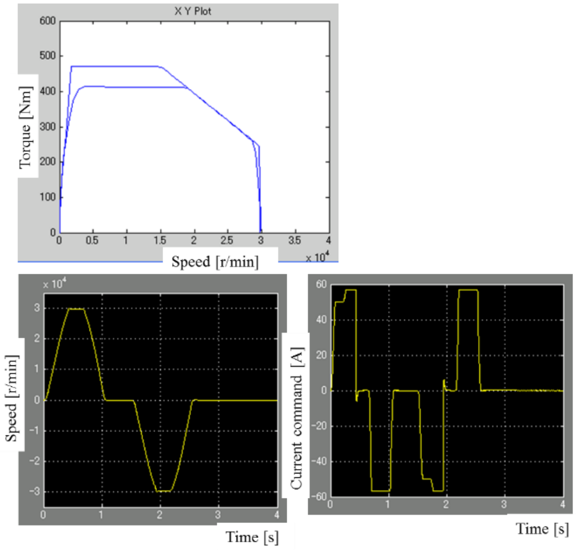

Figure 15: Acceleration/deceleration waveform with tracking delay compensation control enabled.

Moreover, when the torque reaches the maximum motor torque region, the current is limited in the amplifier and the control system enters nonlinear regions. Consequently, the current command behavior becomes unstable and causes reciprocation between upper and lower current limits. This phenomenon causes increase in mechanical impact and significant damage on the machine.

Figure 15 shows the acceleration/deceleration waveform with the tracking delay compensation control we propose. In order to apply the utmost motor torque, the program is built with an acceleration/deceleration time constant to exceed it, enabling acceleration/deceleration along the diagram of the maximum motor torque. Since the motor torque is restricted against the command, the current is limited at the maximum current in the amplifier. Overshooting does not occur and the control loop remains stable.

5 EVALUATION

5.1 Reduction in the Time Required for Control Mode Switching by Performing Consecutive Position Control

The following shows the result of verification of the effect of implementing the proposed approach with an actual spindle amplifier.

The system for verification is a multi-tasking machine with two main spindles for turning (spindle 1 and spindle 2) and a tool spindle for milling. Each main spindle has feed axes X1 and Z1, and X2 and Z2 respectively. Each main spindle can be used for machining of different workpieces, or a workpiece can be pre-cut by spindle 1, re-chucked by spindle 2 for machining without set-up change operation by an operator. Spindle 1 and spindle 2 can be also used to chuck one workpiece for heavy cutting.

[Reduction in the C-axis switching time]

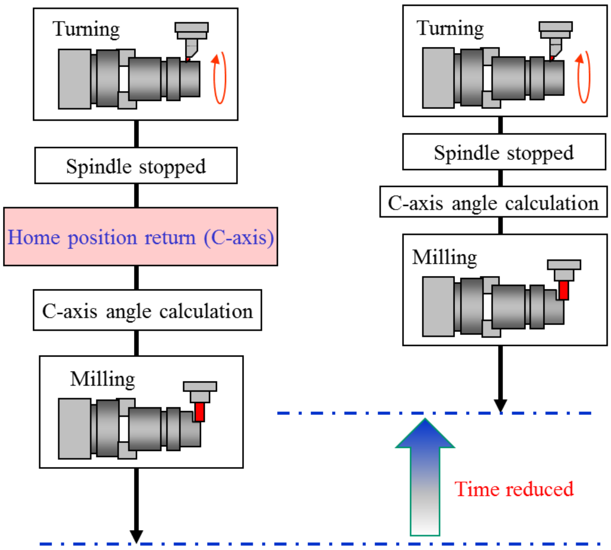

Figure 16: Time reduction for switching from turning to milling (C-axis control).

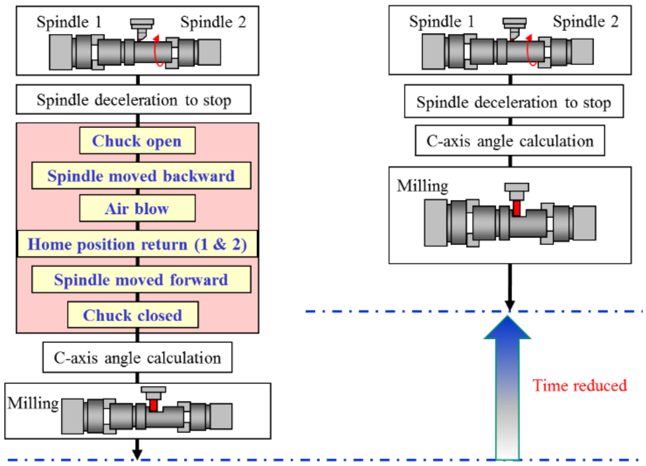

Figure 17: Time reduction for switching from spindle-linked turning to C-axis-linked milling (spindle synchronous control)

Since consecutive position control in the system we propose enables position control with main spindles, it is possible to eliminate processes such as stopping the operation once, home position return of the C-axis, and C-axis angle calculation required for transition from speed control for turning to position control for milling with the tool spindle as shown in Fig. 16.

[Reduction in the spindle synchronization time]

As shown in Fig. 17, basically the same processes as shown in Fig. 16 are followed when the main spindle 1 and main spindle 2 chuck a workpiece for heavy cutting (turning) and C-axis control is required in the next process in former systems. In this case, position control is not performed for the spindle 1 and spindle 2 during turning. To perform home position return, each spindle must release the workpiece. Therefore, the chuck of each spindle is opened and the workpiece is held by the other spindle during home position return. The

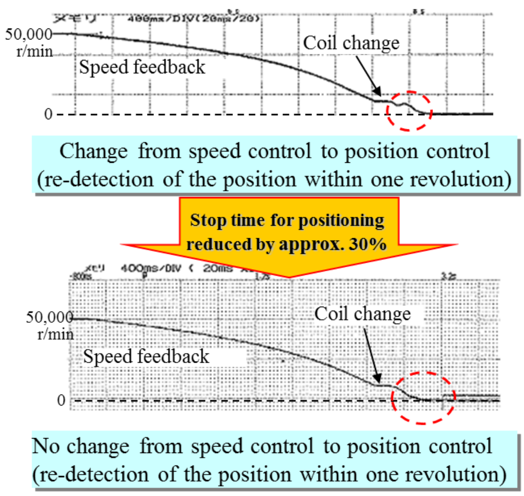

Figure 18: Result of spindle orientation time reduction.

Table 1: Effect of time reduction for operation of the multi-task machining program

New function	Description	Effect		
Spindle consecutive position control	Seamless transition of the operation pattern for switching to C-axis or spindle synchronous control		**Previous amplifier**	**New amplifier**
		Switching to C-axis control	**0.8 to 1 s**	**0 s**
		Switching to spindle synchronous control	**11.2 s**	**0 s**
	Reduction in the orientation positioning time	**(1) Example of orientation from 5000 r/min for the main spindle**		
			Previous amplifier	**New amplifier**
		Stop time for positioning	**0.32 s**	**0.23 s**

proposed approach reduces the no-cutting time required in existing systems.

[Stopping time reduction for spindle orientation]

The tool to be used must be changed according to the machining process. To change the tool automatically by a program using an Auto Tool Changer (ATC) without tool change operation by an operator, the spindle must be stopped at a predetermined angle.

In existing systems, the speed of revolutions is changed from a high speed to a certain low speed once for a while for switching to position control, the spindle (tool) angle is detected, a distance command is generated in the amplifier to stop the spindle at a predetermined angle, and then the spindle is stopped.

These processes can be eliminated when the proposed approach is used since consecutive position control is established to keep tracking the spindle (tool) angle in the amplifier, resulting in reduction in the spindle orientation time. Figure 18 shows the test result of the proposed approach.

Table 1 also shows reduction in time required for above-mentioned switching of the machining mode.

5.2 Improvement of Cutting Accuracy by Integrating Servo Control and Spindle Control

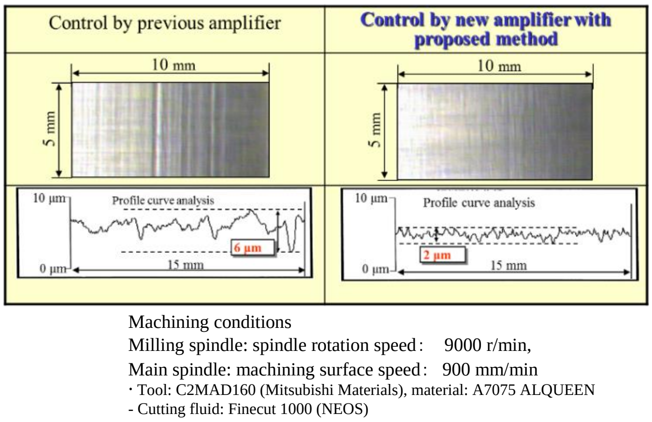

Figure 19: Improvement of cutting performance by integrating servo control and spindle control [reference]

Along with adoption of consecutive position control, we standardized the processor and algorithm between spindle control and servo control, and improved the accuracy of the spindle encoder.

As a result, the feedback control performance level is raised to the same level required for servo axis control that demands high-precision path control.

Figure 19 shows comparison of machining results for C-axis control between the spindle amplifier mainly used for speed control operation and the spindle amplifier with the control performance equivalent to servo control, which is adopted along with adoption of consecutive position control.

6 CONCLUSION

In the past, a focus is put on high-speed revolutions of the tool for spindle motors and spindle amplifiers in machine tools. Therefore, the critical issues are to generate the maximum torque to reduce the acceleration time to reach high speed revolutions, and to generate high power for heavy cutting.

However, in the recent progress in pursuing high productivity for cutting machining, multi-tasking machines for both turning and milling have become more and more dominant. As a consequence, position control such as C-axis control has become essential for spindles (motors and amplifiers) in increasing number of cases and how to reduce the switching time has become a controversial issue.

However, the other ways except for switching had not existed before our proposal. Because no other way but our proposal couldn't solve the overshooting issue of spindle's position loop during acceleration/deceleration with the utmost motor torque.

In this research, we proposed consecutive position control in spindle amplifiers in the same way as in servo amplifiers to address the issue, and verified its validity. This control method has been adopted in our products, which differentiates our products from previous spindle amplifiers and controllers. Furthermore, we are in the process of promoting standardization of amplifiers for motors driving machine tools to remove the barriers between different types of amplifiers.

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