Major Technologies Regarding Servo Systems for Machine Tools

Yoshi Ishizuka　Shintarou koichi　Yuuji Ide

1. Introduction

Machine tools known as "mother machines" have become more common throughout the world along with industry growth, particularly as IT equipment prospers, and the need for Small macnining centers has increased with as equipment is planned for higher performance and higher functionality. At the same time, the specifications demanded of servo systems for machine tools have also become more advanced.

This document introduces the major technologies for servo systems that contribute to high performance and high functionality for current mainstream Small macnining centers.

First, we will show an overview of the specifications demanded of servo systems for machine tools. Then, we will introduce the motor technology and control technology that contribute to improved machining performance and shortened cycle time. At the same time, we will show the servo technology that contributes to energy saving and improvements in suppressing machine vibrations and machining accuracy. Finally, we will introduce the considerations in the motor plans for maintainability and environment resistance characteristics for coolant atmosphere and vibrations.

2. Specifications Demanded from Servo Systems for Machine Tools

The following is an overview of the specifications demanded by servo systems for machine tools.

1) Together with the miniaturization of the equipment, make the servo amplifier and servo motor both smaller.
2) Even with the miniaturization of the equipment, retain top class performance for machining.
3) In order to reduce machining costs, reduce the cycle time.
4) Suppress vibrations and noise.
5) Improve machining accuracy.
6) Improve energy saving performance.
7) Improve environmental resistance characteristics.
8) Improve maintainability.

Fig. 1 shows an example of the servo motor and servo amplifier for machine tools from Sanyo Denki.

Fig. 1: Servo amplifier and servo motor

3. Improvement of Machining Performance for the Spindle Servo Motor

3.1 Low inertia, high speed spindle servo motor

The spindle servo motors for Small macnining centers demand the following performance.

- High speed and high torque characteristics in order to shorten machining time.
- Low inertia and high torque characteristics that achieve machining speed in a short period of time in order to shorten the non-machining time.
- Low loss and high efficiency for energy saving machining.
- Higher speed and higher torque for a wide range of machining targets.

Sanyo Denki has a lineup of inducible and synchronous type machine tool spindles, and in order to meet these demands, we have developed original low inertia, synchronous motors and contributed to the improvement of machine performance.

3.2 Improved machining performance through higher speed spindle servo motors

When the machining target is a small part similar to an HDD aluminum part, most of the processes are light-load surface processing and small hole drilling or tap processing, and high speed operations are demanded for the spindle servo motor characteristics.

There are high speed specification motors with a maximun rotation speed of 16,000 min^{-1}, 22,000 min^{-1}, or 30,000 min^{-1} for every type of machine, and by increasing the number of processes per unit hour, the machining performance was improved.

3.3 Improved of machining performance through higher torque spindle servo motors

When the machining target is ferrous, a shortened machining time is demanded through increasing the number of cuts during surface processing or through continuous processes for tapping or large hole drilling.

There is a high torque specification motor with a maximun rotation speed of 10,000 min^{-1} and a maximum torque that is twice that of general-purpose devices, which contributes to a great improvement in the machining performance. Fig. 2 shows a comparison of torque versus rotation speed characteristics.

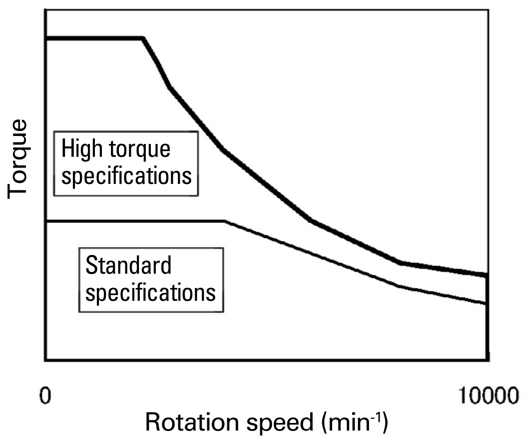


Fig. 2: Comparison of torque for spindle servo motors

4. Shortening the Cycle Time

4.1 Rapid acceleration and deceleration through low inertia, high torque characteristic spindle servo motor

By shortening the start-up time until the spindle reaches machining speed and quickly performing sudden reverse operations during tap processing, rapid acceleration and deceleration becomes an important ability for shortening cycle time.

At Sanyo Denki, we developed a low inertia, synchronous motor and achieved high torque in both the high speed operation range and the slow speed range, while also aiming to increase torque in the mid-speed range that is most often used during tap processing, and thus we realized a shortened time for spindle operations.

4.2 Realized a feed axis servo motor with emphasis on acceleration and deceleration characteristics

In the feed axis motor, the improvement of the fastest feed speed, shortening of the acceleration and deceleration time, and stabilizing of the machining feed are demanded.

The higher the rotor inertia, the more stable the machining feed, but the longer the acceleration and deceleration time, the longer the cycle time. Furthermore, designing a faster maximum rotation speed makes the torque constant for the motor smaller, and thus makes the maximum torque required for acceleration and deceleration smaller. At Sanyo Denki, we tuned the medium inertia motors that are suitable for acceleration and deceleration to retain a torque constant that ensures the necessary maximum torque while tuning the servo parameters that make high speed operations possible. In particular, by applying this to the Z-axis operations that send the blade, the cycle time for continuous drilling or tap processing was shortened.

4.3 Command tracking control

In the control systems for the speed and position of the feed axis, the sampling cycle was shortened, and by reducing wasted time, high gain controls were realized. Furthermore, we reworked the speed controller and made adjustments to shorten the settling time for positioning. In this way, the machining accuracy was improved through high gain controls and the cycle time was reduced by shortening the settling time for positioning.

4.4 High speed orientation

As the technology that stops positioning the spindle servo motor at the desired position, there is a built-in orientation function that runs speed controls until a fixed speed (orientation speed), switches the control mode from speed control to position control, and performing position controls based on the command stop position. Fig. 3 shows these operations. During high speed rotation, the motor is run with the speed controls, and when the orientation command is input, the speed is controlled with the orientation speed command. This way, the motor rotation decelerates to the maximum torque and rotates with the orientation speed. Once reaching the orientation speed, the controls switch to the position control system, the speed command is calculated based on the position command that indicates where the motor should be stopped within one motor rotation, position controls are performed, and the motor is stopped at the command position. When the motor stops, the orientation completion signal is output.

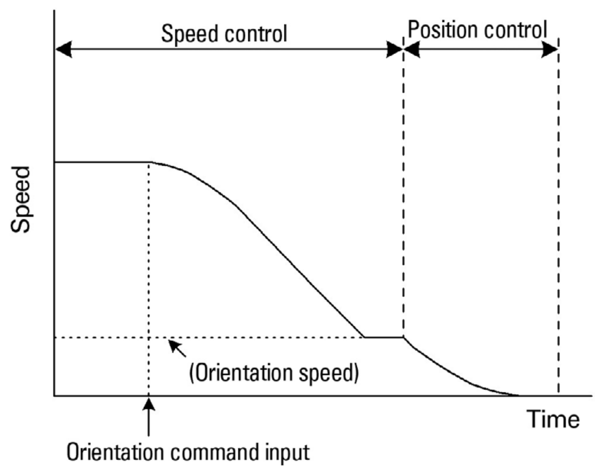


Fig. 3: Orientation operations

5. Suppression of Machine Resonance and Vibrations

5.1 Fine vibration suppression controls

In the feed axis, the position detection is detected using a digital value, so when the motor stops with the position command at 0, fluctuations of ± 1 pulse for the encoder may occur. If there is a large amount of mechanical friction, these fluctuations are not amplified and converge instead, and thus they do not cause large problems. However, when friction is small, these fluctuations are amplified and the fine vibrations in the mechanical system can cause noise. In the amplifier for machine tools, a function is built in to suppress these fine vibrations and the fine vibrations when the motor stops are also suppressed.

5.2 Machine resonance suppression controls

In the mechanical system, there is resonance typical of coupling or other such processes, so when it is amplified by the servo system, large noise can occur.

A notch filter is suitable for suppressing this type of resonance in the mechanical system. However, if the center frequency in the notch filter is close to the control range, a delay occurs in the control range response and the control capability can worsen. In the amplifier for machine tools, a notch filter that decreases phase lag or a notch filter that can adjust depth is built in so that the delay is eliminated and the notch filter can be inserted in such a way that it keeps from worsening the control capability as much as possible. These notch filters are equipped at multiple stages, so even if multiple cases of machine resonance occur, the high-pass resonance can be suppressed without dramatically lowering the cut-off frequency of the low-pass filter. In this way, the servo rigidity can be kept high, greatly improving the basic characteristics. Fig. 4 shows the torque command when suppressing the high-pass resonance with the notch filter. By activating the notch filter, high-pass resonance can be suppressed.

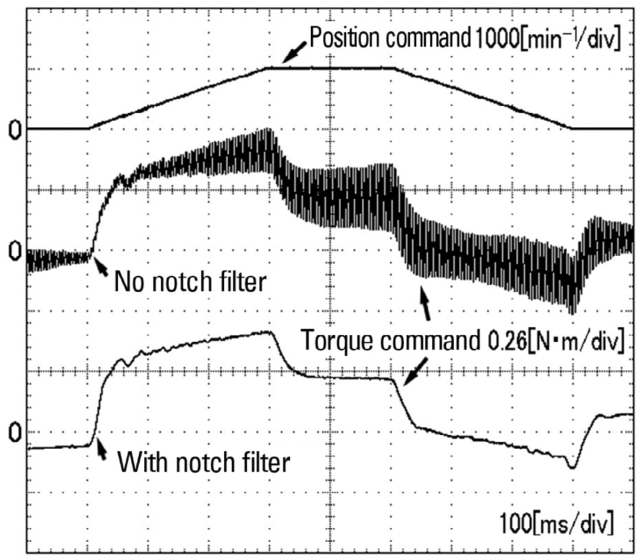


Fig. 4: High-pass resonance suppression characteristics

5.3 Machine damping controls

There are many types of vibrations in the machine tools, from vibrations due to tightening stiffness in the ball screws or other parts of the powertrain, to vibrations at the tip of the machine or in the machine basement. In the amplifier for machine tools, a feed-forward damping control function is built in to suppress the vibrations at the tip of the machine or in the machine basement. Feed-forward damping controls have a structure that provides feed-forward compensation to prevent machine vibrations from occurring. They suppress the vibrations in the machine basement or in the tip of the machine without the installation of special sensors. Fig. 5 shows the damping control operations at the edge of the load for a test stand with low rigidity. By activating the damping controls, the vibrations at the edge of the load can be suppressed.

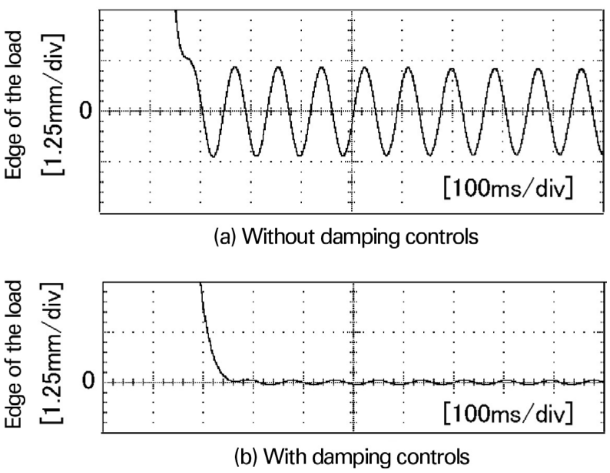


Fig. 5: Damping control characteristics

6. Higher Rigidity and Improved Machining Accuracy

6.1 Disturbance suppression controls

Servo systems in machine tools often have a structure with multiple axes, such as the X, Y, and Z axes. In these types of multiple-axis constructions, a disturbance observer is built in to improve the positioning accuracy by suppressing the effects of other axes and the effects of disturbance, such as with the cogging torque from the motor. In this way, the effects of disturbance are suppressed, the control rigidity is improved, and the positioning accuracy is improved.

6.2 Quadrant glitch compensation

When cutting an arc with machine tools composed of an XY table using the motor and a ball screw, the machine stops and a sticking motion occurs due to mechanical friction when switching quadrants. The sticking motion should be kept as small as possible, as it reduces machining accuracy. In the amplifier for machine tools, a function to suppress this type of quadrant projection is built in and it handles the problem by making the projection smaller when switching quadrants.

7. Improved cooperation with NC

In the amplifier for machine tools, many functions are built in and the number of parameters grows larger. Furthermore, for certain functions, the processing is divided between the NC and the amplifier, so the amplifier has been connected to the NC through high-speed serial communication in order to increase cooperation with the NC. The communication rate is 10MHz, and it uses Sanyo Denki's original protocols.

8. Energy Saving

8.1 High efficiency machining through synchronous spindle servo motor

A synchronous motor, which has higher efficiency compared to inducible motors, was designed especially for the spindle, and it was designed to save energy. Furthermore, the motor is low inertia, and the energy during acceleration or deceleration is also small, so the power consumption during one cycle is reduced to 30% compared to medium-sized machining centers.

8.2 High efficiency torque controls

In the amplifier for machine tools, the dq axis control calculations were made faster due to high frequency PWM and short current loop sampling period. The torque control system controls the dq axis current and outputs the best torque. In the torque control system, measures were added to reduce the d axis current when the torque is small based on the torque command. In this way, the motor current during no-load operations is reduced and the power loss is eliminated. High efficiency torque control was realized through these types of current control measures, high efficiency motors, and low loss main circuit semiconductors.

8.3 Power regeneration

In servo systems for machining tools, a multiple axis amplifier system is used to save energy and a common converter system is used to supply power from the spindle amplifier converter to the feed axis. In the common converter system, when power is supplied from the regenerating axis to the powered axis, the power supplied from the power source can be kept small. Furthermore, the main circuit electrolytic capacitor can be shared, thus improving the life of the electrolytic capacitor. In addition, in systems with an amplifier capacity of 300A, there is a built-in power regeneration function. A 120 degree excitation method is used as the power regeneration method for a structure that restores power to the power source every 120 degrees in the power phase. In this way, the regeneration power resulting from high acceleration and deceleration of the spindle can be restored to the power source. The power that was previously consumed through regeneration resistors is now restored to the power source, resulting in a design with great energy saving.

9. Improved Environment Resistance Characteristics

9.1 Operation during coolant atmosphere

The pursuit of machining performance does not just affect servo performance, but also the oil resistance of the motor. A secondary effect of the coolant (cutting oil) sought for machining finish is an increase in aggression towards plastics, and therefore the sealant material and cable sheaths (covers) tend to degrade more easily. Motor and encoder errors occur as a result of degradation of the plastics, leading to stoppage of the device or line stoppage. Sanyo Denki selected high oil resistance parts for the motors and performed endurance tests, and motors were designed with high oil resistance. However, there were limits to the oil resistance of the motors, and based on the evaluation results, information about highly aggressive cutting oils was shared with device manufacturers so that this information could also be provided to the end users.

In order to improve the oil resistance, coils made of molded resin were also used on cooling fans for spindle servo motors.

9.2 Encoder with superior vibration-proof characteristics

The spindle servo motor for the coolant through spindle uses magnetic encoders for superior environment resistance characteristics. These magnetic encoders use a reworked manufacturing method for the detection element and use measures to protect the substrate in order to improve the resistance to the coolant.

Furthermore, in order to realize miniaturization despite also having machining performance equal to superior classes, measures must be taken on the spindle servo motor to counter vibrations during heavy cutting.

With the coolant through spindle, the heavy cutting vibrations are passed on to the spindle servo motor and errors such as skipped pulse can occur due to exceeding the vibration-proof performance on the encoder. As a measure against this problem, the encoder installation was strengthened and an encoder with improved vibration-proof specifications was used. Through these measures, sufficient vibration-proof characteristics are ensured even against the vibrations of heavy cutting, and errors were prevented.

9.3 Design and use of motor bearing peripheral parts

The rotation speed of the spindle has been improved through developments in machinery, but in the high speed spindle servo motor, consideration for the design of the bearing is required. Attention must be paid to concerns including the bearing material quality, the selection of the grease, and measures against creep and fretting that may occur due to vibrations during machining. To handle these concerns, endurance tests were repeatedly performed under the conditions assumed for the operation of real machinery, and revisions were continuously performed daily in order to meet the mechanical performance.

10. Improved maintainability

Spindle servo motors use a structure that enables cleaning and exchange of cooling fans.

For a spindle servo motor operating in a machining room, chips and residual coolant build up and the cooling performance deteriorates. In particular, these can build up in cooling fans and block exhausted air, leading to motor overheating. In order to prevent these problems from occurring and to make it easier to exchange the consumable cooling fans, innovations were made to the peripherals for a structure where the fan can be cleaned or exchanged without removing the motor from the machinery.

11. Conclusion

This document introduced the following main technologies as the servo technologies supporting machine tools, particularly high performance and high functionality Small macnining centers.

(1) Low inertia, high speed spindle servo motor and feed axis motors

Sanyo Denki's "low inertia, high speed spindle servo motors" are motors that use the best characteristics for machining targets, and feed axis motors are motors that use high speed and high torque characteristics. These motors can contribute to improved productivity of machines (through improved machining performance and shortened cycle times).

(2) Damping and high accuracy positioning control technology

Sanyo Denki's servo amplifiers for machine tools have functions that suppress fine vibrations when the motor stops, mechanical resonance, and vibrations at the tip of the machine or in the machine basement. Furthermore, they have high accuracy positioning functions, including disturbance suppression controls and quadrant glitch compensation. These technologies can contribute to suppression of vibration noise from the machinery and high accuracy machining.

(3) Energy saving technology

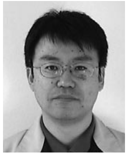
Sanyo Denki's servo motors are low-loss motors designed especially for machine tools. Furthermore, servo amplifiers have functions for high efficiency torque controls along with a power regeneration function. These technologies can greatly contribute to energy saving in machinery.

(4) Environment resistance characteristics and maintainability

Sanyo Denki's servo motors are designed with consideration for coolant (cutting oil) from machine tools and mechanical vibrations from machining. Furthermore, the structure is designed with consideration for maintainability and issues such as exchange of the cooling fans. These technologies can contribute to improved reliability and maintainability of the machines.

The "servo systems products for machine tools" introduced in this document were created based on the ideal design from the point of view of customers who use the products. We shall continue to provide products that the market and customers find to be truly valuable.

Yoshi Ishizuka
Joined Sanyo Denki in 1984.
Servo Systems Division, 1st Design Dept.
Worked on the development and design of encoders.



Shintarou Koichi
Joined Sanyo Denki in 1985.
Servo Systems Division, 1st Design Dept.
Worked on the development and design of servo motors.

Yuuji Ide
Joined Sanyo Denki in 1984.
Servo Systems Division, 2nd Design Dept.
Worked on the development and design of motor control devices.