High-Accuracy Positioning Technology for Stepper Motors

- Development of Load Position Correction Function Using an External Encoder -

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Stepper motors and servo motors are commonly used for processes that require high-accuracy positioning. Since stepper motors can be used in an open-loop control system without gain adjustment and can perform high-accuracy positioning without vibration during stop, stepper motors are widely used in various industrial applications such as semiconductor manufacturing equipment and medical analysis equipment. However, as semiconductor manufacturing processes have become increasingly miniaturized in recent years, the accuracy requirements for stepper motors have also increased.

Oriental Motor has developed the load position correction function, which uses the advantage of the high-accuracy position detection by an external encoder and the features of positioning under open-loop control. This report describes the high-accuracy positioning technology of stepper motors offered by the **CVD** Series fully closed-loop control type driver.

1. Introduction

Stepper motors can be used under open-loop positioning control and do not require gain adjustment even when the load fluctuation is large. As a result, they are easy to use even with a low-rigidity mechanism and can simplify system builds.

However, when stepper motors are combined with mechanisms such as gears or ball screws, it is difficult to meet the accuracy requirements due to lost motion caused by backlash, pitch error, temperature change, and expansion of the mechanism.

As semiconductor manufacturing processes have become more miniaturized in recent years[1], the accuracy requirements for stepper motors have also increased. In applications where position reliability is important, a method is used in which commands for position adjustment are issued sequentially by the host controller while the position of the stepper motor is monitored by an encoder. However, in this case, the whole system will become more complex and the simplicity of an open-loop system is lost.

Alternatively, a fully closed-loop control method[2] is adopted with a servo motor that directly feeds back the load position through an external encoder. In this case, the cost is higher than that of the stepper motor due to the use of the servo motor. In addition, this system has the disadvantage that the stability of the system is difficult to maintain under a load with low rigidity[3], and vibration occurs during stops due to the difficulty of gain adjustment.

This means that the system becomes complicated when a stepper motor is used for high-accuracy positioning with an existing method that uses an external encoder. On the other hand, when a servo motor is used, it is necessary to adjust the gain depending on a load condition in order to maintain the stability of the system, and it has been difficult to find a solution that eliminates both the problem of gain adjustment and high cost.

To solve this challenge, Oriental Motor has developed the load position correction function, which uses the advantage of the high-accuracy position detection by an external encoder and positioning under open-loop control.

This report describes the high-accuracy positioning technology of stepper motors based on the **CVD** Series fully closed-loop control type (see Figure 1, hereinafter referred to as CVD-F) that adopts this function. The CVD-F provides a reliable, high-accuracy positioning system that retains the ease of use and simplicity of stepper motors.

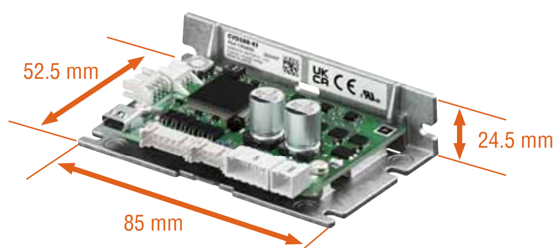


Figure 1. **CVD** Series Fully Closed-Loop Control Type Driver

2. Conventional Correction Method

Two types of control methods are generally used to drive the motor: open-loop control, which does not require a position sensor, and feedback control, which continuously corrects the position monitored by a position sensor in response to a command.

In feedback control, there are two types of control methods: a semi-closed-loop control method that uses feedback from a position sensor built into the motor, and a fully closed-loop control method that uses feedback from a position sensor installed externally(4). The characteristics of these control methods are described below.

2.1. Open-Loop Control of Stepper Motors

Stepper motors rotate under open-loop control, in which commands are sent from the host controller to the motor in one direction.

This method is based on the confidence that the motor has been operated as the instruction in which the driver supplies the current to the required motor phases according to the travel amount and speed by the command pulses of the host controller.

Figure 2 shows an example of a table positioning equipment using a feed mechanism driven by a stepper motor under open-loop control.

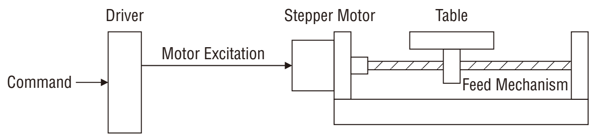


Figure 2. Open-Loop Control of Stepper Motors

The characteristics of open-loop control are as follows.

1) Positioning accuracy

This is a method of indirectly predicting the position of the controlled object, and the positioning accuracy depends on the precision of the mechanical system.

2) Synchronization

There is no need to detect the rotor position and operation can be performed with high synchronization to the position commands.

3) Position holding during a stop state

A stepper motor generates a holding force by applying a constant current. This holding force causes the motor to stop without vibration.

2.2. Feedback Control of Servo Motors

2.2.1. Semi-Closed-Loop Control Method

As shown in Figure 3, this is a method where the load position is detected by the rotary encoder installed on the servo motor or feed screw, and the motor is excited and controlled while the driver monitors and corrects the rotor position and speed feedback. Most servo motor systems today use this method.

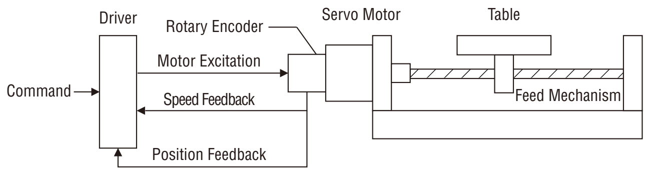


Figure 3. Semi-Closed-Loop Control Method of Servo Motors

The characteristics of the semi-closed-loop control method are as follows.

1) Positioning accuracy

This is a method of indirectly predicting the position of the controlled object, and the positioning accuracy depends on the precision of the mechanical system.

2) Synchronization

When a load fluctuation occurs, the position and speed change greatly and the synchronization is reduced. Therefore, the gain adjustment of the PID control is performed according to the conditions such as the magnitude of the load inertia and the rigidity of the mechanism.

3) Position holding during a stop state

If the position is displaced by only one pulse due to an external force in the absence of a command pulse, the position loop will operate to correct the error and current will be applied to the motor to generate torque against the external force and maintain the stop position. Vibration may increase during a stop due to the response of the gain adjustment, depending on the mechanism conditions.

2.2.2. Fully Closed-Loop Control Method

As shown in Figure 4, compared to the semi-closed-loop control method, the fully closed-loop control method can achieve higher accuracy because it is controlled by feedback of the load position (in this case, the table) using an external encoder such as a linear encoder.

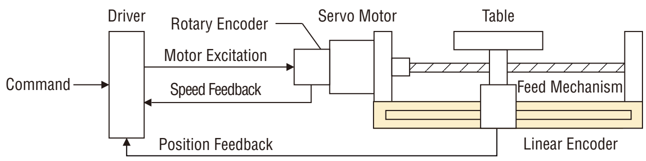


Figure 4. Fully Closed-Loop Control Method of Servo Motors

3. Developed Correction Method

This section describes the control method and features of the load position correction function used in the CVD-F. A stepper motor is used for the drive, as shown in Figure 5. The motor itself does not have a position sensor, but by using the fully closed-loop control method, which is corrected by feedback of the load position from a linear encoder, high-accuracy positioning can be achieved without relying on the precision of the mechanical system.

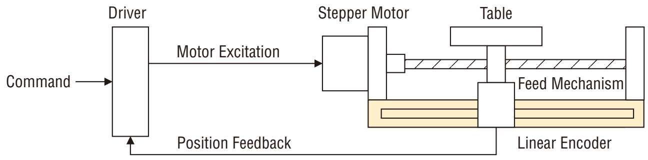


Figure 5. Control Using the Load Position Correction Function

3.1. Load Position Correction Function

Figure 6 shows the flow of control in the basic positioning operation. When a pulse signal is input from the host controller to the driver, the driver starts a positioning operation. The operation is executed according to the command position and speed calculated from the number of pulses and pulse frequency of the input pulse signal. When the pulse signal stops, the operation is completed to switch to the load position correction function.

The load position correction function checks the position deviation, which is the difference between the command position based on the input pulse signal and the feedback position based on the feedback from the external encoder, and performs the correction operation. The permissible range of the position displacement is set in the driver in advance, and when the position deviation exceeding the permissible range is detected, position correction is performed.

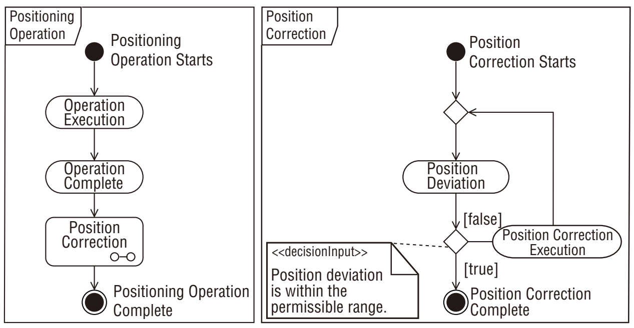


Figure 6. Flow of Control for Positioning Operation

Figure 7 shows the control block of the position command. The pulse counter separately counts the "position command pulse" by the input pulse signal and the "position detection pulse" by the encoder signal. The "position command pulse" generates the position command amount by performing resolution conversion from the count value in the driver according to the setting of the resolution per revolution that has been set in advance. In the case of open-loop control, the excitation position command of the motor is performed based on the generated position command amount.

For position correction, the "position command pulse" is converted from the count value to the resolution in the driver according to the encoder resolution setting that has been set in advance, and the position command amount is generated based on the encoder resolution. The "position correction amount" is generated from the difference between the position command amount and the counted position detection pulse, and the excitation position command is corrected by adding to the position command amount, and the position correction is performed.

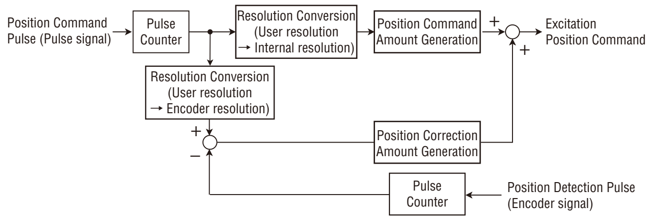


Figure 7. Control Block Diagram of Position Command

3.2. Features

The driver performs the correction operation for the position deviation. High-accuracy positioning can be achieved due to the fully closed-loop control method. Since the correction is independently controlled at a high-resolution rotation angle, positioning operation can be performed without depending on the resolution setting of the driver.

The positioning operation when performing the correction operation is divided into three stages as shown in Figure 8. This function combines open-loop control and fully closed-loop control methods, taking advantage of both. It has the following features:

· High-accuracy positioning can be performed by detecting the load position.

· The difference between the command position and the feedback position of the external encoder is corrected.

· Synchronization and responsiveness to commands are high.

· Gain adjustment is not required according to the load.

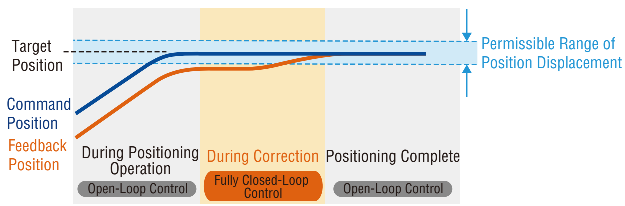


Figure 8. Positioning Operation with the Load Position Correction Function

1) During positioning operation

When an operation command is input, operation is performed in open-loop control. The operation is the same as commonly used stepper motors, the synchronization is high, and no gain adjustment is required.

2) During correction

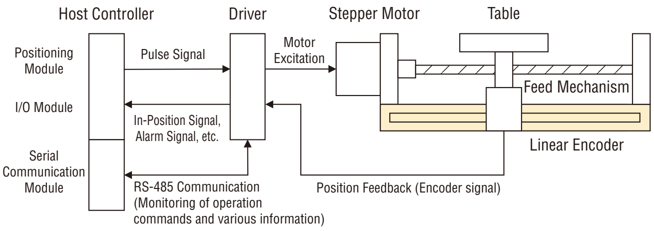
If the feedback position of the load position exceeds the permissible range after the operation stops, the operation to correct the position deviation between the feedback position obtained from the external encoder and the command position is automatically performed. It is necessary to set the permissible range (in-position range) of the position displacement in the driver in advance.

3) Positioning complete

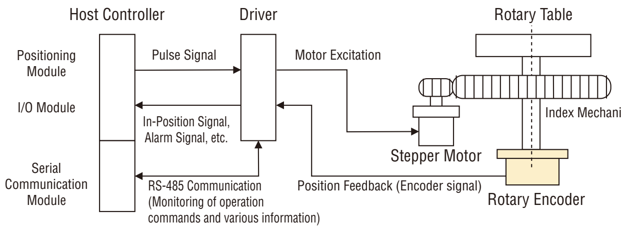
Operation returns to that of open-loop control after the motor enters the in-position range. Therefore, there is no vibration during a stop and the motor stops by its own holding force. If the in-position range is exceeded due to an external force, the operation to correct the position deviation will be performed automatically. The operation can be stopped at the target position because the correction can be performed even if there is the effect of rigidity or an external force between the motor and the load position. This means that the repeatability of operation will be high even if there is lost motion due to backlash, pitch error, and temperature changes or expansion of the mechanism section.

4. System Configuration

Figure 9 shows examples of the overall system configuration using the CVD-F. Figure 9 (a) and (b) show examples of configurations using a linear encoder and a rotary encoder, respectively. The **CVD** Series driver is designed and developed for a DC power supply, making it compact and lightweight. In addition, the driver shape and connector direction can be selected according to the installation method. This contributes to the downsizing and space saving of equipment[5].



(a) Example using a linear encoder



(b) Example using a rotary encoder

Figure 9. System Configuration Examples

4.1. Operating Method

As shown in Figure 9, the CVD-F is compatible with pulse input control and Modbus RTU control(Note 1) and can be connected to a variety of host controllers. Pulse input control and Modbus RTU control can be selected according to customer requirements.

1) Pulse input control

Pulse input control is performed using a pulse generator (positioning module in the PLC) and I/O. Since the in-position signal and alarm signal can be output from the I/O of the driver, operation can be performed while being monitored by the host controller. This enables high-accuracy positioning without significantly changing the system configuration of commonly used stepper motors.

2) Modbus RTU control

Adding a serial communication module to the host controller for Modbus RTU control allows the setting of operation data and parameters and the input of operation commands. This can eliminate a pulse generator (positioning module in the PLC) and obtain various information, such as monitoring motor position information and reading alarm codes.

3) Combination of pulse input control and Modbus RTU control

Pulse input control and Modbus RTU control can be combined for use. The motor is driven using pulse input control, and the position information of the motor and encoder can be obtained using a touch screen that is compatible with Modbus RTU protocol to check that the motor is operating normally.

Since up to 31 units of server devices, such as drivers, can be connected to a single client device on the Modbus network, it is not necessary to install a counter module in the host controller for the number of axes, and monitoring can be performed.

4.2. Compatible Encoders

Incremental encoders with a line driver output specification can be used. There are many incremental encoders on the market and a wide range of choices available regardless of manufacturer. Since the signal is output as a differential signal, this encoder has the advantage of high noise immunity and allows long wiring distances.

In addition, 5 VDC is output from the encoder input connector of the driver, which also helps save wiring.

4.3. Compatible Stepper Motors

The CVD-F is a driver for 5-phase stepper motors. Although there are 2-phase and 3-phase stepper motors in the stepper motor category, a 5-phase stepper motor is easy to use because its vibration is low and it does not easily resonate when installed to a mechanism. As an example, vibration characteristics were measured when 2-phase and 5-phase stepper motors were rotated in microstep drive using the conventional **CVD** Series drivers. Driver and motor combinations are shown in Table 1.

Table 1. Driver and Motor Combinations

Number of Phases	Driver	Motor
2-Phase	**CVD223FB-K**	**PKP244D23B2**
5-Phase	**CVD518B-K**	**PKP544N18B2**

At that time, the measurements were made with the ratio of the inertia of a load to the rotor inertia of the motor (inertia ratio) as 9:1. Figure 10 shows the measurement results of the 2-phase and 5-phase **CVD** Series. This figure shows the characteristics of the relationship between the rotation speed and the vibration component voltage using a speed sensor called a DC tachogenerator, which converts the rotation speed into voltage. It shows that the vibration of the 5-phase is lower than that of the 2-phase.

Medium vacuum, high vacuum, and ultra-high vacuum

(Note 1) Modbus is a registered trademark of Schneider Automation Inc.

stepper motors are also available as stepper motors that can be connected to the **CVD** Series. Combined with an external encoder for use in vacuum environments, these motors can be used for automatic adjustment or high-accuracy positioning in narrow vacuum vessels. This contributes to automation in vacuum environments[(6)].

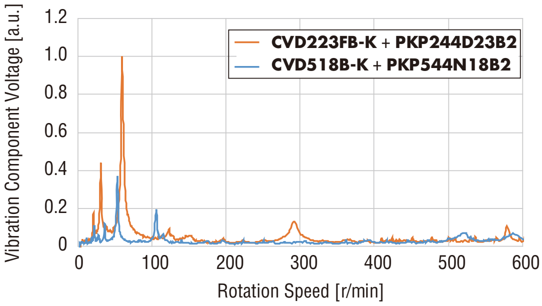


Figure 10. Comparison of Vibration Characteristics of 2-Phase and 5-Phase Stepper Motors

4.4. Comparison with Conventional System Using an External Encoder

Traditionally, when high-accuracy positioning was performed using an external encoder and a stepper motor, the method used was that open-loop control was made between the motor and the driver, and the host controller took responsibility for making the positioning adjustment command to improve the positioning accuracy. The problem caused by this method is that it increases the complexity of the whole system and loses the simplicity that stepper motors have.

First, let us consider the case where correction is performed on the host controller side using an external encoder of the incremental type. The encoder pulse count rate becomes high due to the need for position feedback from a high-resolution encoder. Therefore, it is necessary to obtain the feedback position using the high-speed counter on the host controller side, calculate the position deviation from the command position by the positioning module, and input the pulse signal for correction to the driver to perform high-accuracy positioning. In this case, the stepper motor itself must be controlled by fine rotation angles to correct the fine position deviation that has occurred. The resolution setting for each revolution of the motor must be set to a high value in advance, and the pulse signal for correction also requires a higher frequency to the command position. Therefore, it is necessary to select a high-speed command pulse generator on the host controller side.

When the CVD-F is used to address these issues, the system can be improved over the conventional system as shown in Figure 11. The system can be built without installing a high-speed counter in the host controller because the position feedback signal from an external encoder can be input to the driver.

And because the driver automatically calculates the position deviation and determines the positioning completion, the operation can be performed without losing the simplicity of stepper motors.

In addition, the operation for correcting a fine position deviation that has occurred is independently controlled at the high-resolution rotation angle without depending on the resolution setting of the driver. This makes it easy to build a high-accuracy positioning system without having to select a high-performance command pulse generator on the host controller side.

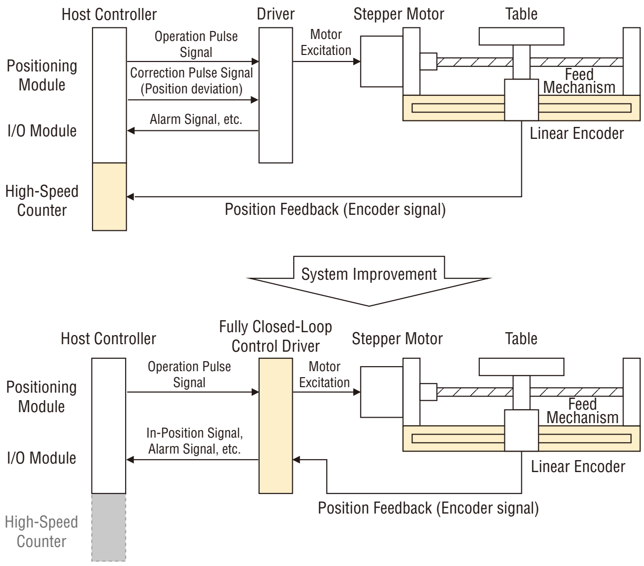


Figure 11. System Improvement Using a Conventional External Encoder

5. Effect Verification

The effect of the load position correction function was verified using a mechanism that combines a motor and a precision linear stage with a linear encoder. The measurement conditions are as follows.

- · Feed screw lead: 1 mm
- · Linear encoder resolution: 0.1 μm
- · In-position range: ±1 count (±0.1 μm)

In this time, 1 count of the in-position range corresponds to 0.1 μm of the linear encoder resolution.

Figure 12 shows the effect of the load position correction function on the command position of 100 μm when positioning operation is performed using the CVD-F in the above mechanism, in terms of the relationship between the command position and the feedback position.

Correction operation with the load position correction function is performed for the position deviation that occurred during open-loop control, enabling more accurate positioning.

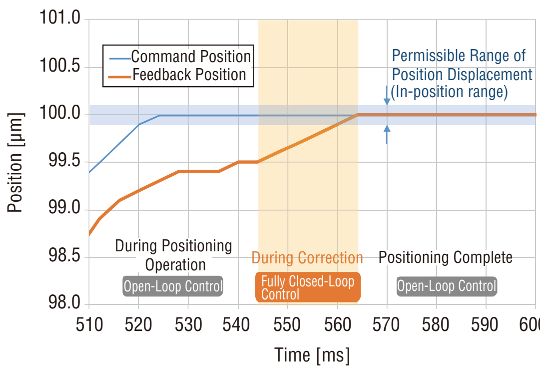


Figure 12. Effect of Positioning Operation with the Load Position Correction Function

Figure 13 shows the effect of positioning operation in which a fine step feed is repeated in 1 μm increments in the positive and negative directions in the same measurement environment.

In the case of open-loop control, when the direction of travel is reversed, lost motion occurs due to the effect of the backlash of the feed screw. In contrast, the load position correction function performs a precise feed of 1 μm per step, correcting the influence of lost motion and achieving highly repeatable positioning operation.

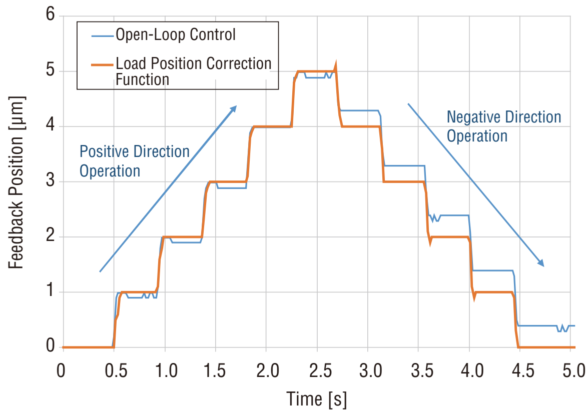


Figure 13. Effect of Fine Step Feeds with Load Position Correction Function

6. Summary

This report introduced high-accuracy positioning technology for stepper motors based on the CVD-F. This technology provides a reliable, high-accuracy positioning system that retains the ease of use and simplicity of stepper motors.

Oriental Motor will continue to develop products that meet customers' needs by further advancing the technologies obtained through research and development.

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