Dynamic Characteristics and Positioning Performance of Piezoactuator–integrated Ball Screw Drive

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Abstract:
This paper presents a new fine and coarse (dual) positioning system with a piezoelectric actuator integrated into the support unit of a ball screw. On the developed system, frequency response tests were carried out and a dual controller was designed. By using this dual positioning system, positioning tests were carried out. Test results show that the positioning system has good tracking capability with a tracking error of less than 0.2 μm by decreasing the stick motion.

Keywords: Precision positioning, Dual servo control, Ball screw drive, Piezoelectric actuator

1. Introduction

In the recent manufacturing of high precision parts such as optical parts and MEMs, not only higher accuracy but also higher productivity has been demanded for machining. The demand for machine tools that can support the accuracy of submicron order is increasing Generally, the positioning resolution of feed drive systems of such machine tools should be several times smaller than the required accuracy tolerance. For example, in order to obtain the geometry accuracy of 0.1μm, the positioning resolution of 10nm is necessary for the drive system.

As ball screws have high load capacity and high rigidity, they are widely used in machine tools. However, due to the friction in nut-screw, it is difficult to obtain the positioning resolution of submicron order. On the other hand, since linear motors have no friction and high response, it is easier to obtain high precision positioning capability with the combination of linear encoders [1]. A critical problem with linear motors is that their smaller load capacity makes it difficult to design the entire configuration small and high rigidity.

Dual servo (double-stage) positioning systems have been developed to achieve the positioning in a long stroke with high resolution [2-4]. Typical designs of these dual servo systems stack a fine positioning system with a piezoelectric actuator on a coarse positioning table driven by a ball screw. However, since the piezoelectric actuator driven table is loaded on the ball screw driven table, the offset (the Abbe offset) between the fine and the coarse axes makes it difficult to control both axes synchronously. In addition, a preload spring is needed in the piezoelectric actuator, which decreases the overall rigidity. As for their control law, most of the proposed systems mainly use switching control: for the coarse positioning, only the coarse drive is activated; when the positioning error is within some threshold, the fine drive is switched on [2-5]. There are few researches that report synchronous drive of fine and coarse motion.

Tanaka presented a new fine and coarse positioning device where a piezoelectric actuator was installed inside a support unit of the ball screw driven by a stepping motor [6]. In this system, since preload spring is not necessary, the decrease of the rigidity is minimized, and 5nm PTP (point to point) positioning resolution with 50mm stroke was achieved.

In this research we develop a fine and coarse positioning system based on the device that Tanaka presented. The developed system uses a servo motor for coarse motion actuation, which can obtain higher positioning accuracy for not only PTP but also CP (continuous path) controls. This paper presents the dynamic characteristics and the positioning performance of the proposed system. To investigate them experimentally, frequency response tests are carried out in the open loop. Then fine-and-coarse synchronous controller is designed and examined to find out the performance of the system.

2. Principle and Experimental Set up of Nano Positioning Dual servo

2.1 Drive Mechanism

Figure 2.1 shows the mechanism of the positioning system and a close-up of the fine motion mechanism. Since the motor and the piezoelectric actuator are installed on the same axis, the Abbe error between fine and coarse drives can be minimized. In addition, this fine motion mechanism can be produced simply by modifying the structure of support unit of a ball screw drive system. An inner spacer is installed between two bearings in the support unit, such that the gap is given between the outer races. The inner race is locked with the screw axis by the lock nut .The outer race is attached to the piezoelectric actuator via an outer spacer, and entire structure is integrated into the housing. By adjusting the size of outer spacer, any preload can be given to the bearings. Since this preload is also imposed to the piezoelectric actuator, the preload spring for piezoelectric actuator is not needed. Through the spacer, the outer race of the bearing is pushed by piezoelectric actuator. Then, the table moves by the displacement half of the extension of the piezoelectric actuator.

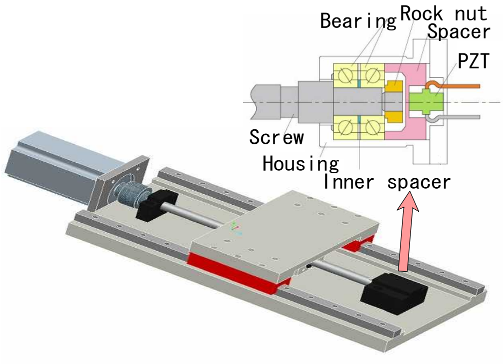

Figure 2.1 The positioning mechanism

2.2 Developed System

We designed and developed a positioning system by using the fine motion mechanism above, for a vertical axis of the high precision machine tool. Table 1.1 shows the specification of this system. As an AC servo-motor is suited for CP control compared to a stepping motor, an AC servo motor is adopted for the coarse motion mechanism. The coarse motion mechanism consists of a servo-motor, a high precision ball screw, an elastic coupling and a support bearing. The fine motion mechanism consists of a piezoelectric actuator and support bearings. The positioning table is supported by linear ball guide ways.

Table 1 Specifications of the system

Coarse motion travel distance		200 mm
Table mass		5 kg
Ball screw	Diameter	12 mm
	Lead	5 mm
Resolution of the rotary encoder		65536 pulse/rev
resolution of coarse positioning		76.3 nm
Fine motion travel distance		10 μ m
Resolution of fine positioning		10nm

The experimental setup is shown in Fig. 2.2. All experiments are carried out by setting this system in the Z (vertical) direction. Position commands are made on Simulink / MATLAB. Commands are output to the servo amplifier and the piezoelectric amplifier from 12bit DA converter installed in a PC-based controller (Real Time Simulator made by DSP technology). In the servo amplifier, the torque command from the PC-based controller is received. The motor torque is controlled by the current feedback loop made on the servo amplifier. The piezoelectric driver magnifies the command voltage from the DA converter by 30 times and gives it to the piezoelectric actuator. In addition, a rotary encoder and a linear encoder give feedback position signal to the PC via a 32bit counter board.

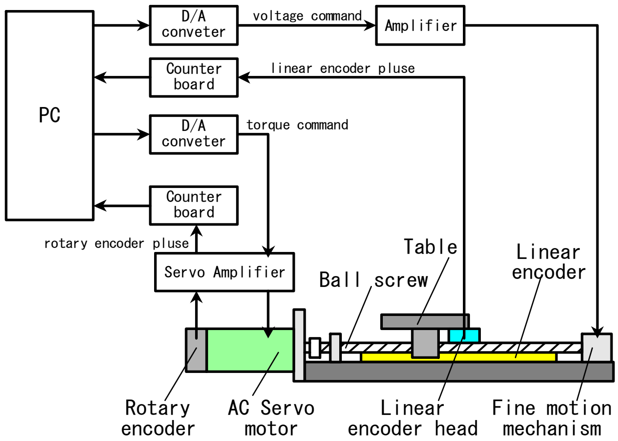

Figure 2.2 Experimental setup of the system

2.3 Dynamics of the Coarse Motion Mechanism and its Parameter Tuning

In order to evaluate of the decrease of the rigidity caused by the installation of the fine motion mechanism, the open loop frequency response of the coarse motion mechanism is measured. In addition, control parameters for the coarse motion mechanism are tuned from the frequency response. White noise torque command signal with the average that corresponds to torque of 2.0 Nm is given to the servo amplifier from the PC. The table displacement is measured with the rotary encoder and regarded as output. The frequency response is shown in Fig. 2.3. The peak is seen in 397 Hz. Since the resonance peak of the coarse motion system without the fine motion mechanism is simulated to be 409 Hz, it is found that the decrease of the natural frequency is sufficiently small.

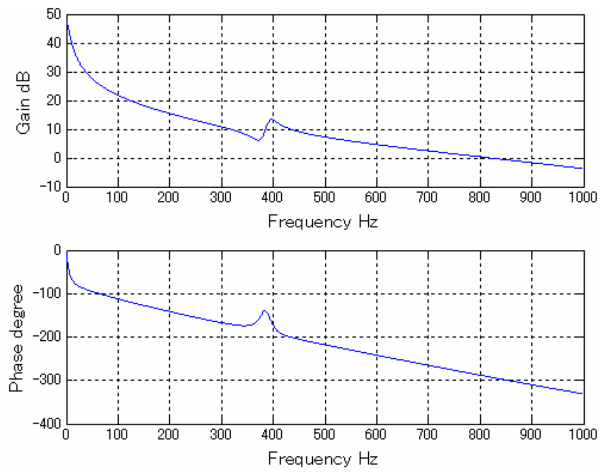

Figure 2.3 Open loop frequency response of the coarse motion mechanism

The coarse motion mechanism is controlled by semi-closed loop control. The coarse motion controller is a typical controller which has three cascade connections. In Fig. 2.3, when the phase is -180 degrees, the gain is 10 dB. To obtain the gain margin of 6 dB, the gain crossover frequency must be at ω_v=150 Hz. To this goal, we tuned control parameters as: K_{vp}=100, K_{pp}=100 and K_{vi}=0.16.

Using these parameters, positioning experiments were done with stairway-shaped commanded trajectories. Commanded step widths are 50 μm, 10 μm, 1 μm and 0.5 μm. The holding time is 1 s. The table displacement of the linear encoder is shown in Fig. 2.4. It can be observed that the positioning resolution up to 0.5 μm was obtained.

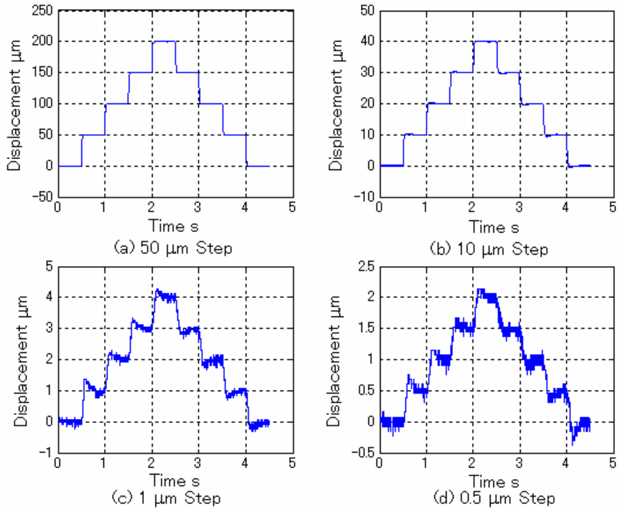

Figure 2.4 Measured step responses of the table position under the semi-closed control

3. Fine Motion Control

3.1 Controller Design and Parameter Adjustment

The open-loop frequency response of fine motion mechanism is measured in order to design a fine motion controller. From the 12bit DA converter, white noise command of an average voltage 1.3 V is given to the piezoelectric amplifier. The frequency response from the command voltage to the table displacement is shown in Fig. 3.1. The bandwidth is 550 Hz and the gain margin 5 dB. In addition, a clear peak can be seen at 385 Hz.

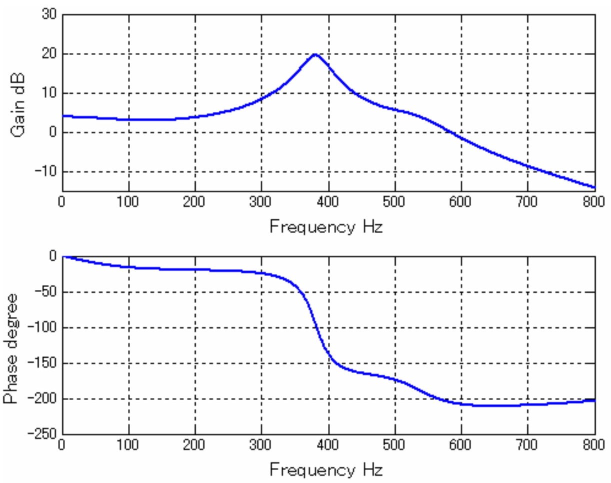

Figure 3.1 Open loop frequency response of the fine motion mechanism

As the control law, we use PI + feedforward(FF) controller as shown in Fig. 3.2. The saturation function is used as voltage limit. By using the measured open-loop frequency response, we simulated the frequency response of the closed-loop system in order to tune the control parameter. To meet the bandwidth of 50Hz as a tuning objective, the control parameters are adjusted as: K_P=0.14, K_I=200 and K_f=0.2. We experimentally verified that this set of parameters gave the closed-loop bandwidth of 45 Hz.

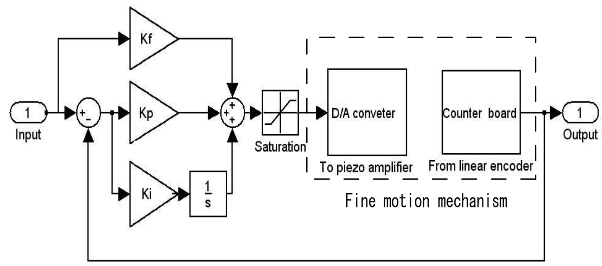

Figure 3.2 Closed loop controller for the fine motion mechanism

3.2 Closed Loop Tests of Fine motion

The step positioning experiment of the fine motion mechanism with the closed-loop control is carried out. Command step widths are 500 nm, 100 nm, 50 nm and 10 nm. The measurement was repeated by three times in each case. The experimental results are shown in Fig. 3.3. It can be observed that the table responded to 10 nm steps. There is an error of ±10 nm in table displacement because the sensor resolution of the linear encoder is 10 nm.

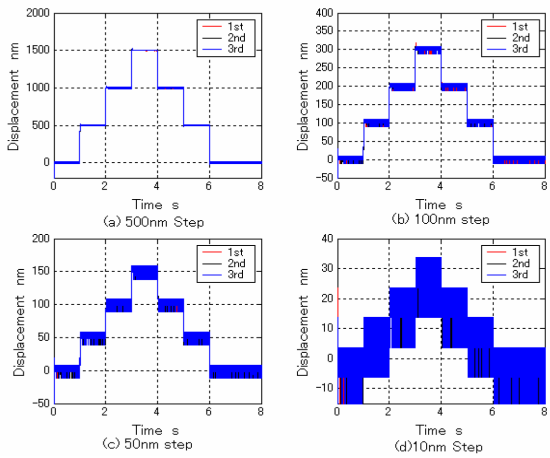

Figure 3.3 Step responses of the table position by fine motion positioning

4. Synchronous Drive of Fine and Coarse motion

4.1 Controller Design

In order to drive the coarse motion mechanism and the fine motion mechanism synchronously, we designed a synchronous controller. The controller we designed is shown in Fig. 4.1. The synchronous controller combines the coarse controller and the fine motion controller. In order to drive fine motion mechanism efficiently, the reference position for the coarse drive is shifted by 2 μm from the given reference position. The command for the fine motion controller is the deviation of command position and linear encoder position. In addition, the difference in the positions measured by the rotary encoder and the linear encoder is given to the fine motion mechanism loop as an input to the feedforward compensation.

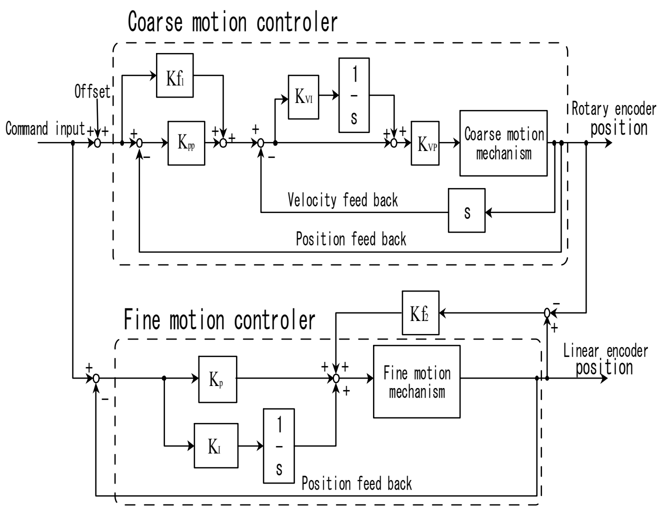

Figure 4.1 Fine and coarse synchronous controller

4.2 Synchronous Tracking Experiment

In order to evaluate the performance of CP control, we compare the synchronous tracking to single coarse motion tracking by semi-closed control. The commanded trajectory is a sign wave of the amplitude 100 μm, and the period 5 s. The results of positioning experiment are shown in Fig.4.2.

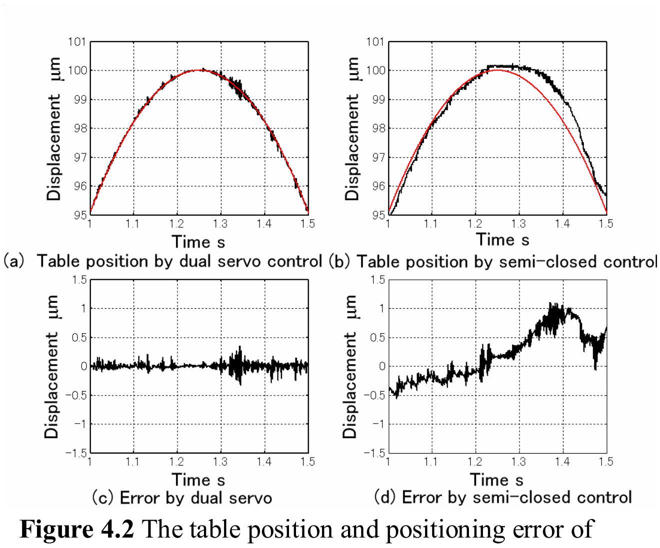

Figure 4.2 The table position and positioning error of synchronous control and semi-closed control

When only the coarse mechanism was used, the maximum tracking error was about 1 μm. In addition, the delay of the table displacement of about 10 ms was observed. On the other hand, when the fine motion mechanism was synchronously used, the maximum tracking error was decreased to 0.2 μm. It was decreased also the stick motion which was observed when only the coarse motion mechanism was used. In addition, the delay from the command trajectory was not seen.

5. Conclusion

In this research, we developed the fine and coarse positioning system and its control laws. We evaluated its dynamic performance and positioning accuracy. The conclusion of this research is summarized as follows.

(1) The fine motion controller was designed from frequency responses of the fine motion mechanism. The positioning resolution of 10nm was achieved.

(2) A controller to synchronously control fine and coarse motion mechanism was designed.

(3) By using the synchronous controller, the positioning error became less than 0.2 μm. When only the coarse mechanism was used, the maximum positioning error was about 1 μm.

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