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Development of Precise Control System for Compact Magnetic-levitation Stage System

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Abstract: Nanometer-scale positioning accuracy is required for semiconductor manufacturing systems and ultra-precision machine tools. One way to improve the accuracy is to support the table with a noncontact guide system that prevents the occurrence of guide friction and heat transfer from the lower table or base structure. For this purpose, we are developing a compact magnetic-levitation (maglev) stage that can be installed for nanometer-scale positioning of an XY stage system. The stage system contains an XY coarse stage driven by linear motors and a 6-DOF maglev fine stage driven by VCMs. The maglev stage has a compact structure and its levitation mass is less than 1 kg, which is dramatically more lightweight than existing maglev stages. Our stage system also has long strokes, such as 200 mm in the X and Y directions on a horizontal plane. In this paper, we describe a precise control system for the maglev fine stage and XY coarse stage and present its evaluation results. The control system consists of a levitation-stabilizing controller and an FF controller for improving the responsiveness of the coarse stage. The evaluation results demonstrate that the developed stage is capable of nanometer-scale positioning.

Keywords: Positioning systems, servo systems, control precision, levitation control, stage system.

1. INTRODUCTION

High positioning accuracy is required for semiconductor manufacturing systems and ultra-precise machine tools. One way to improve the positioning accuracy is to support the moving table with a noncontact guide system that prevents the occurrence of guide friction and heat transfer from the lower table or base. An aerostatic guide is normally used for this purpose (Tomita, Sugimine and Koyanagawa (1996), Takahashi, Yoshioka and Shinno (2008)); however, in a vacuum condition, it is difficult to achieve high vacuum pressure without a differential vacuum system, as such a system would enlarge the machine dimensions (Tanaka (2009a)). For this reason, a maglev stage was developed (Kim, Trumper and Bryan (1997), Laro (2013)), and some have long strokes in a single direction (Tanaka (2009b)). The levitated masses of these conventional maglev stages, which have strokes of several hundred mm, are commonly over 10 kg, which makes their total dimensions too large to be installed as a fine stage on a coarse stage. In one study, a triangular compact maglev stage with a short stroke was developed, and the positioning resolution of 10 nm was confirmed (Kim, Verma and Shakir (2007)). However, it is difficult to use this structure as an XY fine stage due to the triangle layout of interferometers.

We aimed to develop a compact maglev stage for which the levitated mass is less than 1 kg and which is dramatically more lightweight than existing maglev stages (Takahashi, Ogawa and Kato (2019)). Our developed stage system also has long strokes, such as 200 mm in the X and Y directions on a horizontal plane.

This paper describes our development of a control system for the magnetic levitation (maglev) stage with a compact structure that can be installed for nanometer-scale positioning of an XY stage system.

2. COMPACT MAGLEV STAGE SYSTEM

2.1 OVERALL STRUCTURE

Coarse-fine structure stages have frequently been used to fulfill requirements for both positioning accuracy and long strokes. The vibration canceller was developed as a coarse-fine structure stage that enables vibration reduction from the coarse stage (Takahashi, Ogawa and Odai (2017)). However, heat transfer through the elastic hinge is a problem. To resolve it, we developed a fine stage with noncontact support using maglev.

Figure 1 shows the overall structure of the developed coarse-fine stage system. We installed a 6-DOF maglev stage as a fine stage on the coarse XY stage with a conventional stuck structure composed of a linear motor and linear guides. The coarse stage has strokes of 200 mm in both the X and Y directions. Its table position (X and Y tables in Fig. 1) is measured by a linear scale. The table position of the fine stage is measured by capacitance proximity sensors (CPS) fixed at the table of the coarse stage, and after the levitation is stable, X and Y axis measurements are changed to those measured by the laser interferometer, which is fixed at the base. This measurement system prevents errors from the

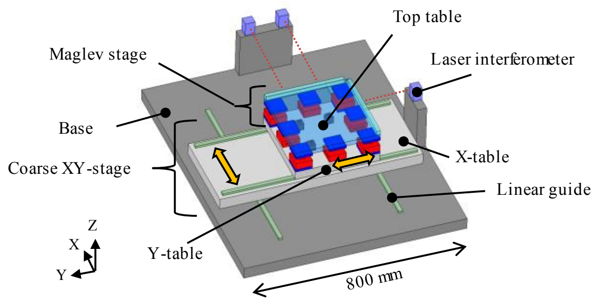


Fig. 1. Overview of structure of developed coarse-fine stage system. Position of top table is measured from base.

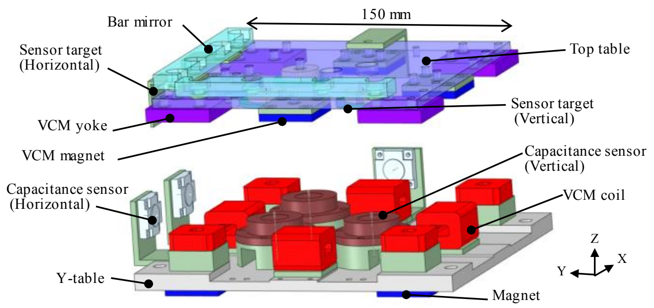


Fig. 2. Configuration of 6-DOF fine stage with maglev mechanism.

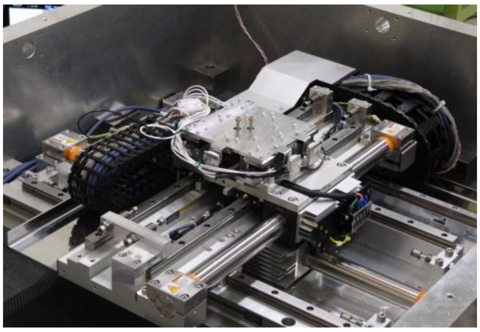


Fig. 3. Appearance of developed stage system.

Table 1. Specifications of maglev stage.

Levitation mass		0.81 kg
Total mass of fine stage		2.3 kg
Dimensions		150 × 150 × 53 mm
Strokes	XY	±3 mm (±200 mm with coarse XY stage)
	Z	1 + (0–9.5) mm
Max. acc.	XY	4.9 m/s^2
	Z	9.8 m/s^2

coarse stage from affecting the fine-stage positioning accuracy in the XY position.

2.2 Configuration of maglev stage

We developed our maglev stage with the following design concepts to create a compact structure.

(1) Reduce top table mass to minimize the motor dimensions and enable a light weight and high responsiveness.

(2) Measure the top table XY position from the base to eliminate positioning errors and isolate vibrations of the coarse stage.

(3) Install a motor in a symmetrical layout in view from the Z axis to enable the same driving characteristics between the X and Y axes.

Figure 2 shows the configuration of the 6-DOF fine stage with the maglev mechanism. The top table is levitated against the Y table, which is the upper table of the coarse XY stage; this enables vibrations, heat transfer, and strain to be isolated from the coarse stage. The magnets and yokes of the voice coil motor (VCM) are installed in the surface below the top table. The coils of the VCM are installed in the Y table to prevent disturbances and heat generation from the power cable and coil current, respectively.

Bar mirrors, used for the noncontact, long-stroke measurement of the top table position in the X and Y directions with laser interferometers, are installed on the top table. Capacitance sensors, which measure displacement of sensor targets fixed on the top table, are installed on the Y table to measure the 6-DOF position of the top table. These laser interferometers and capacitance sensors are used for 6-DOF feedback control of the fine maglev stage. Table 1 lists the specifications of the developed stage system.

In addition, the compact structure of the fine stage enables the minimization of the moving mass of the coarse stage. Figure 3 shows the appearance of the developed coarse-fine stage system. The fine maglev stage is small enough to prevent increases in moving mass of the coarse stage.

2.3 Motor design

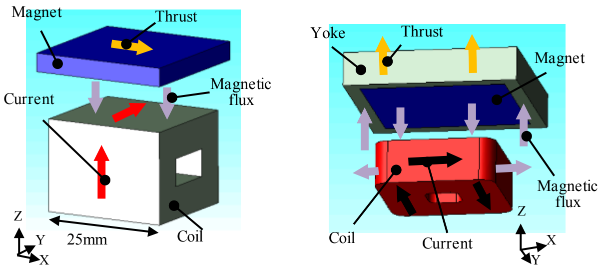
In this study, magnets and yokes are installed in a planar layout to reduce the top table mass and vertical dimensions and to enable high responsibility. Yoke volume, especially, increases levitated mass dramatically and should be used minimally. Therefore, we designed a planar-shaped and simply structured VCM on the basis of magnetic analysis.

Figure 4 shows the VCM structure of the horizontal axis. (a) shows the X-VCM structure (the same as that of Y-VCM), which turns 90 degrees from the Y axis to the X axis. The magnetic field of the Z direction is made by a neodymium magnet in the upper half of the coil unit. Thrust in the X direction is made by the magnetic field and coil current of the Y direction. (b) shows the Z-VCM structure. Vertical thrust is generated by the coil current around the Z axis.

3. CONTROL SYSTEM AND EVALUATION

3.1 Configuration of control system

According to Earnshaw's theorem, a maglev stage generally cannot maintain levitation without control. We configured 6-



(a) X axis (b) Z axis

Fig. 4. Configuration of VCMs for maglev stage.

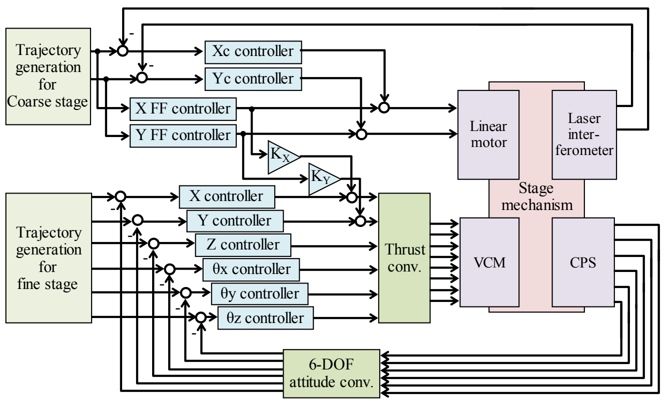


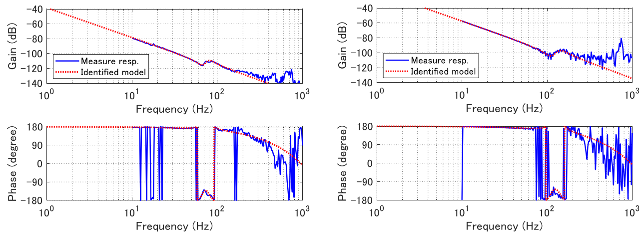
Fig. 5. Block diagram of control system.

DOF control for stable levitation. Figure 5 shows a block diagram of the control system for positioning in the coarse-fine stage. The stage mechanism contains ten input signals (two linear motors and eight VCMs) and eight output signals (two laser data and six CPS data).

The driving currents for eight VCMs are converted from six thrust signals for the levitation stage (F_x, F_y, F_z, τ_x, τ_y, τ_z). This thrust conversion is based on the geometric arrangement of the VCMs. Also, the 6-DOF motions of the levitation stage (X, Y, Z, θ_x, θ_y, θ_z) are converted by six CPS signals. This attitude conversion is based on the geometric arrangement of the CPSs. Thus, levitation controllers are decoupled from each other and can be designed independently. We utilize a PID controller and several stabilizing filters as the levitation controllers, e.g., the X controller and θy controller. The reference signal for levitation motion is normally set to zero.

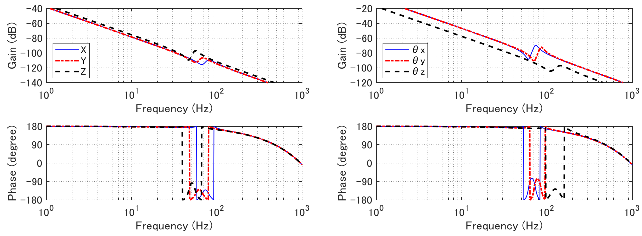
The control system of the coarse stage is configured as a 2-DOF controller consisting of feedback and feedforward control. The feedback signals of the coarse stage are stage displacement measured by bar mirrors and a laser interferometer. We utilize a PID controller and several stabilizing filters as the coarse controllers (X and Y axis). Feedforward thrust is calculated by the acceleration of the coarse stage in the reference trajectory.

Levitation feedforward thrust, which is multiplied by the feedforward thrust of the coarse stage and coefficient K_x or K_y, is added to the levitation X and Y thrusts. Here, K_x and K_y are



(a) X axis (b) θz axis

Fig. 6. Measured and identified frequency responses of levitation stage.



(a) Translation axes (b) Rotation axes

Fig. 7. Frequency responses of identified models of levitation stage.

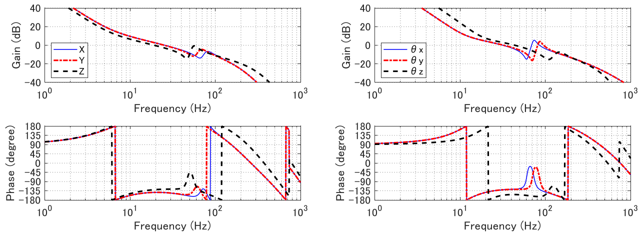
conversion factors between the coarse and fine stages, and they depend on moving mass and thrust constant.

3.2 Levitation controller design

Figure 6 shows the frequency responses of the levitation stage. Here, X axis and θz axis are shown as examples. The measured response consists of the transfer characteristics from input to thrust conversion before VCM (F_x or τ_z) to attitude conversion after CPS (X or θ_z). The identified models include rigid model, resonant model, and delay model. In Fig. 6, the response of the identified model matches the measured response.

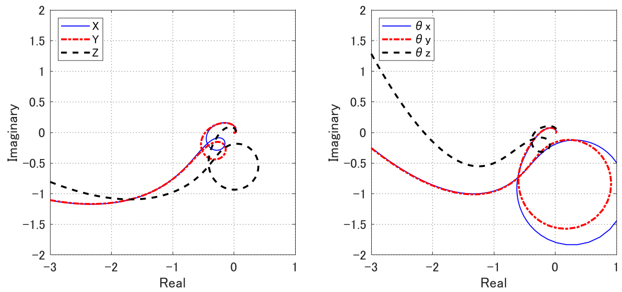
Figure 7 shows the frequency responses of the identified models of all levitation axes. Each model shows a characteristic of a moving-mass system without friction. Also, each has a resonant mode from 50 Hz to 150 Hz. We assume this resonant mode is related to deformation of the top plate or other parts.

Figures 8–10 show the characteristics of the designed levitation control system. A Bode diagram of the open-loop system is shown in Fig. 8, where each control system ensures stability and has a crossover frequency from 20 Hz to 40 Hz. Here, the crossover frequency of the θ_z control system is designed to be slightly higher than that of the other axes because the θ_z axis requires high stiffness due to the gravity compensation mechanism. Figure 9 shows a Nyquist diagram of the open-loop system and Fig. 10 shows the sensitivity functions of the levitation control system. We can see in both figures that the levitation control system achieves a sufficient stability margin and that the maximum gain of the sensitivity function is less than 10 dB.



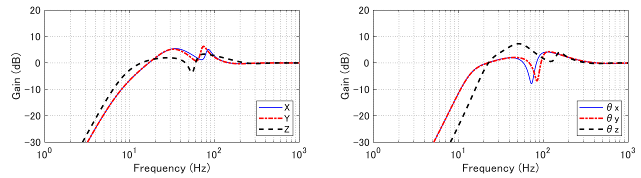
(a) Translation axes (b) Rotation axes

Fig. 8. Bode diagrams of open-loop characteristics.



(a) Translation axes (b) Rotation axes

Fig. 9. Nyquist diagrams of open-loop characteristics.



(a) Translation axes (b) Rotation axes

Fig. 10. Sensitivity functions of levitation control system.

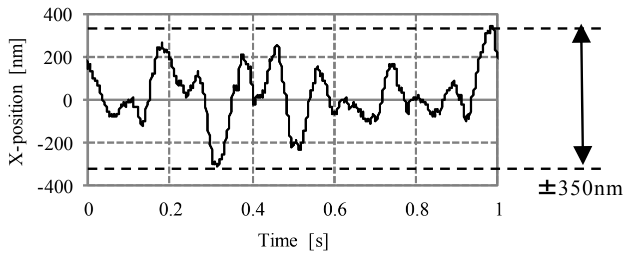
3.3 Evaluation

We evaluated the static vibration of the levitated top table. Figure 11 shows the vibration of the top table while the stage was levitated constantly. Vibration controlled with capacitance sensors in all axes is shown in (a). We can observe fluctuation of the low frequency, about 10 Hz, and the fluctuation's amplitude is about ±350 nm. (b) shows vibration controlled with laser interferometers in the X, Y, and θz axes and with capacitance sensors in the Z, θx, and θy axes. We can confirm here the positioning error within ±10 nm.

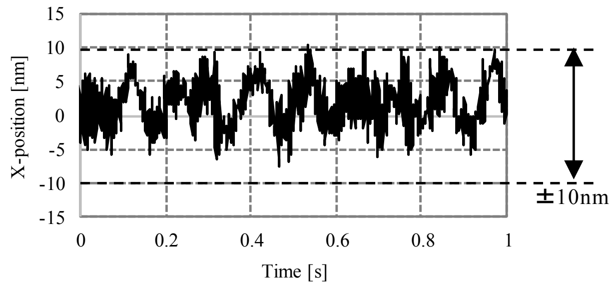
These results demonstrate the stage's capability of nanometer-scale positioning. We will further evaluate and improve the positioning performance in future work.

4. CONCLUSION

We developed a control system for a maglev stage with a compact structure for a fine stage. The compact VCM design enables a light weight for the levitated mass and a high responsiveness for the stage control. Evaluations of the developed stage demonstrated its capability of nanometer-scale positioning.



(a) Control with capacitance sensors



(b) Control with laser interferometers

Fig. 11. Evaluation results of top table static vibration.

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