euspen's 26th International Conference & Exhibition, Krakow, PL, June 2026
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# Investigation of Motor Characteristic Analysis under Low Magnetic Field Conditions in Planar Maglev Stages

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**Abstract**
This study investigates a low-leakage magnetic field planar maglev stage with the movable magnet array for applications requiring both nanometre-scale positioning and leakage magnetic field reduction, such as semiconductor inspection equipment. In this study, we employ a coil array in a single-layer pattern with staggered coils and a Halbach magnet array, which concentrates magnetic flux density beneath the motor to reduce leakage magnetic fields. The planar maglev stages with the movable magnet array currently under development require complex coil-switching control during operation due to changing thrust application points. To efficiently analyze and design the control system, including coil-switching, a novel modeling method based on grid partitioning is proposed. Unlike simplified models with fixed thrust application points (e.g., grid = 1), the proposed grid-partitioning-based model enables control-oriented positioning performance simulation with sufficient accuracy while maintaining practical computational efficiency.

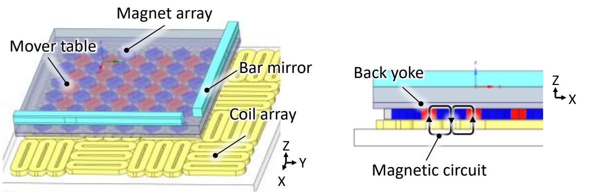
Keywords Ultra-precision, Positioning, Magnetic guide, Mechatronics, Stage system

## 1. Introduction

In recent years, the miniaturization of semiconductor devices has necessitated nanometer-scale positioning accuracy in manufacturing and inspection equipment [1]. Moreover, the global expansion of semiconductor demand has driven the adoption of magnetic levitation guides to enhance equipment throughput. Planar maglev stages substantially reduce the moving mass, enabling high-speed operation while maintaining high-precision positioning. From a thermal management perspective, positioning the magnets on the levitated side and the coil on the non-levitated side is advantageous. However, in planar motor systems, the proximity between the motor and the electron beam irradiation point allows leakage magnetic fields from the motor to interfere with the electron beam in inspection systems, thereby deteriorating inspection accuracy [2]. The planar maglev stage with the magnet array currently under development requires complex coil-switching control during operation due to changing thrust application points [3]. To efficiently analyze and design the control system, including coil switching, this study proposes a novel modeling method based on grid partitioning.

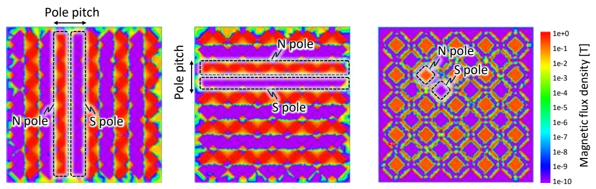
## 2. Stage mechanism

The configuration of the planar maglev stage with the movable magnet array is shown in Figure 1. This structure shortens the distance between the magnets and coils by arranging the non-levitation side coil array with single-layer coils in three-phase sets in an alternating configuration. Furthermore, the Halbach magnet array and back yoke concentrate the magnetic flux density toward the lower side (coils). In addition, coil currents are turned off at coordinates not covered by the movable table. These configurations reduce leakage magnetic fields above the motor. Lightweight magnetic shielding is under consideration to further reduce the leakage magnetic field. The magnetic flux density distribution of the planar motor is shown in Figure 2.




(a) Overview (b) Side section

**Figure 1.** Overview of the planar maglev stage with movable magnet array.




(a) X-axis (b) Y-axis (c) Z-axis

**Figure 2.** Magnetic flux density distribution on the planar maglev stage.

The magnetic flux density varies along the pattern for each magnetic pole pitch on the X and Y axes, enabling the generation of levitation thrust along the Z axis throughout the entire movable range. Furthermore, the thrust along the X and Y axes is generated by the magnetic flux density along the Z axis of the lattice pattern. A simplified model simulating this characteristic is employed as a magnetic field model for calculating motor thrust [4].

## 3. Analysis approach of planar motor control characteristics

The analysis model for planar maglev stage control characteristics is shown in Figure 3. This stage control system employs a model-based commutation algorithm [5]. This commutation algorithm calculates the phase coil currents to achieve the desired thrust and torque with decoupling across the 6-degree-of-freedom displacement. Furthermore, the 6-axis feedback controller consists of a PID controller, notch filters, and

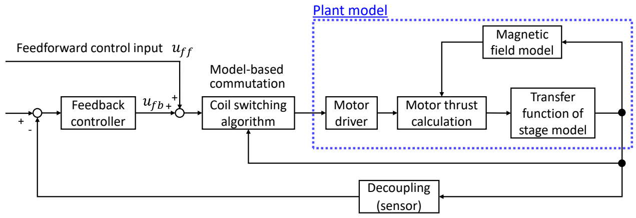



**Figure 3.** Analysis model for planar stage control characteristics.

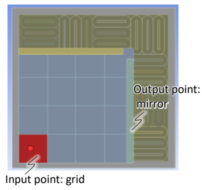



**Figure 4.** Grid partitioning for the motor thrust application point.

a low-pass filter. These parameters were designed to ensure a sufficient stability margin, while setting the control bandwidth for the X-axis and Y-axis to 100 Hz.

The planar maglev stage with movable magnet array requires complex coil-switching control due to the changing thrust application points during motion. Therefore, in the proposed method, the mechanism characteristics from thrust to position are efficiently calculated for control-oriented simulation by dividing the spatially varying thrust application points into a grid.

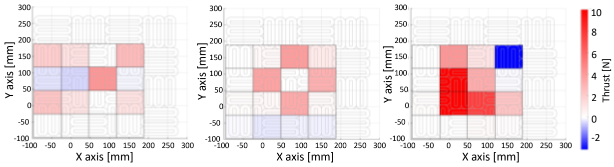
The grid partitioning for the motor thrust application point is shown in Figure 4. The mechanism model is defined as a state-space model of a multi-input multi-output system, and its parameters are calculated using the modal analysis results from Ansys Mechanical. The input points in modal analysis are each grid point, and the output points are the bar mirrors.

The driving reaction force by the Lorentz force of each phase coil is distributed to the grid on the movable table, enabling calculation of the thrust along the X, Y, and Z axes. An example of motor thrust calculation on the grid is shown in Figure 5. These calculated thrust on the grid are input into the mechanism model, and the position of the planar stage is calculated.

Figure 6 shows the errors in thrust in the translational direction and torque in the rotational direction when the grid partitioning number is changed. The errors in thrust in the translational direction are zero regardless of the grid partition number. While a coarse baseline model (grid = 1) is computationally inexpensive, it introduces non-negligible torque errors due to insufficient representation of spatially varying thrust application points. As shown in Figure 6, increasing the grid number reduces the torque error asymptotically. In this study, grid = 16 was selected as an efficient compromise that provides sufficient accuracy for control-oriented positioning performance evaluation with practical simulation time.

## 4. Positioning performance evaluation

Positioning simulation was performed by implementing the planar maglev stage control system shown in Figure 3 in MATLAB/Simulink. In this simulation model, the magnetic flux density distribution of the planar motor varies according to the X-, Y-, and Z-axis coordinates, and motor drive current is calculated using the model-based commutation algorithm. Figure 7 shows the waveforms of the position and tracking error when positioning 60 mm in the X-axis direction using a trapezoidal acceleration profile of 3 m/s$^2$. Position tracking error during stage movement was within ±2 µm. The simulation time was evaluated using the Simulink sim execution time (tic/toc). The proposed model with grid = 16 required approximately 7.55 s, which is almost identical to that of the baseline model with




(a) X-axis (b) Y-axis (c) Z-axis

**Figure 5.** Motor thrust calculation on the grid.

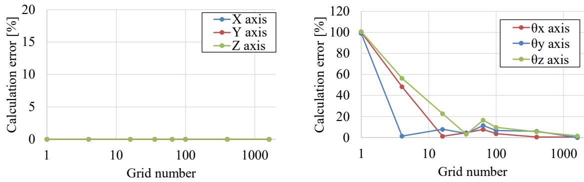



**Figure 6.** Errors in thrust in the translational direction and torque in the rotational direction when the grid partitioning number is changed.

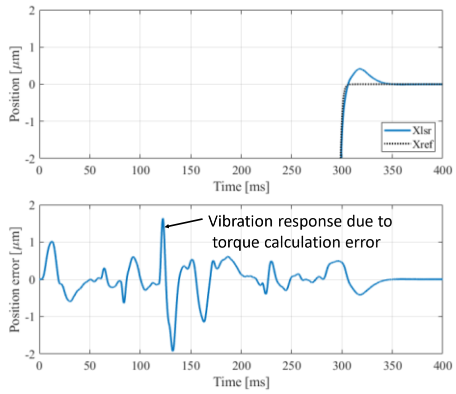



**Figure 7.** Waveforms of position and position error in the positioning simulation.

grid = 1 (7.4 s), while providing significantly improved torque calculation accuracy. This result indicates that the proposed grid-partitioning approach enhances modeling accuracy without sacrificing computational efficiency.

## 5. Conclusion

This study proposes an efficient analysis method for the low-leakage magnetic field planar maglev stage with the movable magnet array utilizing grid partitioning for the input points of the mechanism model. Analysis time can be reduced by optimizing the number of grid partitions. The effectiveness of this analysis method was confirmed through performing positioning simulations.

Detailed results on leakage magnetic fields for different planar maglev stage structures and additional leakage magnetic field reduction structures will be presented in the poster session.

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