INTRODUCTION

The reticle handling task in photo lithography machines is becoming increasingly challenging in the extreme ultraviolet (EUV) era [1]. In the next generation lithography machines, the reticle needs to be transported through a distance of 2 m between the storage position and the scanning position in high vacuum, and the transportation mechanism needs to satisfy the ultra-tight contamination requirements. In addition, due to the increased system complexity, the allowed height for the reticle transportation mechanism in the machines is constraint within 100 mm. To fulfill these requirements, the use of the traditional robot manipulator is challenging.

In this work, we present a new concept of in-vacuum transportation mechanism using a magnetically levitated linear stage (MLLS). Compared with robot manipulators, linear stages usually require less volume for long distance transportation tasks, and thus can satisfy the tight volume constraint with less challenge. In addition, we introduce magnetic levitation to the linear stage to eliminate particle generation of mechanical bearings. To reduce the system’s complexity, we present a linear bearingless slice motor design [2], where the stage’s magnetic levitation in several degrees of freedom (DOFs) are achieved passively. This design helps reduce the number of actuators and sensors in the system.

Linear hysteresis motor is selected as the driving principle for the MLLS. Hysteresis motor has the advantages of simple structure and high thermal and mechanical robustness [3]. In addition, the secondary of a hysteresis motor can be made from permanent-magnet-free solid metal material. This is desirable for in-vacuum operation, since permanent magnets (PM) can out-gas in high vacuum when it is not encapsulated. Hysteresis linear motor also allows using the same secondary material for magnetic and structural purposes, thereby beneficial for a compact design. In the past, most of the developed hysteresis motors are in rotary form and operate in open-loop. Our past work [4] studied the position control for rotary hysteresis motors. To our knowledge, this paper presents the first experimental study of linear hysteresis motor.

HARDWARE OVERVIEW

Fig. 1 shows the CAD model and the photograph of the magnetically levitated linear stage system, which comprising two stators, one moving stage, and a sensing system. The coordinate system is shown in Fig. 1a. Here the moving stage is driven along the $y$-axis. The magnetic levitation of the moving stage is active in $x$- and $\theta_z$-directions, and is passive in $z$, $\theta_x$, and $\theta_y$-directions. In our design, the moving stage is vacuum compatible. When the system is integrated in the lithography machine, a channel with thin walls (not shown in figures) needs to be configured along the motion range of the moving stage, and separates the moving stage and the stators. The moving stage is levitated and transports the reticle inside the channel in clean vacuum, while the stators are configured outside the channel, and are in a rela-
Motor Stator:
3-phase windings

Yaw control stators:
5-phase windings

Stage base:
6061 Aluminum

Hysteresis motor secondary:
D2 tool steel

Bias flux collector:
1018 low carbon steel

Back iron:
1018 Low carbon steel

FIGURE 2. Photograph of front view of the stator.

FIGURE 3. Photograph of the moving stage in the magnetically levitated linear stage.

Fig. 2 and Fig. 1 show the photograph of the front and side views of the stator, respectively. The stator assembly mainly consists of a motor stator, two yaw control stators, and a flux-biasing structure comprising two rows of PMs and one stator back-iron. The stators are fixed on the base via three angle plates. Lumped windings are selected for the stators due to volume constraints. The windings on the motor stators are 3-phase, while the windings in the yaw control stators are 5-phase. There are 11 currents independently controlled in the system, including two sets of 3-phase windings in the left and right motor stators, and one set of 5-phase windings in the yaw control stators. The current controlled switching type power amplifiers AMC B30A40 is being used to drive currents in the windings. The DC bus voltage is 300V.

Fig. 3 shows a photograph of the moving stage, which comprising an aluminum stage base, two stage back-irons, two hysteresis motor secondaries, and four bias flux collectors. The hysteresis motor secondaries are made of D2 tool steel. The D2 tool steel has relatively large magnetic hysteresis, which allows it being used for hysteresis motor secondary. It also has large permeability, which is advantageous for reluctance force generation for magnetic suspension purpose. The total mass of the stage is 4.9 kg.

Two kinds of displacement sensors are used to measure the stage’s motion in $x$, $y$, and $\theta_z$-DOFs. To measure the $x$- and $\theta_z$-directional displacements of the stage at different $y$-positions, 16 optical displacement sensors are arranged along the stator on the printed circuit boards (PCBs) mounted on the front surface of the stators. The signals from the sensors engaged with the stage are used for feedback control to stabilize the stage’s magnetic suspension. In addition, two rows of magnetic encoders are arranged along the motion direction for measuring the $y$-directional displacement of the stage. Two magnetic encoder scale are attached on the moving stage, and in each row there are 4 encoder read heads configured along the moving direction of the stage. With this sensing system design, there is no cable attached on the moving stage. Note that the magnetic encoders are not vacuum compatible. When the system is operating in vacuum, different displacement sensors are needed, for example laser interferometers.

OPERATING PRINCIPLE

Suspension Force Generation

Fig. 4 shows a cross-section diagram of the MLLS and the magnetic flux distributions in the system, and Fig. 5 shows the top view of the air gap magnetic fluxes. There are three kinds of magnetic fluxes in the system. The black lines in Fig. 4 and Fig. 5b show the PM bias magnetic fluxes, which are used to generate passive magnetic suspension force/torque in $z$, $\theta_z$, and $\theta_y$-DOFs. When the stage is displaced in these directions, the
PM fluxes in the air gaps provide restoring forces, and therefore stabilize the magnetic suspension passively. Note that the PM bias flux also generates destabilizing force/torque in x- and θ₂-directions, and feedback control is required to stabilize the magnetic suspension in these DOFs. Rotary motors with this magnetic suspension design are often referred as slice bearingless motors, and typical applications of bearingless slice motors include pumps [5], high-speed fans [6], centrifuges [7], etc. To our knowledge, our paper presents the first linear slice bearingless motor design.

The red lines in Fig. 4 and Fig. 5a represents the motor fluxes, which are generated by the windings in the motor stators. The common mode of the left and right motor fluxes is used to generate y-directional thrust force to the stage by interacting with the hysteresis motor secondaries. The differential between the left and right motor fluxes generates x-directional reluctance force, which is used to control the x-directional magnetic suspension.

The blue lines in Fig. 4 and Fig. 5b show the yaw suspension control fluxes, which are generated by the 5-phase windings in the yaw control stators. In the top and bottom air gaps, the yaw suspension control flux is distributed sinusoidally, and is synchronous to the moving stage. This flux steers the PM bias flux to generate θ₂-directional suspension torque. For example, in Fig. 5b, the yaw control flux attenuates the PM bias flux in areas b and c, while intensify the flux in areas a and d, therefore the reluctance forces in the air-gaps generates a torque about z-axis as is shown by the arrow.

**Thrust Force Generation**

The proposed MLLS uses linear hysteresis motors for the thrust force generation. When the motor windings are excited, the induced magnetization in the secondaries lags behind the external field due to the magnetic hysteresis of the secondary material, and therefore generates thrust forces. The hysteresis motor secondaries are often pre-magnetized using a large current amplitude to improve the force generation capability of the motor. In addition, reluctance thrust forces are existing in linear hysteresis motors at the edges of the motor secondaries. As a result, linear hysteresis motors’ characteristics resemble that of hysteresis-reluctance hybrid motors [8].

The linear hysteresis motor in our MLLS system operates in synchronous mode. There are two reasons for this selection. First, the reluctance force in the linear hysteresis motor is oscillatory when the motor is asynchronous, which introduces undesirable vibration to the system. Second, synchronous operation of the motor eliminates secondary hysteresis and eddy current losses. This is highly desirable for the reticle transportation system because cooling the moving stage is extremely challenging since the stage is in vacuum.

![Block diagram of the control system for the magnetically levitated linear stage.](image)

*FIGURE 6. Block diagram of the control system for the magnetically levitated linear stage.*

![Thrust force and phase angle relationships in hysteresis-reluctance hybrid motors.](image)

*FIGURE 7. Thrust force and phase angle relationships in hysteresis-reluctance hybrid motors.*
TABLE 1. Magnetic levitation stiffnesses and resonance frequencies in the passive levitated DOFs

<table>
<thead>
<tr>
<th>DOF</th>
<th>Resonance Frequency</th>
<th>Passive Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>z (Vertical)</td>
<td>11 Hz</td>
<td>37 N/mm</td>
</tr>
<tr>
<td>θz (Pitch)</td>
<td>9 Hz</td>
<td>54 Nm/rad</td>
</tr>
<tr>
<td>θy (Roll)</td>
<td>9 Hz</td>
<td>163 Nm/rad</td>
</tr>
</tbody>
</table>

Fig. 7 shows the thrust force and phase relationship of linear hysteresis-reluctance hybrid motor in synchronous operation. Here, the horizontal axis shows the phase difference between the stator excitations and the position of the stage. It can be seen that the hysteresis thrust force demonstrates its maximum values at phase angle of ±π/2. With the reluctance thrust force added, the peak of the total thrust force shifts toward the center.

CONTROL DESIGN

Fig. 6 shows a block diagram of the control system for the magnetically levitated linear stage. The x- and θz-directional displacements of the moving stage are estimated from the encoder and air-gap sensor measurements, and are feedback for suspension control. The x-DOF magnetic suspension control signal $u_x$ is the differential magnitude of the left and right motor current amplitudes, and a bias current $I_{bias}$ added to the motor stator currents for thrust force generation and maintaining magnetic suspension. The θz-DOF suspension control effort signal is used to determine the yaw control stator current amplitude. The two stators operates in synchronous mode. The position control loop for the linear stage is closed with the encoder signals being used for feedback, and the control effort signal is used to determine the phase between the motor stator excitation and the position of the linear stage. The signals from the D/A converters of the real-time controllers are send to power amplifiers as current commands.

EXPERIMENTS

Suspension Tests

Table 1 shows the magnetic suspension stiffness in the passive levitated DOFs, which is estimated through measuring the natural frequency of these modes when the stage is levitated. The stage sags below the equilibrium position in the vertical direction by 1.45 mm due to its weight.

Fig. 8 shows the measured plant and loop frequency responses of the x- and Rz-directional magnetic suspension of the moving stage under a bias current of 2.5 A. In the plant frequency responses, the magnitude curves show a notch and peak around 9 Hz, which corresponds to a pair of complex zeros and poles in the x- and θz-directional magnetic levitation plants. To our understand-

**FIGURE 8.** Measured plant and loop Bode plots of the x- and θz-directional magnetic suspension systems.

**Linear Motor Tests**

The thrust force and phase relationship for the linear stage is measured under different bias current amplitudes, as shown in Fig. 9. In this measurement, the stage is levitated, and the motor secondaries are pre-magnetized with a zero air-gap and 5A current amplitude. It can be seen that the phase angles of the peak thrust force are between ±π/4 and ±π/2. This is a result of the combination of hysteresis force and reluctance force. The maximum thrust force that the stage has demonstrated is 3.2 N under 3A bias current amplitude, which corresponds to an acceleration of 650 mm/s².

We conducted initial test for the closed-loop position control of linear stage using the method shown in Fig. 6.
ACKNOWLEDGEMENT
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REFERENCES

FIGURE 9. Measured thrust force and phase relationship of linear stage under different bias current amplitudes.

FIGURE 10. Measured position step response of the MLLS.

Fig. 10 shows the measured position step response. Data show that the bandwidth of the position control loop is about 5 Hz. It can be observed that there is a 9 Hz oscillation in the steady-state position signal. This is due to the $\theta_x$-directional (pitch) mode is coupled to the $y$-directional position control loop. We expect that this oscillatory signal in position can be eliminated if the crossover frequency of the position control loop is above the pitch mode natural frequency. This test shows the availability for the position control for linear hysteresis motors.

CONCLUSIONS AND FUTURE WORK
This work presents a MLLS driven by linear hysteresis motors. Passive magnetic suspension is utilized to reduce actuators and sensors. The prototype system can magnetically levitate the stage and drive its linear motion with a maximum acceleration of 650 mm/s².

In the position control tests for the linear stage, we have demonstrated the feasibility of the linear position control, however the bandwidth of the control is relatively low in the presented tests. We are currently working on improving the position control bandwidth of the linear stage. We also plan to test different motor secondary materials with larger magnetic hysteresis to improve the motor’s thrust force capability.