ABSTRACT
MAPS is a low cost six degree of freedom precision positioning system with interchangeable modules designed and built for next generation lithography techniques such as Nano-scale Imprint Lithography (NIL) and Plasmonic Imaging Lithography (PIL). MAPS will also be capable of performing surface topography measurements by using an interchangeable Atomic Force Microscopy (AFM) module. The design of MAPS is discussed by Fesperman and Ozturk [1-3]. The moving platform of the stage (Platen) glides on a vacuum preloaded air bearing and translates laterally. Mechanical damping for the platen is obtained by four copper plates that are attached to the platen moving in a magnetic field causing eddy currents on the plates to create forces opposing to the motion. The displacement measurement of the platen is obtained by using double-pass heterodyne interferometers. Since laser displacement measurement interferometry is a relative measurement, optical density gradient scales are used as homing sensors for absolute positioning sensing. In this paper the eddy current dampers and the optical homing sensors of the MAPS will be discussed.

INTRODUCTION
Precision position stages require non-contact actuators and guideways in order to obtain higher accuracy and resolution. MAPS utilizes four Halbach linear motors to provide motion to the platen which glides on a vacuum preloaded air bearing in the lateral directions. Mechanical dampers are required to increase the performance of the system. A non-contact type damper is designed for MAPS by using the eddy current theory. Eddy currents are generated in a conductor by a moving or changing magnetic field, or by moving the conductor in a stationary magnetic field. Eddy currents are generated in the direction to oppose the effect of the magnetic field. Eddy currents have many applications areas such as generating electricity from movement, microphones, non-destructive testing, displacement sensors and mechanical braking. Mechanical dampers can be designed by using the eddy currents. Mechanical damping is always helpful to obtain better performance in precision positioning systems. There are several techniques to add damping to a system but eddy current damping was selected since it is non-contact and relatively clean. Double-pass heterodyne interferometers with 0.15nm resolution are used to measure displacements of the platen along both x- and y-axes. Two interferometers are used for measuring displacements along the x-axis and rotations about the z-axis (yaw) and one interferometer is used for measuring displacements along y-axis. However, the displacement laser interferometer system can only provide relative feedback. Homing sensors are required to start and return the machine to its nominal position. Once the machine is returned to its home position, the reference coordinate system can be defined and all the axes can be reset to “0”. This is important for phasing of the linear motors and for error mapping the machine. MAPS uses a unique method of determining the absolute position of the platen in X, Y and theta that also provides proportional position sensing adequate for servo use.

EDDY CURRENT DAMPING
MAPS utilizes four eddy current dampers located 90 degrees apart from each other at each corner of the stationary base structure. Three L-brackets are used to locate the dampers and Belleville spring washers are used to adjust the tilt and therefore the gap between the copper plates and the magnets. The magnet yoke is composed of a top plate, a bottom plate and a spacer. This made the assembly much easier than using a single monolithic yoke. The yoke components are made of mild steel (c1018). Totally eight magnets are used in one damper where four are attached to the bottom plate and the other four to the top plate (FIGURE 1).
Neodymium Iron Boron (NdFeB) magnets with flux density (Br) of 1.3 Tesla are used. Each magnet has the opposite polarization next to itself. Therefore magnetic flux is concentrated mostly in between the magnets (FIGURE 2) preventing the yoke being saturated and the generation of stray field around the damper. The stray fields can interfere with the magnetic field of the Halbach magnets arrays and can cause problems [4]. Although Br is specified as 1.3 Tesla for each individual magnet, the flux density between the magnets is expected to be different and was measured to be 0.95 Tesla [5]. Oxygen-free high conductivity copper plates are used as the conductive plates. Each copper plate is about 76 mm x 110 mm and has thickness of 3.5 mm. Four plates are attached to the platen 90 degrees apart from each other.

When copper plates move in the stationery magnetic field between the magnets, eddy currents are induced in the copper. The induced currents on the conductor plate create Lorentz forces impeding the motion. The formulations to calculate the damping coefficient and therefore the force are explained by Bae et al. [6] in detail.

The damping coefficient for each damper can be calculated by using the formula

$$C_s = \sigma B^2 A(\alpha_1 + \alpha_2)$$

where $\alpha_1$ and $\alpha_2$ are plate geometry related constants. The damping coefficient is calculated to be 216.4 per damper and 856.6 total. The total opposing force to the motion can be calculated with the formula

$$F = 856.6V$$

where $F$ is in newtons and $V$ is the copper plates speed in m/s.

The force prediction of the eddy current damper is compared with the actual measurement taken on the Moore Tool measuring machine (model no: 35-11-B03-2500-6350G). The results are as shown in the following table.
### TABLE 1. Eddy current damper test results

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>Predicted Force (N)</th>
<th>Measured Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00072</td>
<td>0.157</td>
<td>0.150</td>
</tr>
<tr>
<td>0.00036</td>
<td>0.078</td>
<td>0.070</td>
</tr>
</tbody>
</table>

### FIGURE 4. Eddy Current Damper and Homing sensor locations

**HOMING**

Three homing sensors are used in MAPS to home the stage in X, Y and θz. Two of the sensors are positioned across from each other along the x axis for the rotation about the z axis and the 3rd one is positioned along the y axis. The main elements of the sensors are optical elements with variably optical density. These elements are mounted on the platen on top of the Halbach magnet arrays. A special holder is designed to hold each sensor.

The optical density gradient scales are printed on a 5 mm by 12 mm clear Mylar by a commercial typesetter service. The scales are modeled using Autocad’s shading tool. The scale is most transparent in the middle and most opaque at the outer edges along the length as seen in Figure 5.

Each homing sensor is composed of a scale and a pair of optical interrupters similar to the ones used in CDROM drives to detect the presence of a CD. The optical interrupters are spaced 6 mm apart and one half of the gradient passes through each interrupter. When the stage moves in one direction, one of the optical interrupters sees through the more transparent portion of the gradient while the other optical interrupter sees the more opaque portion of the gradient.

### FIGURE 5. Optical density gradient scale

### FIGURE 6. Homing Sensor

The IR phototransistor sections of the two optical interrupters are connected to a differential amplifier whose output voltage is a function of the light passing through the scale and thus the platen position. This voltage output is scaled for an output voltage of -10 volts DC for -5mm and +10 volts DC for +5mm. The midpoint output is 0 Volts.

The optical density gradient scales are mounted to the platen in such a way that during normal operation the X axis optical interrupters do not register motion in the Y direction and the Y axis optical interrupter does not register motion in the X direction.

The first step in the homing procedure is to rotate the platen so as to measure the same voltage from the two X axis optical interrupters. The second step is to move the stage in the Y direction until the output of the Y axis optical interrupter is 0 volts. The third step is to move the platen in the X direction until the X axis
optical interrupters output 0 volts. This puts the platen in home position for both X and Y axis as well as a $\theta_0$ of 0.

The performance of the homing sensors is measured by using the double-pass laser interferometers. The controller (using the lasers as the feedback sensors) of the system is turned on and the stage is commanded to go to the predefined home position (Position 1). Then the stage is commanded to travel to the numbered locations (2, 3, 4, and 5) shown in figure 7 respectively by returning back to the home position (Position 1) after each move.

![Homing Sensor Test Path](image)

**FIGURE 7. Homing Sensor Test Path**

The results show that the homing sensors have ranges of $\pm 4 \mu m$ repeatability in both X and Y axes. However the short term (10 minutes) drift of the stage due to the temperature variations in the lab is measured to be $\pm 6 \mu m$.

![Homing Sensor Repeatability](image)

**FIGURE 8. Homing Sensor Repeatability**

**CONCLUSION**

The eddy current dampers provided the expected damping forces. They were designed to be simple and cheap. However some modifications could be done if they are to be designed again. Instead of using rectangular magnets, circular magnets could be used to reduce the edge effects. Since it is hard to find off the shelf circular magnets, the rectangular magnets were cheaper.

A special kind of homing sensors was designed and tested. The homing sensors are good enough to phase the linear motors and provide location for software correction. The gradation quality could be improved by using different techniques. Also a more robust and stable mounting technique could also be applied.

**ACKNOWLEDGEMENTS**

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**REFERENCES**

[4] Private communication with Dr. David L. Trumper