Active Magnetic Bearing
Controls Strategy and Calibrations

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INTRODUCTION

Guide-ways in positioning systems (stages) for semiconductor applications are often realized by air bearings and roller bearings. For X-Y stages, a so-called H-bridge design is often utilized (see *FIGURE 1*): an X-stage-module stacked on top of a Y-stage-module. Although these bearing systems are passive, and therefore seemingly rather cost-effective compared to active systems, the motion performance is limited. Moreover, active bearing systems have the advantage that additional motion degrees of freedom are automatically obtained

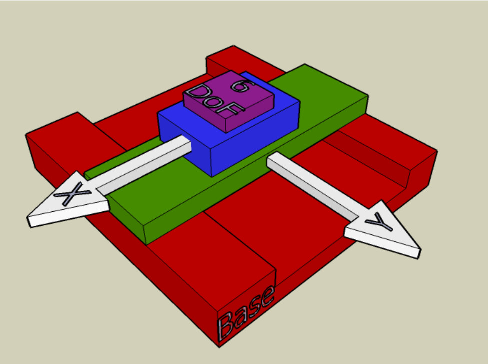

FIGURE 1. Standard High Precision Stage. The X- and Y-modules form the long stroke X-Y stage. The top module is a 6 DoF short stroke module. This article describes the integration of the 6-DoF module with the X-module.

Until now, nm-level motion performance in 6 degrees of freedom (DoF) has been realized only through the application of a hybrid stage concept, i.e. by stacking an active 6-DoF short stroke stage-module providing fine adjustments (e.g. horizontal and vertical) on top of a passive long stroke X-Y stage-system, as depicted by the top module in *FIGURE 1* (see also [1]).

In our work we successfully integrated the X-module and 6-DoF-module functions by using Active Magnetic Bearing (AMB) technology. The result is a full 6 DoF active positioning system with nm-level motion performance in one single module. It allows for a much simpler stage design that can be reproduced at low cost, suitable for next generation semiconductor applications.

Motivation

Applying AMB technology combining long stroke and 6-DoF functions in one single module yields significant advantages, compared to stages with conventional passive bearings, as is highlighted in [2], [3].Specific advantages are:

- Full 6-DoF motion capability (eliminating the need for stacking modules)
- Ultra-low contamination (no contact, no lubrication, enabling vacuum applications)
- Infinite static stiffness, enabled by the active position feedback control-loop.
- Applicability in machine architectures with isolated metrology frames, enabled by force-type actuators.

Contents

This article concentrates on the basic design of an Active Magnetic Bearing stage. After describing the basic building blocks, and the controller schematics, three examples of calibrations are presented:

- AMB non linearity compensation;
- Linear Motor Gain Calibration and the
- Static Force Compensation.

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BASIC DESIGN

Philips Applied Technologies has designed and built several motion platforms utilizing AMBs. This section describes some of the building principles of a one-long-stroke, 6-DoF stage.

Active Magnetic Bearing Element

Basically, an AMB can be comprised of an E-shaped piece of SiFe transformer laminations, equipped with a coil around the center leg (see *FIGURE 2*). In order to compensate for gravity, and to ensure a more linear operating behavior, a permanent magnet is added to the center leg. A typical magnet would be 1 mm thick NdFeB with a residual flux density of 1.4 Tesla. A counter material, called 'the bridge', is placed opposite to the AMB legs. The total flux generated by permanent magnet and coil generates an attracting force between the AMB legs and the bridge. The current through the coils is used to control this force and, as a result, the position of the stage.

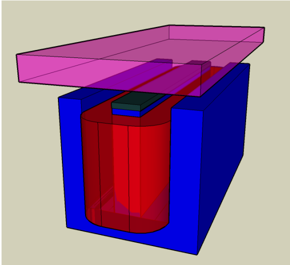

FIGURE 2. AMB element.

Stage Actuators

A theoretical minimum of 6 actuators is required in order to actively move a stage in 6 degrees of freedom (DoF). For reasons of symmetry, guided by design principles and additional requirements a combination of 6 AMBs and 2 linear motors was used to build a 6 DoF stage; a total of 8 motors, enabling actuation of one long- and 5 short-stroke movements.

The long stroke X-axis is guided (that is: stage movements are constrained) in vertical direction (Z, Rx and Ry) by four vertical AMBs (see *FIGURE 3*). Simultaneously, these AMBs are used as short stroke actuators in Z, Rx and Ry directions, enabling stage excursions up to 1 mm and 1 mrad. As mentioned before, AMBs are equipped with permanent magnets, each compensating 25% of the stage mass. As a result, the coils only need to offset the magnet force when moving away from the nominal position, resulting in a very energy efficient floating mechanism.

For movements in horizontal Y direction, the stage is equipped with two opposing AMBs, allowing for up to 1 mm stroke.

Finally, two standard off-the-shelf brushless linear motors are used as X- and Rz-axis actuators, one on each side of the stage.

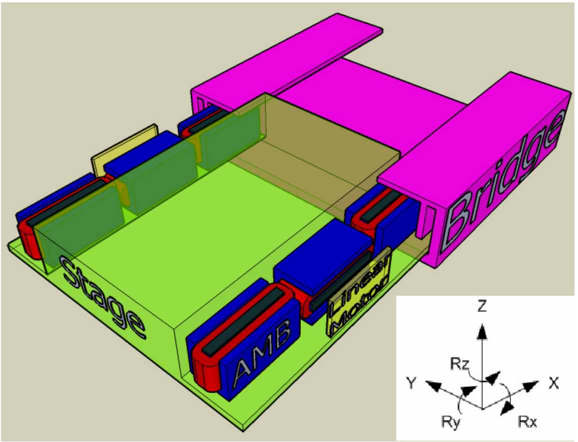

FIGURE 3. AMB Stage. The AMBs and the Linear Motor Coils are connected to the 'Stage'. The stationary part serves as the 'bridge' and holds the linear motor magnets.

Position Sensors

To measure the stage position, a combination of 8 displacement sensors is used: 6 short-stroke probes, and two encoders. The probes measure the stage's Z, Rx, Ry and Y location; the linear encoders measure the X long stroke position and the Rz orientation of the stage. The signals of these sensors are fused to calculate the 6 DoF stage position (also called the 'logical position'). A 6 DoF Laser Interferometer (IFM) measurement system is installed in addition to above mentioned sensors to achieve the accuracies required for semiconductor applications.

Imprint Lithography Prototype

As part of the US Navy and SPAWAR project "NanoImprint lithography at Manufacturing Scale" (NIMS, contract#: N66001-06-C-2003) a prototype AMB high precision stage has been designed and built for an Imprint Lithography application (see [4] and *FIGURE 4*).

In this application, the substrate on the stage is positioned underneath and moved up against a template (not shown). The negative image of the template features is transferred onto the substrate. Some of the design characteristics of the stage are: 30 kg moving mass; 0.4 m X-range; 1 m/s max velocity and 2.5 m/s^2 acc.

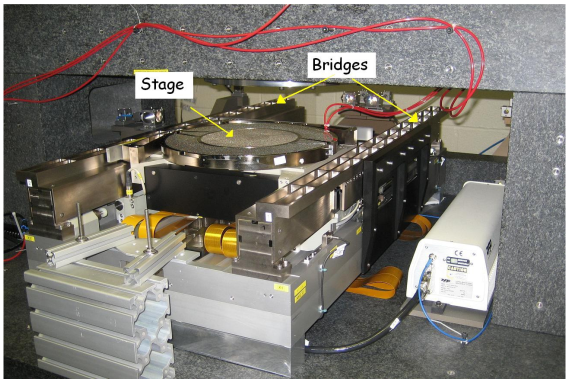

FIGURE 4. Prototype Imprint Lithography stage.

Slow stictionless move

In today's leading edge lithography applications, the ratio between the wafer size (300 mm) and smallest feature size (50 nm) is significant; it is therefore important to combine the ability of high velocities and accurate positioning. To demonstrate the absence of stiction and friction (which often prohibit accurate positioning) a 0.5 nm/s move in X-direction was performed (see *FIGURE 5* and [5]). With a maximum velocity of 1 m/s, this design supports an impressive dynamic range for the velocity of over 9 orders.

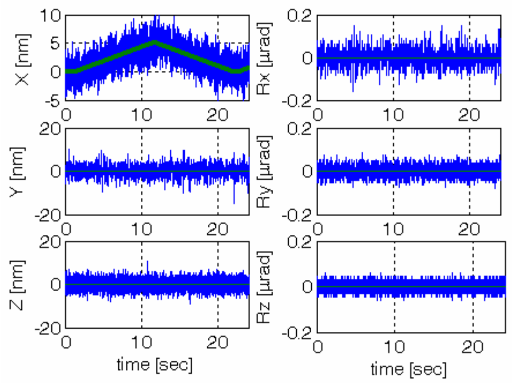

FIGURE 5. 6-DOF stage position, during 0.5 nm/s move (b-) with setpoint (g-). Notice the absence of cross talk from X to the other axes.

Summary

In this section the basic building blocks and architecture of an AMB stage are described.

Four Z-AMBs enable movement and guidance in Z, Rx, Ry, and two Y-AMBs move and guide the stage in the Y direction. The X- and Rz-directions are actuated by the two linear motors.

Six inductive probes and two encoders measure the location and orientation of the stage, which is calculated in the controller. An Interferometer system can be installed for increased accuracy.

CONTROLLER SCHEMATICS

This section describes some aspects of the controller implementation. First a short description of the controller hardware is presented. Then, the sensor- and actuator transformations and the AMB non linearity compensation methodology are discussed.

Controller Hardware

The servo controller is implemented on proprietary controller hardware and software developed at Philips Applied Technologies.

The controller schematics are designed and implemented in Simulink, and the C-code, generated using MathWorks' Real Time Workshop is downloaded and executed on an industrial PC running VxWorks. Commercially available IO-cards (some with application specific firmware) are used to interface with sensors and actuators. This platform is capable of controlling multiple axes, allowing for a stacked X-Y stage configuration. The flexibility of Simulink allows for complex interactions between individual axes, such as cross axes Feed Forward, and the implementation of sensor fusion and actuator non-linearity compensation. The complete controller design, comprising of approximately 150 filter orders and several 100s of parameters, offers the capability of tracing 15 parallel signals at sampling frequency and executes at a rate of up to 5 kHz.

A higher level software layer governs the start-up-and shut-down procedures, setpoint generation and measurement system switching.

Sensor Transformation

In many multi-DoF industrial control solutions, kinematics relations are used to decouple the motion system into rigid body modes to facilitate decoupled controller design (see "Sensor Transform." block in *FIGURE 6*). This decoupling transforms sensor readings into logical positions and orientations (X, Y, Z, Rx, Ry and Rz) by means of the Sensor Transformation. For an optimal decoupling, this logical position represents the location and orientation of the Center of Gravity (CoG) of the stage.

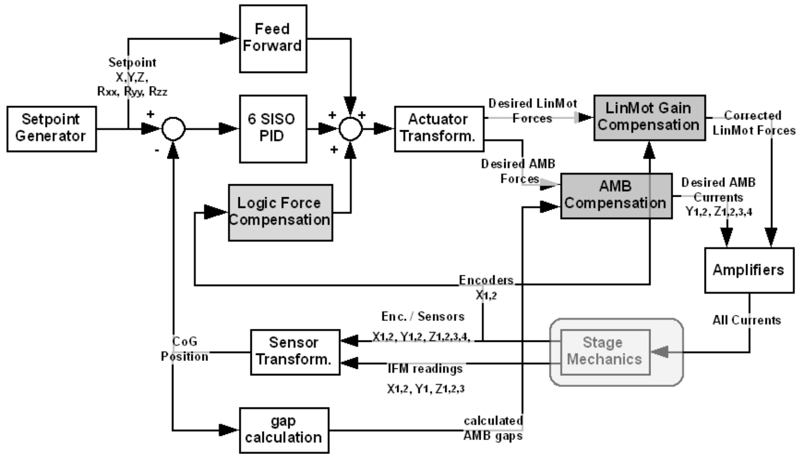

FIGURE 6. Basic control scheme: PID feedback and feed-forward with setpoint generator, geometric decoupling matrices and actuator linearization algorithm.

Actuator Transformation

On the controller's actuator side, controller forces and torques are distributed over 8 available actuators, by means of an Actuator Transformation. The Actuator Transformation (AT) is basically the (pseudo) inverse of the relation between the set of actuator forces and their resulting logical Forces and Torques:

$\vec{M} = AT^{-1} \cdot \vec{F}$ where:

- $\vec{M}$ is a vector containing the logical Forces and Torques: $\begin{bmatrix} F_x & F_y & F_z & T_x & T_y & T_z \end{bmatrix}^T$
- AT represents the Actuator Transformation
- $\vec{F}$ is a vector with individual actuator forces: $\begin{bmatrix} F_{X1} & F_{X2} & F_Y & F_{Z1} & F_{Z2} & F_{Z3} & F_{Z4} \end{bmatrix}^T$

AT^{-1} is constructed using the actuators-orientations and -positions relative to the CoG.

AMB Non linearity Compensation

Since the AMBs are reluctance actuators, the *Current-Force* relationship is non-linear, and inversely related to the *Gap* between AMB and counter material. In some AMB applications (for example AMB systems that operate at a fixed position, like rotary applications) this non-linear relationship is dealt with by introducing sufficient controller robustness. The instability introduced by the non-linearity of the AMBs is stabilized by the controller, which is acceptable at bandwidths of more than a few 100 Hz.

When a relatively large range of motion is desired ($> 400\ \mu\text{m}$), the non-linearity of the AMBs is thought to be too large (in combination with relatively low 50 Hz bandwidth), to be compensated for by the controller. Therefore, in the presented application, in order to achieve the highest possible performance, the AMB's non linearity is compensated by means of parametric functions calculating the required *Current* based on desired *Force* and a calculated air-*Gap* for each individual AMB. The *Force-Current-Gap* relationship is obtained through linear regression using an e.g. 5-parameter polynomial function and a data set obtained through off-line actuator identification (see [6] for more details).

Summary

In this section the controller hardware was presented. Further, the Coordinate Transformation, Actuator Transformations and AMB's Nonlinearity Compensation were described.

CALIBRATIONS

This section describes some of the calibrations methods that were developed and implemented in order to optimize the stage's servo performance of stage. The calibrations relate to the controller components that are indicated by the dark grey blocks in *FIGURE 6*. First an in-situ identification of the AMB characteristics is presented, where a sinusoidal disturbance is injected while the AMBs response is measured. Secondly, a similar identification of the Linear Motor Gain is described. Finally, the static force correction is described, revealing the AMB's magnetic hysteresis.

AMB Calibration

The off-line measured *Force-Current-Gap* relationship is an approximation of the real AMB's behavior in the stage. Factors like mounting errors and amplifier gain variations will contribute to a discrepancy between model and actual relationship. Especially for applications where an exact knowledge of the stage-forces interacting with the process-forces is important (for example in the Imprint Lithography application this stage was designed for) having a proper AMB model is beneficial. In order to improve the static model of the actual AMB characteristics, an in-situ calibration is executed.

In order to find the real force, generated by each of the AMB's at any given location for any given current, a calibration is implemented where a sinusoidal disturbance is injected in the servo loop. The forced stage movements and motor currents are used to identify the AMB model. With the real current and the real position known (through separate calibrations of the amplifiers and the measurement system), the only unknown is the real force generated by the AMBs. These forces are estimated by using the stage's position and the already discussed AT .

FIGURE 7 shows the result of one AMB calibration. In this case, a 10 kg mass was added to the stage in order to perform a second measurement at a higher force level.

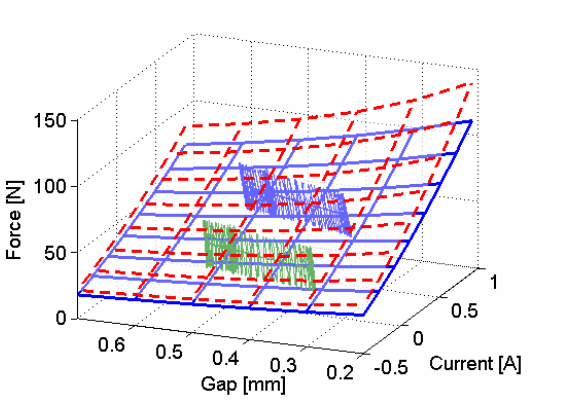

FIGURE 7. In-situ calibration results of one of the Z- AMB. Original model (dashed) and new model (solid). Note that the two data-sets are located on the (solid) plane.

One of the flaws of this calibration is that there is no guarantee that diagonally opposing AMB's are not 'fighting' each other during the acceleration and deceleration phases. This is undesirable from both a calibration and an energy dissipation viewpoint. A separate calibration could, still under floating conditions, search for a minimal RMS value of the four real AMB currents, minimizing this 'fighting' behavior.

Linear Motor Calibration

The accuracy of the acceleration feed forward has a significant impact on the settling time. In our application, a linear motor gain variation of 10 % was observed, likely caused by the non-optimal location of the linear motor coil assembly in the magnet track, and the HALL-effect sensor based commutation. This section describes the linear motor gain calibration.

The contents of the "LinMot Gain Compensation" block from *FIGURE 6* are detailed in *FIGURE 8*.

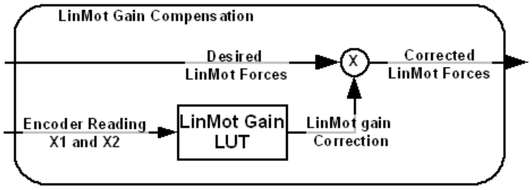

FIGURE 8. Implementation of LinMot Gain Compensation.

The goal of this calibration is to determine the linear motor gain as function of the stage position. Again, a sinusoidal disturbance is injected into the servo loop, this time forcing the stage to 'shake' in the X-direction and, due to the difference in motor gain between motor 1 and 2, also in Rz. The data is traced, analyzed and translated into lookup tables for the actuator K-factors.

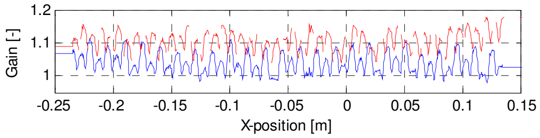

FIGURE 9. Result of LinMot Gain calibration for Linear motor 1 (solid) and 2 (dashed).

FIGURE 9 shows the results of one of these calibrations. In this case, the average real linear motor gain is slightly smaller than designed, resulting in a larger than 1 compensation gain. The spatial frequency content of the gain correction indicates that most of the gain error is present at the 4th harmonic of the 30 mm linear motor magnet pitch.

Static Forces Calibration

During slow movements in the long stroke X direction, disturbance forces from cables, cogging forces and other position dependent factors are evident from observing the controller's integrators. A fairly straightforward correction is to measure these forces and torques during a slow move back and forth covering the X-axis stroke, as a function of stage position, and adding them to the controller output. The upper plot in *FIGURE 10* shows the result of the calibration measurement (solid) and the calculated correction (dashed).

The lower plot in *FIGURE 10* shows the effectiveness of activating the generated Static Force Calibration. Most observable in this plot is the residual hysteresis force in the X-direction.

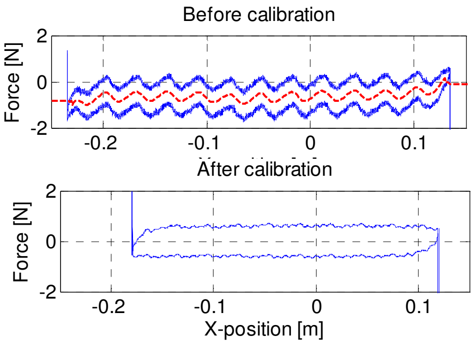

FIGURE 10. Static Force Calibration measurement (UPPER) with measurement (solid) and resulting calibration table contents (dashed), and the result after calibration (LOWER).

In Active Magnetic Bearings, hysteresis is generally observed during movements in both the direction of the magnetic force (e.g. Z and Y) and perpendicular to this magnetic force (X); and indeed both are observed in our application and influence the accuracy of force generation of AMBs.

The observed hysteresis force is approximately ± 0.6 N while moving in the X direction and ± 0.05 N during a ± 100 μm move in Z direction with a note that increasing the range of the Z-move also increases the measured hysteresis.

Summary

In this section, three examples of calibrations as applied to the Active Magnetic Bearing stage are described:

1. In-situ calibration of the AMB behavior,
2. Linear Motor Gain calibration and
3. Static Force Compensation.

From the third calibration magnetic hysteresis became evident.

CONCLUSION

In this article, a description of a high precision Active Magnetic Bearing stage is given. Using a combination of Active Magnetic Bearings and linear motors as actuators, a full 6 DoF free floating stage was designed and built.

The position feedback controller is described, including the Sensor- and Actuator-Transformation that deal. A measurement of a slow 0.5 nm/s move was shown demonstrating the frictionless design characteristic.

Several calibrations that aim to improve the overall performance in general and the accuracy of force generation in particular, are described:

- AMB non linearity compensation;
- Linear Motor Gain Calibration and the
- Static Force Compensation.

The last compensation revealed the hysteretic characteristic of Active Magnetic Bearings.

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