Active Magnetic Bearing Technology applied in High Precision Application

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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, if six degrees of motion is required, passive guide ways "do not help". 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 magenta module in Figure 1.

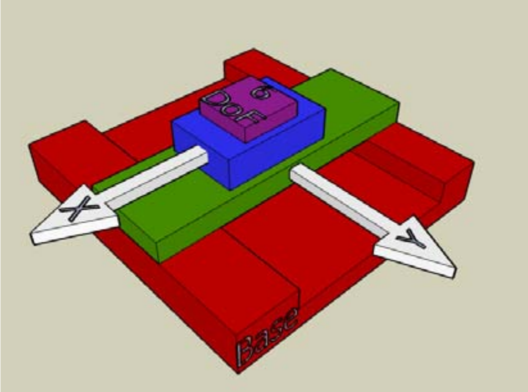

Figure 1. Standard High Precision Stage. The Y-module (green) and the X-module (blue) form the long stroke X-Y stage. The top (magenta) module is a 6 DoF short stroke module. This article describes the integration of the 6-DoF module with the X-module.

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.

Contents

This article concentrates on the basic design of such a stage and elaborates on some of its components: the basic Active Magnetic Bearing building blocks, AMB linearization and controller implementation. Finally, one example of an AMB stage is described, together with experimental results.

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 [1], [2] and summarized by the following items:

1. Full 6-DoF motion capability (eliminating the need for stacking modules)
2. Ultra-low contamination (no contact, no lubrication, enabling vacuum applications)
3. Infinite static stiffness, enabled by the active position feedback control-loop.
4. Allows for isolated machine architecture, enabled by force-type actuators, reducing the transmission of base disturbances.

Basic Design

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

Basically, an AMB can be comprised of an E-shaped piece of SiFe transformer laminations, called 'the E-core', with a coil around the middle leg (see Figure 2). In order to compensate for gravity, and simultaneously ensure a more linear operating behavior, a permanent magnet can be added to the center leg. A typical magnet would be a 1 mm thick NdFeB with a residual flux density of 1.38 T. A counter material, called 'the bridge', is placed opposite to the E-core. The total flux generated by permanent magnet and coil generates an attracting force between the E-core and the bridge. The current through the coils is used to control the force and, as a result, the position of the stage.

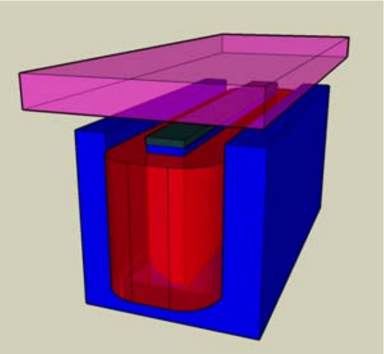

Figure 2. Basic design of Active Magnetic Bearing: E-core (blue), coil (red), magnet (black) and counter material (magenta).

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 two 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 axis is guided (that is: the stage's movements are constrained) in the vertical direction (Z, Rx and Ry) by four AMBs (see Figure 3). This comprises the long stroke X direction guide of the stage. At the same time these AMBs are used as short stroke actuators in Z, Rx and Ry directions, enabling stage excursions up to 1 mm and 0.1 mrad. As mentioned before, the AMBs are equipped with permanent magnets compensating the mass of the stage; in nominal position, each of the four Z-AMBs passively carries a quarter of the stage's mass. As a result, the coils only need to generate a DC force when moving away from the nominal vertical position. This results in a very energy efficient floating mechanism.

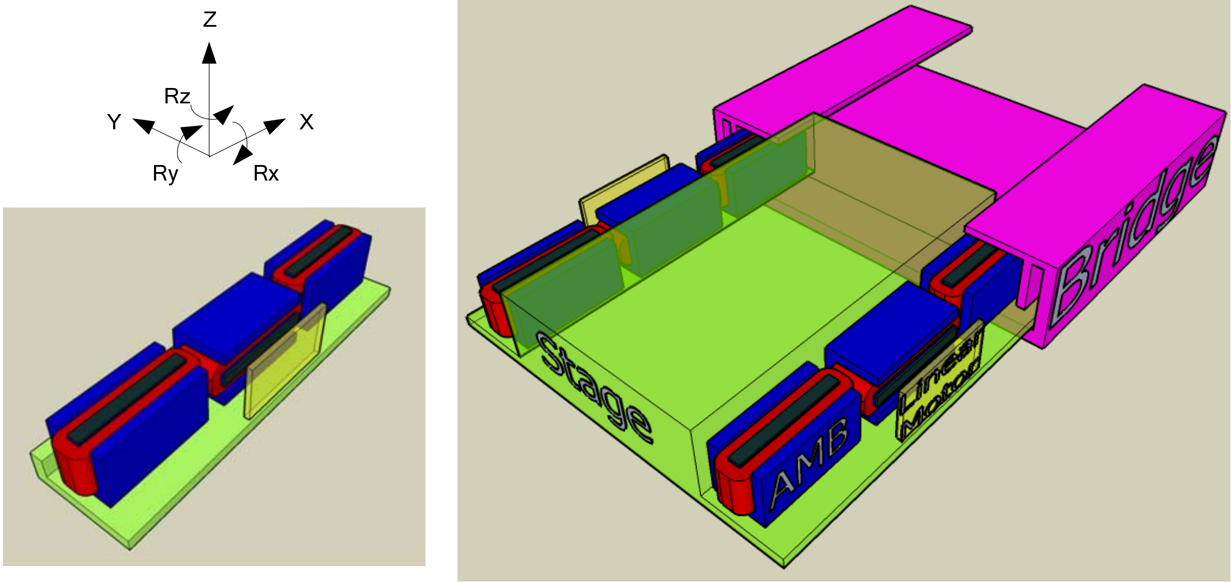

Figure 3. Basic design of AMB-Module (LEFT) and AMB High Precision Stage (RIGHT). The AMBs and the Linear Motor Coils are connected to the (green) moving part of the stage. The stationary (magenta) part of the stage serves as the counter material (bridge). This also contains magnets for the linear motor.

For movements in horizontal Y direction, the stage is equipped with two opposing AMBs, allowing for up to 1 mm stroke. The preload magnets, also used in this direction, allow for the actuators to operate in a more linear range.

Finally, two standard off-the-shelf brushless AC linear motors are used to actuate the X-axis, one on each side of the stage. These motors also actuate the Rz direction.

To measure the stage position, a combination of 8 displacement sensors is used: 6 short-stroke (inductive) probes, and two long-stroke (encoders) sensors. 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 and the 6 DoF stage position (also called the 'logical position') is calculated in the controller (see below). For semiconductor applications oftentimes a higher accuracy is required; in such cases an additional 6 DoF Laser Interferometer (IFM) measurement system can be installed in addition to above mentioned sensors. The controller will than be equipped with the ability to switch back and forth between both measurement systems as a reference for position control.

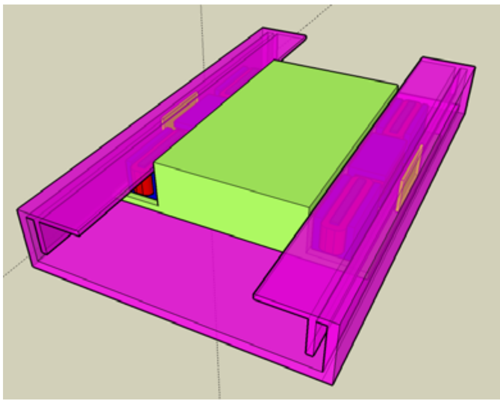

Figure 4. Image of stage fully inserted in stationary bridge.

In summary, four Z AMBs enable movement and guidance in Z, Rx, Ry, and two Y AMBs move and guide the stage in the Y direction. Together, these 6 actuators allow the stage to move freely in the X-and the Rz-directions, which 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.

Control Scheme

In many multi-DoF industrial control solutions, kinematics relations are used to decouple the motion system into rigid body modes to facilitate a decoupled controller design (6 SISO PID, see Figure 5). This decoupling is carried out by Sensor Transformations, calculating 6 decoupled or logical positions (X, Y, Z, Rz, Ry and Rz) from above mentioned set of sensors (see 'sensor transform' block). The result is the position and orientation of the Center of Gravity (CoG) of the stage.

A position error is now calculated by comparing logical positions to a desired setpoint. Based on this error, controllers calculate the desired forces and torques for each logical axis. Because the position errors are decoupled, 6 SISO controllers can be applied, each controlling one DoF. The advantage of applying a decoupled design is that each logical direction can be dealt with as individual (SISO) control loops. For example, an X-force, exactly through the CoG of a mass will not introduce a movement

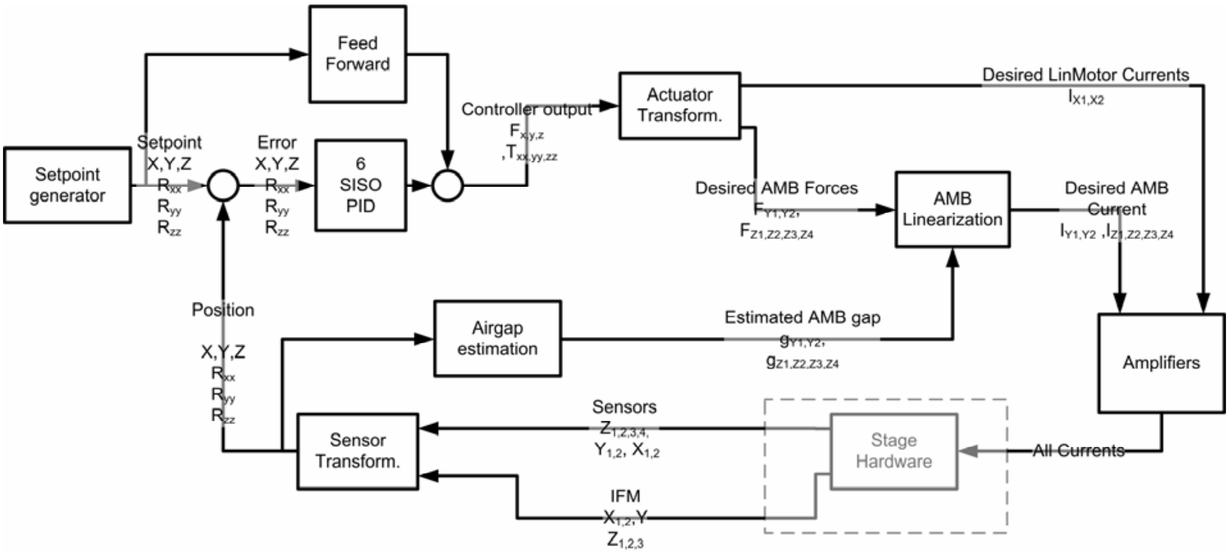

Figure 5. Basic control scheme: PID feedback and feed-forward with setpoint generator, geometric decoupling matrices and actuator linearization algorithm including air gap estimation.

other than in X-direction.

On the actuator side of the controller implementation, forces and torques, calculated by the controllers are distributed over 8 available actuators, by means of the Actuator Transformation.
For linear motors this is fairly straight forward; each linear motor generates half of the X force, and an additional, opposing force resulting in an Rz torque. Each of the Y-AMBs receives half of the Y-force, and the Z-force, and the Rx- and Ry-torques are distributed over the four Z-AMBs.

Since the AMBs are reluctance actuators, the *Current-Force* relationship is non-linear, and heavily dependent on the *Gap* between the AMB and the counter material. In some AMB applications (for example AMB systems that operate at very small range of motion, like rotary applications) this non-linear relationship is dealt with by sacrificing part of the controller's performance. The disturbances introduced by the non-linearity of the AMBs are suppressed by the controller. When a relatively large range of motion is desired (> 400 μm), the non-linearity of the AMBs is thought to be too large to be compensated for by the controller (read: disturbance rejection is not large enough). Therefore, in our application, in order to achieve the highest possible performance, AMB's are modeled by means of parametric functions that calculate the required *Current* based on desired *Force* and an estimated air-*Gap* for each individual AMB. In the presented application, the *Current-Force-Gap* relationship is a 5-parameter static-model, fitted on a data set obtained through off-line actuator identification (see [4] for more details). The *Gap* is estimated based on the logical position of the stage and the location of the AMBs.

Application

A prototype AMB high precision stage has been designed and built for an Imprint Lithography application (see [3] and Figure 6). In this application, the substrate on the stage is positioned underneath and moved up against a template. The negative image of the template features is transferred onto the substrate. Some of the design characteristics are:

- moving mass: 30 [kg]
- X-range: 0.4 [m]
- max. velocity: 1 [m/s]
- acceleration: 2.5 [m/s^2]

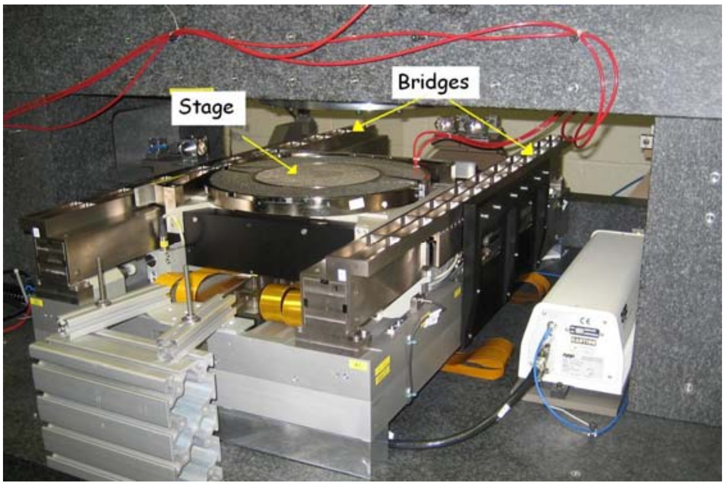

Figure 6. Prototype Imprint Lithography AMB High Precision stage.

Measurements

The stage as displayed above is equipped with an additional laser interferometer system. To demonstrate the servo performance at standstill, a 10 second measurement trace is displayed showing tracking errors smaller than 10 and 150 nrad (see Figure 7).

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 accurate positioning and high velocities. To demonstrate the absence of stiction and friction (which often prohibit accurate positioning) a slow move in X-direction was performed at 0.5 nm/sec. No stiction or cross coupling to the other directions is visible. With a maximum velocity of 1 m/s, this design supports an impressive dynamic range for the velocity of over 9 orders.

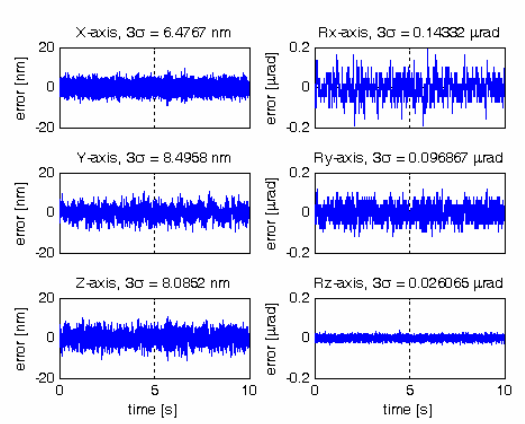

Figure 7. Sub 10 nm-level stand still performance (servo-error) with Laser IFM system.

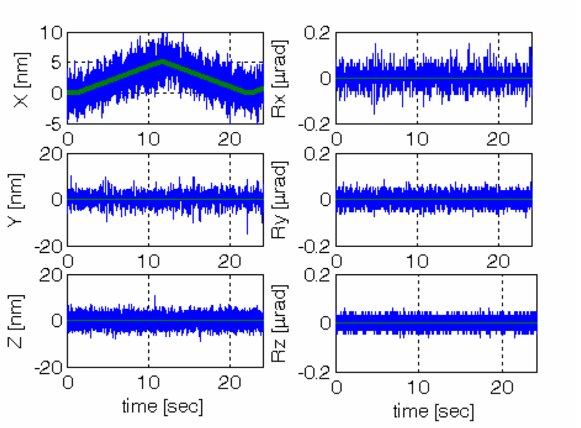

Figure 8. Position error during 0.5 nm/s move (b-) with setpoint (g-).

Conclusion

A description of a high precision Active Magnetic Bearing stage is given. Using a combination of AMBs and linear motors, a full 6 DoF free floating stage was designed and built. The position feedback controller is described, explaining the advantage of decoupling the servo system into 6 independent control-loops and the AMB linearization method.

Measurements are presented showing sub-10 nm servo performance at stand still and the absence of mechanical friction and stiction.

[1] A.T.A. Peijnenburg et. al., *in Proceedings of the 31st International Conference on Micro- and Nano-Engineering, Vienna, Austria*, 205, pp 1372-1375

[2] A.C.P. de Klerk, et al. *Design of a next generation 6DoF stage for scanning applications in vacuum with nanometer accuracy and mGauss magnetic stray field*, Proc. of the 19th ASPE Annual Meeting, Orlando, Florida, October 24-29, pp 60-63

[3] J.P.M. Vermeulen, et al. *'Active magnetic bearing technology suitable for nanoimprint lithography applications*, Proc. of the Nanoimprint and Nanoprint Technology 2006 (NNT2006) in San Francisco, CA, November 15-17, 2006

[4] M.L.Norg, *et al. Active Magnetic Bearing Technology applied in High Precision Application.* 2007 Magnetics Conference, April 3-5 2007, Chicago, IL, USA

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