Precision Magnetic Bearing Six Degree of Freedom Stage

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SUMMARY

Magnetic bearings are capable of applying force and torque to a suspended object without rigidly constraining any degrees of freedom. Additionally, the resolution of magnetic bearings is limited only by sensors and control, and not by the finish of a bearing surface. For these reasons, magnetic bearings appear to be ideal for precision wafer positioning in lithography systems. To demonstrate this capability a linear magnetic bearing has been constructed which uses variable reluctance actuators to control the motion of a 14.5 kg suspended platen in five degrees of freedom. A Lorentz type linear motor of our own design and construction is used to provide motion and position control in the sixth degree of freedom. The stage performance results verify that the positioning requirements of photolithography can be met with a system of this type. This paper describes the design, control, and performance of the linear magnetic bearing.

INTRODUCTION

Lithography steppers currently produced use a combination of mechanical stages to achieve control of the wafer location in six degrees of freedom. In these stages, the wafer is carried on a fine stage which provides six degree of freedom control with approximately 100 μm travel. This fine stage is then mounted on a coarse mechanical stage which provides X-Y positioning with approximately 200 mm travel. The fine stage is typically comprised of multiple piezo-actuators and or voice coil drives which are used to position a platen mounted on flexures. These mechanical stages generally suffer from poor dynamics, a result of the compound flexures used. This method of X-Y positioning can become very complicated and could be approaching its maximum speed and resolution capabilities. In comparison magnetic bearings can provide speed and simultaneous control of six degrees of freedom with a single moving element. This eliminates the complicated flexures and mechanical actuators used in the current mechanical designs. Additionally, magnetic bearings have no mechanical contact. This makes them ideal for clean room use where particle generation from mechanical friction is a major source of contamination.

STAGE DESCRIPTION

A six degree of freedom magnetically suspended X-Y stage has been constructed which uses variable reluctance actuators to control the motion of a 14.5 kg platen in five degrees of freedom (three rotational and two translational) and a unique permanent magnet Lorentz type linear motor to control motion in the sixth degree of freedom. For fine focusing the stage can provide 400 μm of travel normal to the wafer surface and milliradian rotations around three axes. The linear motor has 200 mm of X travel and consists of a permanent magnet Halbach array attached to the underside of the platen and a planar, ironless, six phase stator fixed in the machine frame [2]. A conventional mechanical linear slide will be used to provide 200 mm of travel in the other major axes (Y). This design increases power efficiency and yields increased performance by capitalizing on the typical operation of a lithography X-Y stage. Typical operation of a stage is to step in the X direction 10 - 20 times along a row of die sites, before a single step is made in the Y direction to the next row of die sites. Since the stage operation is dominated by X positioning, this mechanical-magnetic bearing stage design results in a simple magnetic bearing structure while simultaneously increasing the stage precision and throughput. The stage is sized to accommodate an eight inch wafer and platen dimensions are 25 cm x 20 cm.

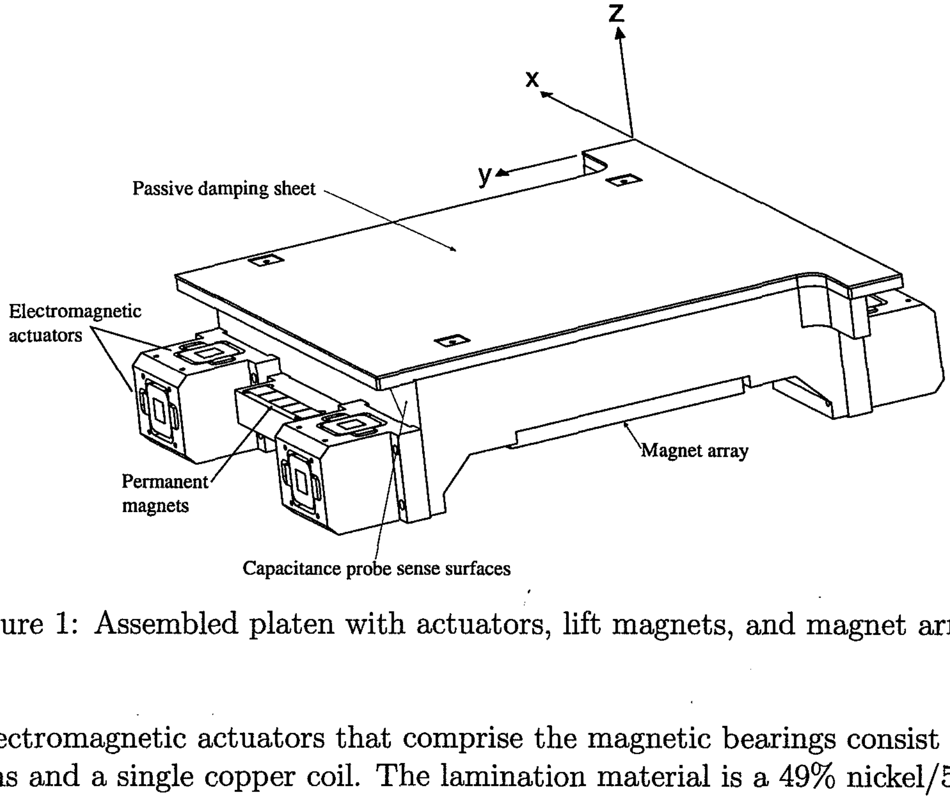

Figure 1: Assembled platen with actuators, lift magnets, and magnet array

The electromagnetic actuators that comprise the magnetic bearings consist of E type laminations and a single copper coil. The lamination material is a 49% nickel/51% iron alloy. This alloy was selected for its negligible hysteresis and moderately high saturation flux density. Negligible hysteresis is critical to ensure that the actuator force is single valued on the control current. In addition to the core material, the lamination size can be optimized for power. The dimensions of the core lamination can optimize force by sizing the pole face area in relation to the core length and height. Thus, for an optimum square pole face area the maximum force can be obtained for a given power level [1]. A theoretical model for the actuator force-current-airgap relationship can be derived from classical magnetic circuit theory. However, this is accurate only at very small airgaps and low flux densities. As the gap and the coil current increase, the actuator core saturates and the theoretical model is no longer effective. To obtain an accurate model, the actuator can be characterized for its force-current-airgap relationship [3]. This characterization data can be linearized in real time and implemented in a digital control algorithm. The actuators are located on the moving platen to provide a constant force relative to the platen center of gravity. Located at each corner of the platen is a housing which contains three E-core and coil assemblies. Within this housing the actuators are arranged at 90° intervals. This provides a total six pair of opposing push-pull actuators which provide five-degree of freedom control of the platen. The actuators have a nominal bearing air gap of 300 μm with displacements of ± 200 μm from the nominal in the Y and Z translational direction. Rotations of about one milliradian are possible around all three axes. These translational and rotational ranges are sufficient to provide the local alignment, focus, and leveling required in typical lithography equipment. The actuator control current is passed to the moving platen through a highly flexible flat conductor which rolls under the platen. The bend radius of the flexible conductor is consistent throughout the platen travel to help minimize any disturbance force.

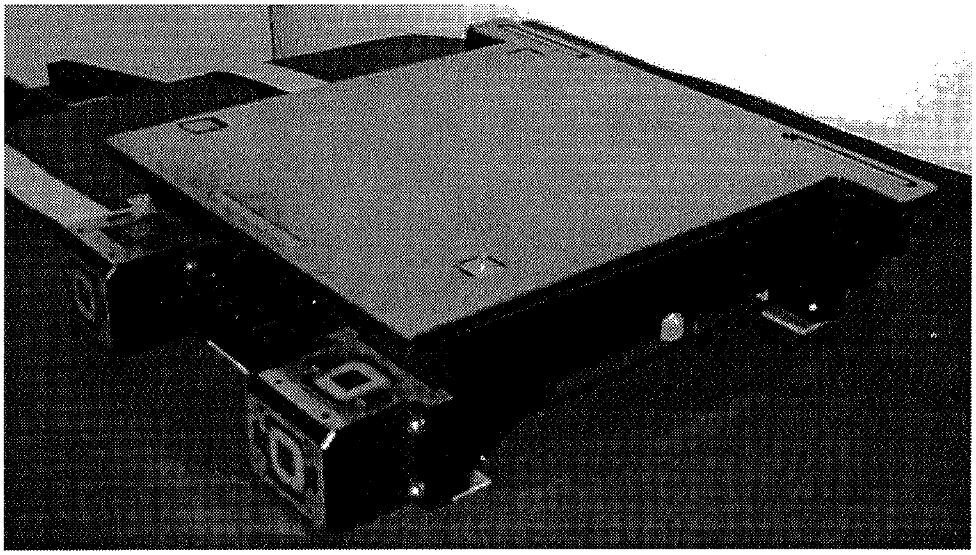

Figure 2: View of platen which shows the actuators and permanent magnet housing

Located between the actuator housing on each side of the platen are rare earth permanent magnet Halbach arrays. These lift magnets offset the mass of the platen and allow the vertical actuators to dissipate power only for platen position control. The permanent lift magnets are operated at a relatively large airgap so the force is not a strong function of position. This results in a slow open loop time constant associated with the lift magnets allowing the actuators easier stabilization of the system. The actuators and the lift magnets act upon a laminated magnetic material target rail that runs the length of the machine base. The machine base is mounted on three points and is kinematically constrained using a system of brackets and Belleville washer stacks.

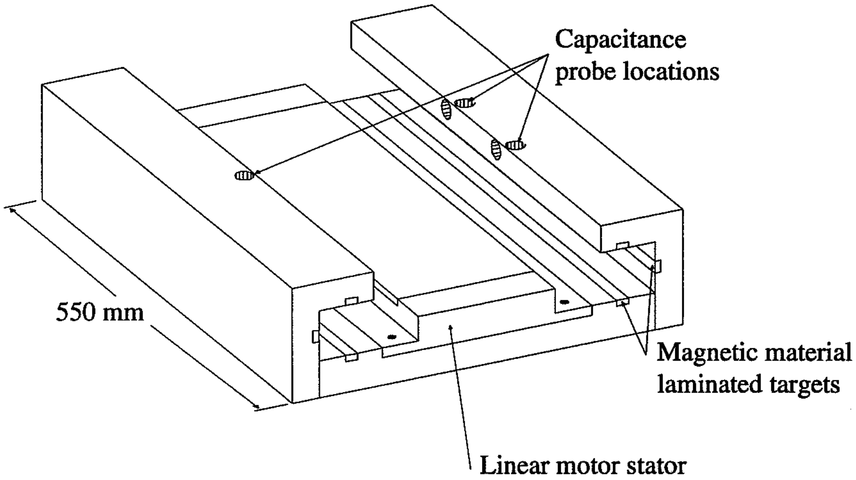

Figure 3: Stage base with linear motor stator

The stage parts were machined from 6061-T6 aluminum and are hard coat anodized. The fundamental resonant frequency of the suspended platen is located at 1030 Hz. While this mode is well above the control system crossover frequency, it is very lightly damped ($\zeta = 0.02$) and is easily excited even with a closed loop bandwidth of 100 Hz. This characteristic was anticipated from finite element modeling and a viscoelastic constrained layer damper was designed. This damper consists of a stainless steel plate machined to fit the top surface of the platen. The plate is 0.125" thick with a 0.05" thick layer of viscoelastic adhesive material which attaches it to the platen. This provides an order of magnitude better damping which effectively eliminated the resonant problem within the control bandwidth.

Since five platen degrees of freedom are controlled by the actuators, five independent position measurements are required. This is achieved by locating capacitance probes in the stationary frame which sense relative to a flat ground surface located on the platen. Laser interferometry is used to measure platen displacement along the X-axis. For lithography operations the stage would be positioned and locally focused using six axes of laser metrology.

To reduce the stage power dissipation the linear motor stator winding thickness is power optimized and a Halbach type magnet array is used which doubles the power efficiency of the motor. The key concept in the Halbach array is that the magnetization

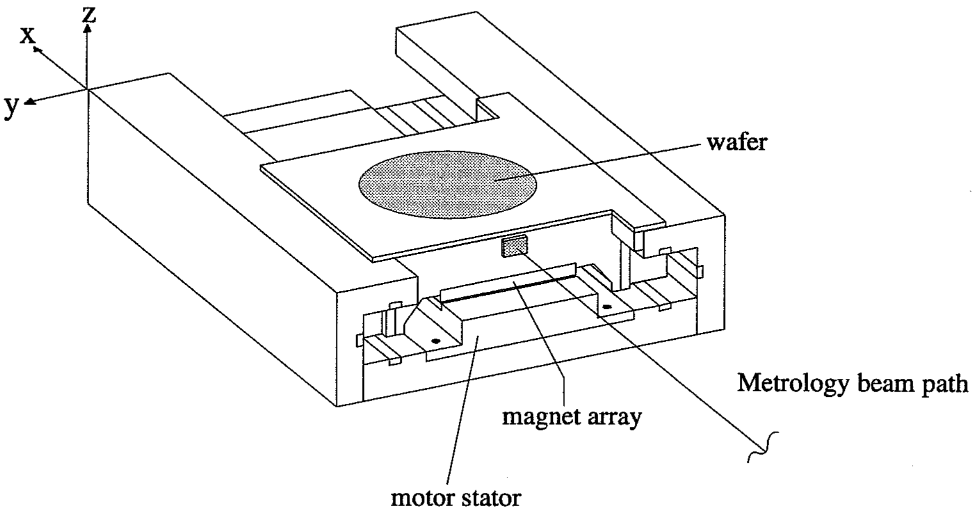

Figure 4: Suspended platen in base

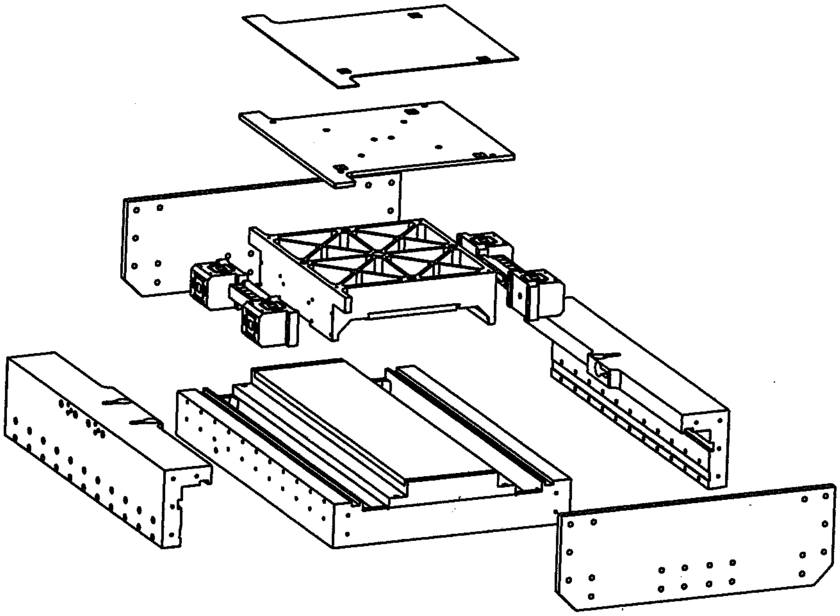

Figure 5: Complete stage assembly

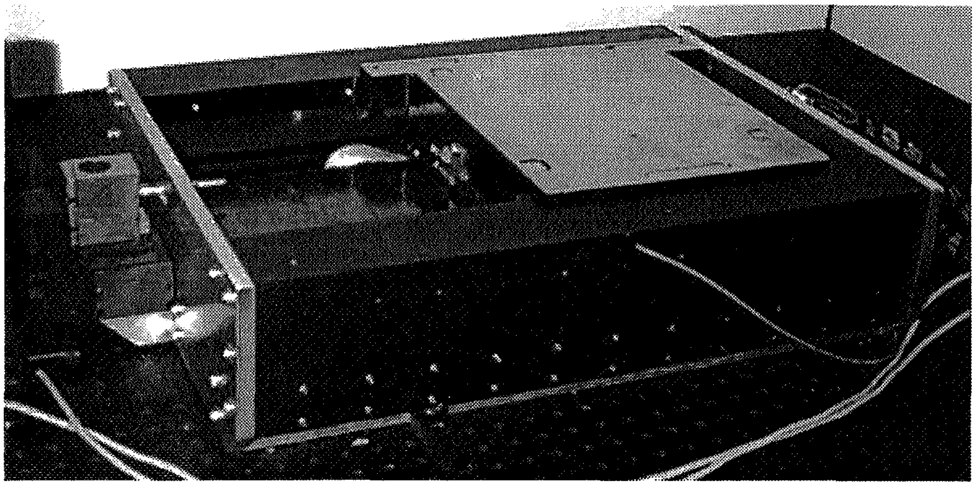

Figure 6: Overall view of assembled platen in the stage base

vector should rotate as a function of distance along the array. In fact if the vector rotates continuously, the field on one side of the array will be identically zero, while the field strength on the opposite side of the array is doubled relative to an array with a sinusoidally varying purely vertical magnetization [2]. While the ideal case calls for continuous rotation, in practice it is not possible to construct magnetic material with a continuously rotating magnetization vector. Therefore, each spatial wavelength of the magnet array is constructed of four uniform blocks of magnets, square in cross section each rotated by 90°. This geometry achieves 90% of the ideal continuously rotating field and is easily manufactured. The magnet sections are sized to provide one full rotation in one spatial period of the stator winding. The magnet array is 150 x 250 x 12.7 mm in size and is constructed of sixty individual rare earth magnet elements. The motor is designed to accelerate the 14.5 kg mass at 5 m/sec^2 while dissipating 6 watts of electrical power. In the photograph (Figure 7) the magnet array is visible. Also shown in Figure 7 are actuators and the flexible cable and cable connectors.

STAGE CONTROL

The linear motor and the linear magnetic bearing are digitally controlled using a TMS320C30 floating point digital signal processor implemented on a VME chassis. The structure of the bearing control scheme is to use decoupled equations of motion about the stage center of gravity. This is accomplished with modal transformations performed in real time on the digital control platform. The modal transformations are a function of stage position since the feedback sensor positions change relative to the stage center of

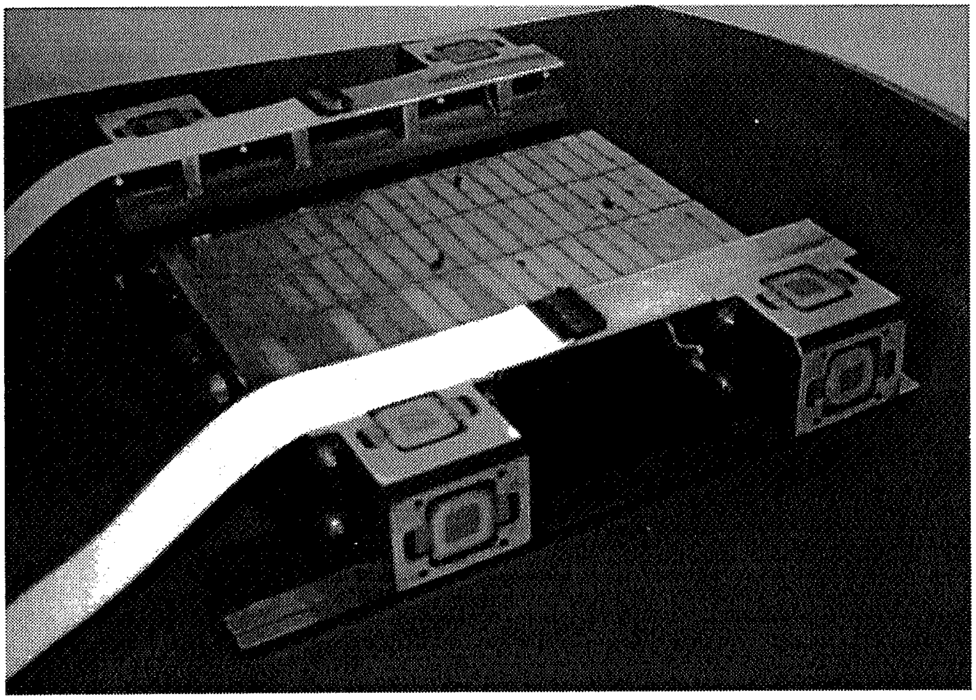

Figure 7: Underside of platen showing linear motor magnet array and actuators

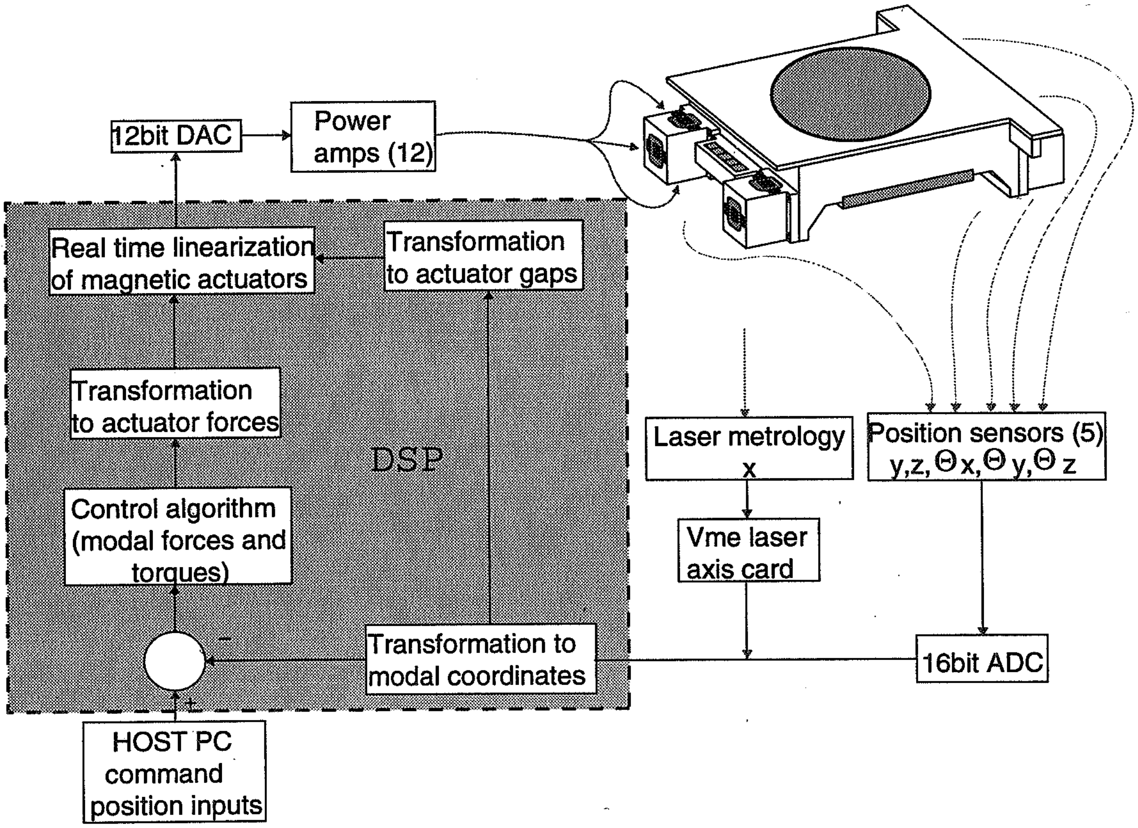

Figure 8: Bearing control flow diagram

gravity. The control algorithm used is a lead-lag compensator with two second order digital filters in each feedback path. The control bandwidth of the bearing axes is presently 100 Hz with a future goal of 200 Hz crossover frequency. The control bandwidth is currently limited to 100 Hz by the resonant modes of the pnuematic vibration isolation table that the stage is on. Figure 8 is a representation of the bearing control system algorithm. The linear motor is controlled as a single degree of freedom actuator which is designed to be mostly decoupled from the bearing axes. This axis decoupling is accomplished through the platen design. The platen center of gravity was placed as closely coaxial with the linear motor force as was possible. The center of gravity is located at a position on the centerline of the stage about 1 cm above the plane of the motor force. This offset is accounted for in the modal transformations. The linear motor is a six-phase Lorentz type sinusoidally commutated motor. The motor controller is a lead-lag compensator with a bandwidth of 40 Hz. Figure 9 is a schematic representation of the linear motor control loop.

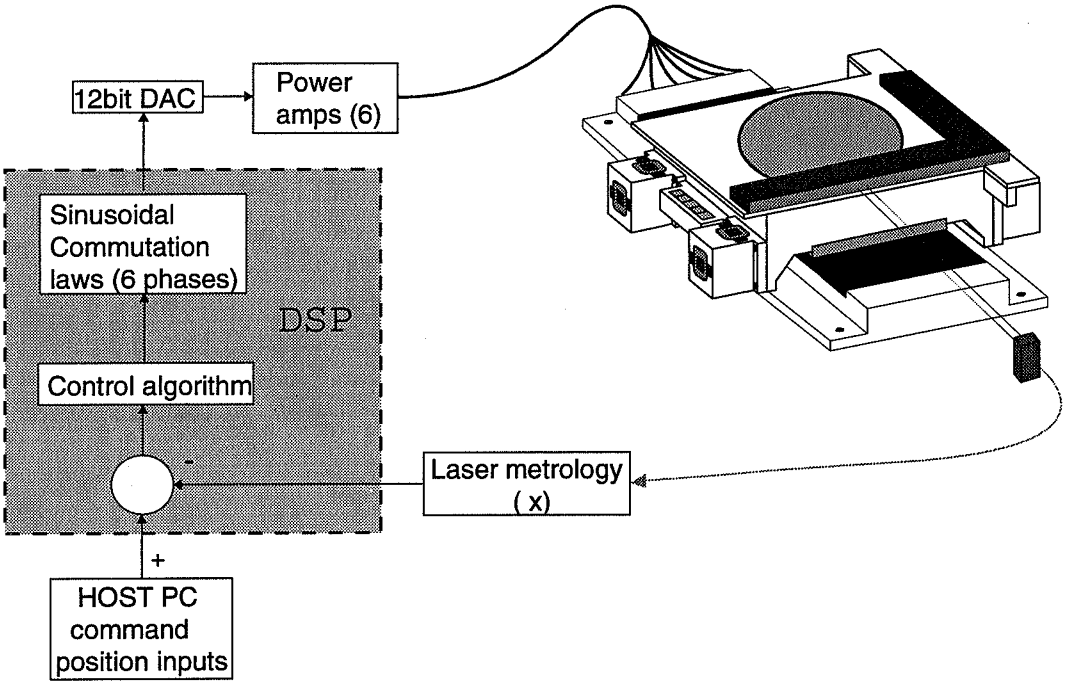

Figure 9: Linear motor control flow diagram

STAGE PERFORMANCE

Step response curves for both the bearing and linear motor are shown in the curves. A 100 nanometer step is shown in Figure 10. The peak-to-peak positioning noise is approximately 100 nm. The level of this noise can be attributed to the 16 bit analog to digital converter that is used to sample the capacitance probe voltage levels. The ADC has 7-8 least counts of inherent noise This noise limits the position resolution of the bearing degrees of freedom and translates to approximately 70-80 nm (10 nm/count). The other four bearing degrees of freedom exhibit similar behavior.

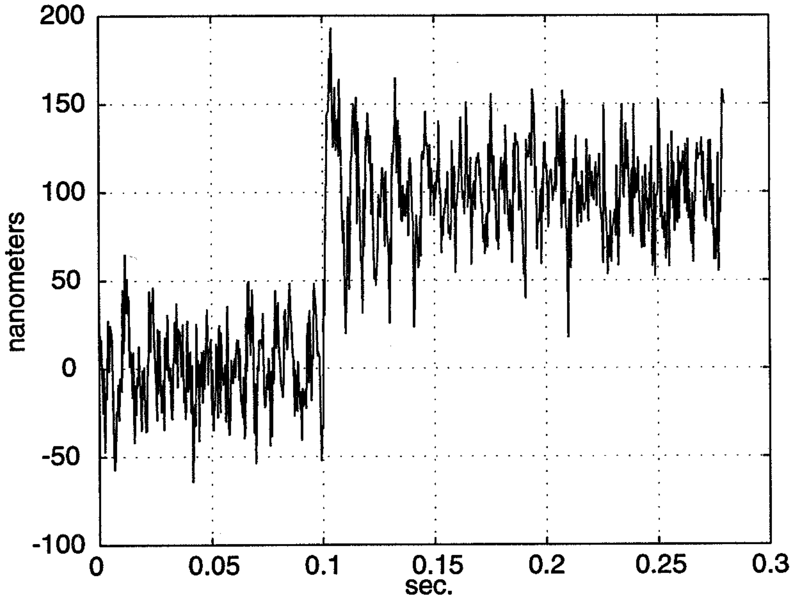

Figure 10: 100 nm bearing step in Z-direction

Figure 11 is a 20 nm step of the linear motor in the X direction. The peak-to-peak positioning noise in this axis is approximately 15 nm. This noise is dominated by noise from the bearing degrees of freedom being injected into the X-axis. There is also a 4 Hz component of noise that is directly attributable to rocking of the vibration isolation table. Figure 12 is a 2 cm step response that is a typical photolithography step size. The response shows that the stage will step and settle in 130 msec with no overshoot. However, the fine settling includes a 4 Hz component due to the optical table rocking mode.

CONCLUSIONS

We have presented the performance of a six degree of freedom stage which demonstrates that magnetic bearings have the capabilities for precision X-Y positioning at the level required for photolithography. We have demonstrated bearing resolution of

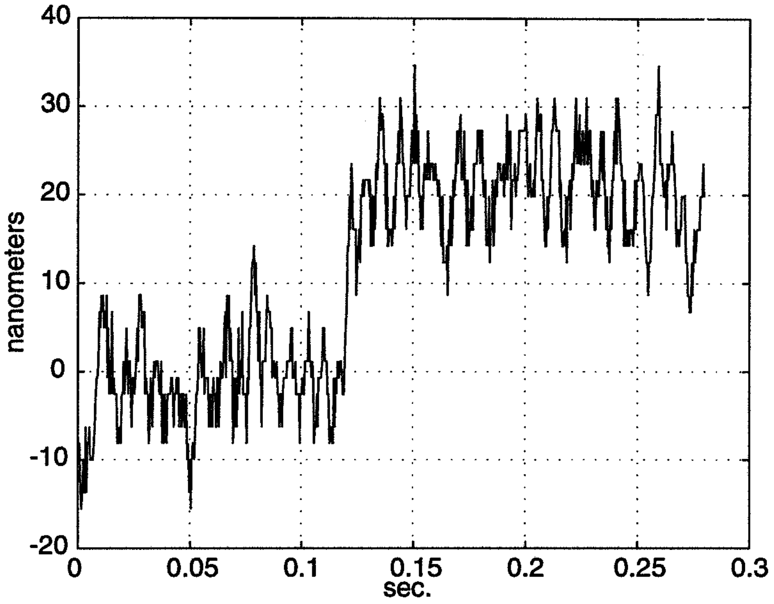

Figure 11: 20 nm linear motor step

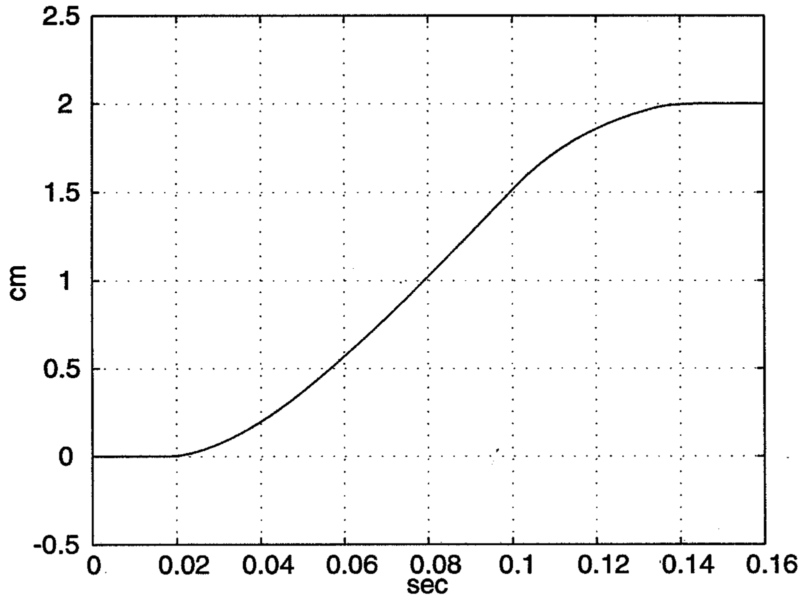

Figure 12: 2 cm linear motor step

100 nm peak-to-peak which is at the noise level of the ADC. The linear motor position resolution is at 15 nm peak-to-peak. The stage step and settle is at 130 msec., a dramatic improvement over the current state of the art in lithography steppers. Using laser metrology to feedback the stage position could significantly improve the baseline noise in all degrees of freedom. In the present configuration the stage performance is well within the position requirements of lithography with significant improvements made in manufacturability, speed, and durability.

Acknowledgments

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References

[1] Williams,M.E. and Trumper, D.L., "Materials For Efficient High Flux Magnetic Bearing Actuators," NASA 2nd International Symposium on Magnetic Suspension Technology, Seattle, Washington, Aug. 11-13,1993.

[2] Trumper, D.L., and Williams,M.E., "Magnet Arrays for Synchronous machines," IEEE Industrial Applications Society Annual Meeting., Toronto, Canada, Oct.,1993

[3] Poovey,T., and Holmes,M., "A Kinematically Coupled Magnetic Calibration Fixture." Precision Engineering, 16(2), Apr 1994.