Magnetic Bearings for Precision Linear Slides

David Eisenhaure (SatCon), Alexander Slocum (MIT),
Richard Hockney (SatCon)

SatCon Technology Corporation
71 Rogers Street
Cambridge, MA 02142

Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

Abstract

Early uses of scanning tunneling microscopes indicate that many areas of science could greatly benefit if centimeter scale objects could be probed on an atomic scale. This could be accomplished by the development of a linear slide having one Angstrom resolution and a one-tenth meter range of travel. Magnetic suspension technology has been proposed as an ideal candidate for the suspension of the linear slide. This technology is attractive since it combines low noise, excellent positioning accuracy, zero wear, and requires no lubrication. The paper examines the feasibility of developing a magnetic suspension with a required resolution exceeding one Angstrom and establishes the requirements for this suspension. The achievable resolution is shown to be determined by position measurement accuracy, suspension gain, suspension bandwidth, and disturbance force levels. Expected disturbance force levels from ground motion, air currents, and acoustic effects are projected. Given the expected disturbance force levels, measurement accuracy, and required controller performance, a magnetic suspension could be developed which would provide resolution better than the one Angstrom required.

Introduction

Several Angstrom resolution devices currently exist. Scanning electron microscopes (STMs) are flexural linkage structures with Angstrom resolution and range of motion only on the order of one micron [1]. Because of its small range of motion, an STM can be made small enough to make it virtually immune to thermal and vibration problems that would plague a machine with centimeter range of motion. Researchers at the National Physical Laboratories (NPL) in England have built a linear stage with 1 A smoothness of motion over a range of centimeters. The stage uses Rulon^{TM} pads as bearings that are arranged kinematically on a Vee way [2]. However, questions regarding long-term stability of the plastic bearings and controllability in the presence of sliding friction remain unanswered. Current designs of other precision machines such as wafer steppers and diamond turning machines [3] are principally performance limited by mechanical contact between moving parts, misalignment between actuators and bearings, bearing stability, and attainable temperature control [4,5,6]. To help overcome these problems, coarse-fine positioning systems, have evolved as shown in Figure 1. Although they can be effective, they are mechanically cumbersome and are intrinsically difficult to control. The design envisioned for the ARMM would address these issues by way of its kinematic magnetic bearing design.

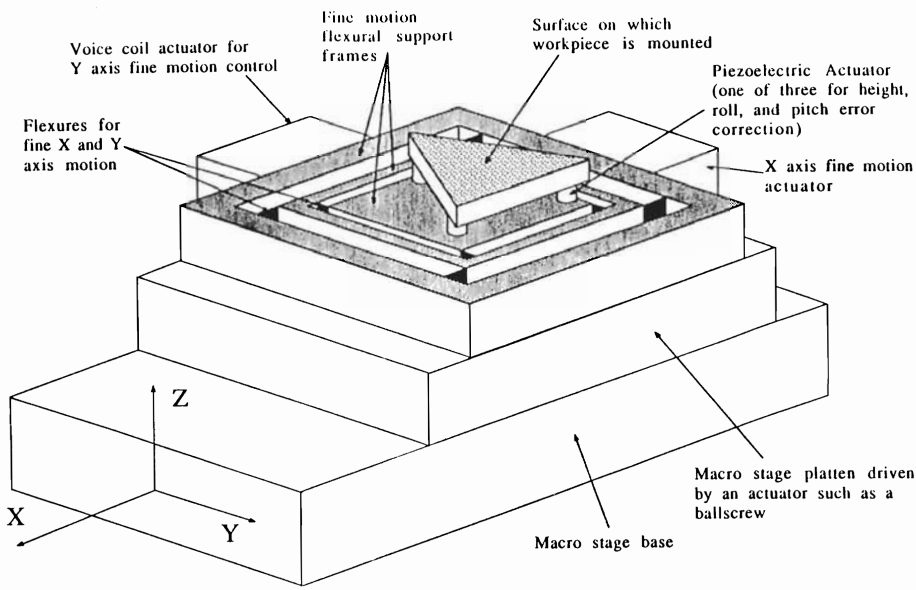

Fig.1. Example of a Coarse-Fine positioning system used to correct for slide errors caused by errors in slide geometry and forces caused by a misaligned actuator

The design of the ARMM evolved into the crossed axis design shown in Figures 2-4. A two-axis version only requires fabrication and installation of a "mirror image" of the first axis. The resultant two-axis machine would have a spherical or cubic shape to maximize structural efficiency with respect to stiffness and thermal stability. The axis' moving structural members would be mirror finished and be used as reflectors for the laser interferometers that provide position feedback signals to magnetic bearings (The axis would be designed so servo forces from the bearings and the weight of the part caused less than 0.1 A deformation.). The magnetic bearing actuators would be configured kinematically: five magnetic bearing actuators positioned to control five degrees of freedom.

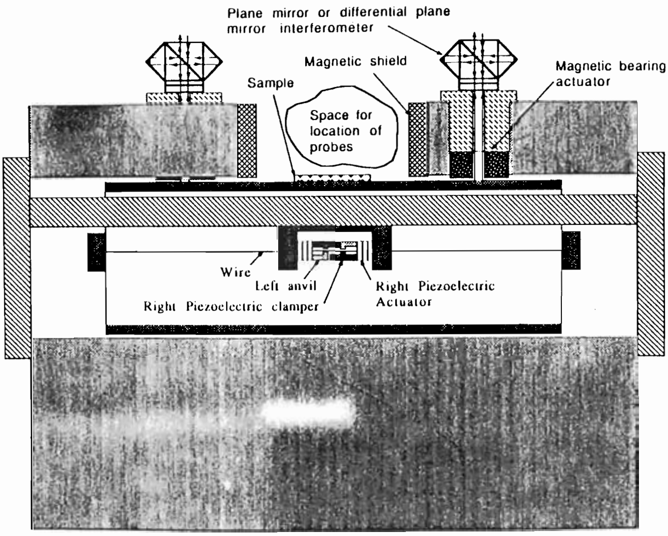

Fig.2. Cutaway side view of Atomic Resolution Measuring Machine (ARMM)

MIT/SatCon Magnetically Suspended Linear Slide

Current designs of precision machines such as wafer steppers and diamond turning machines are generally performance limited by mechanical contact between moving parts, misalignment between actuators and bearings, stability of air

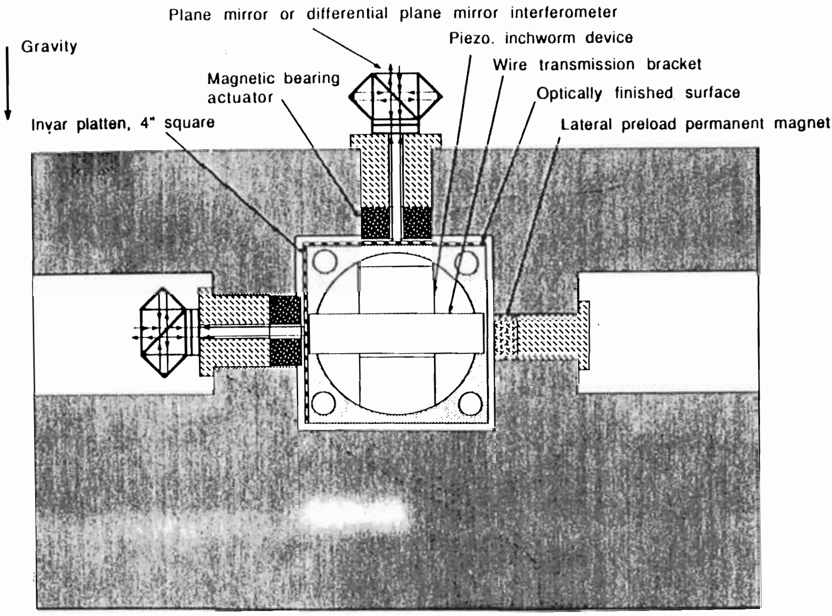

Fig.3. Cutaway right end view of Atomic Resolution Measuring Machine (ARMM)

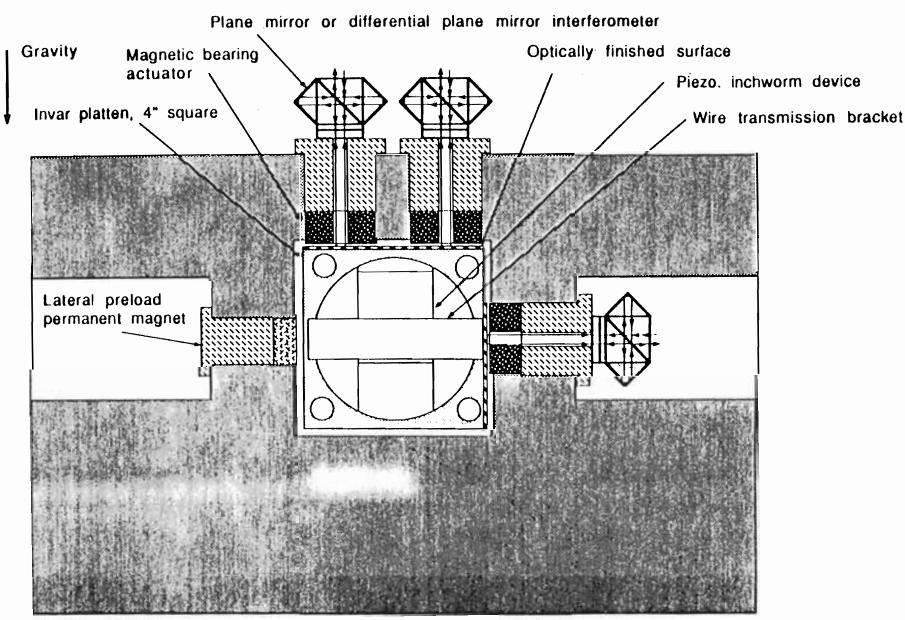

Fig.4. Cutaway left end view of Atomic Resolution Measuring Machine (ARMM)

bearings, and/or attainable temperature control. To help overcome some of these problems, coarse-fine positioning systems have evolved such as shown in Figure 1. Although effective, they are mechanically complex when compared to a magnetic bearing supported slide.

In order to maximize performance and minimize cost of magnetic bearing supported linear slides, kinematic design principals must be adhered to. With respect to spacing of components, in one extreme, the farther apart bearings are placed, the less chance of the system "walking". However, the farther apart the bearings are, the larger the structure needs to be in order to span the bearings, and thus the lower the system natural frequency.

Hence spacing and size of members should be kept in proportion: following the rule of the Golden Rectangle seems to provide for dynamically stable and structurally stiff systems. The Golden Rectangle was discovered by the Greeks and is seen in their ancient architecture quite frequently. A Golden Rectangle is a rectangle of dimensions a x b, whose proportion is such that when a square of size a x a is cut from the rectangle, the ratio of the sides of the remaining rectangle is the same as the ratio of the sides of the original rectangle. This ratio is (1 + (5)0.5)/2.

If a kinematic design is used, then a closed form solution for the effect of motion induced by one of the actuators on the motion of any point of the sample can be formulated. Similarly, if the position and orientation of a region of the slide is measured, the inverse kinematic solution allows for the precise quasi-independent servoing of each of the magnetic bearing actuators.

Even if direct measurement of the position and orientation of a region on the slide is made, precise position measurements of each bearing's distance from the surface of the slide must be made in order to maximize performance. This is due to the fact that a magnetic bearing's performance is sensitive to the speed of its controlling servo-loops and the accuracy of the gap measurement. If the inverse kinematic solution were used in lieu of a direct sensor measurement, the speed of the servo-loop may be five to ten times slower.

The baseline slide as currently envisioned would have envelope dimensions of 12 inches by 6 inches by 2 inches. This baseline slide would have a weight in Earth's gravity of ten pounds. In this paper the baseline slide will be used as a conceptual model to examine the resolution capabilities of a magnetic suspension system. The analysis assumes that the slide dynamics are beyond the bandwidth of the magnetic bearing and will not be a factor in the suspension's performance.

A baseline magnetic suspension block diagram is shown in Figure 5. The principle of operation of a magnetic suspension system is quite simple: the position of the suspended slide is measured and the control system regulates the current to an electromagnet by a gain the slide at the desired location. A simple control system might be characterized by a gain (stiffness) which relates errors in position to applied magnetic force and a bandwidth which indicates the frequency range over which the magnetic force may be applied. In addition to gain and bandwidth, the control system would require electronic compensation for stable operation. However, discussion of this is beyond the scope of this paper and has no impact on the conclusions. Magnetic suspensions generally have unstable plant characteristics which lead to a minimum required system bandwidth for stability of about 10 Hz for many suspensions. Maximum achievable bandwidths could range from 100 Hz for a simple attractive system to 40 KHz or higher for systems implemented with ferrite or voice coil actuators. As with all position control servos, accuracy is determined by position measurement accuracy, controller gain, controller bandwidth, and disturbance forces acting on the suspended slide.

Suspension Performance

At low frequencies suspension performance is determined almost completely by the ability of the controller to cancel disturbances. The primary control system parameter effecting disturbance cancellation is the controller gain which determines suspension stiffness. The higher the suspension stiffness, the greater the ability to reject force

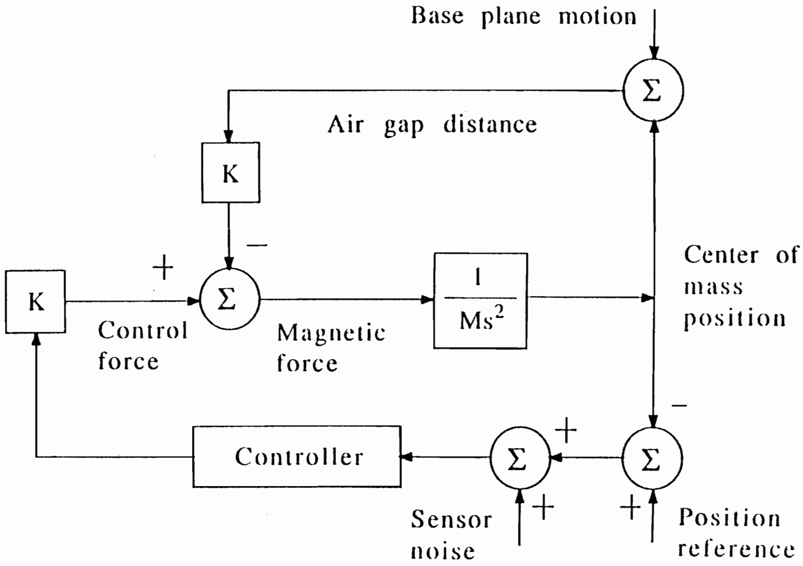

Fig.5. Basic magnetic suspension block diagram

disturbances. At high frequencies, however, all the disturbance force is absorbed by the slide inertia. The required bandwidth is the frequency at which the inertia of the slide alone could keep the slide motion below the required resolution. At frequencies below the required bandwidth, position measurement errors translate directly into resolution errors in the slide. At frequencies above the required bandwidth, resolution is independent of position measurement errors. Figures 6 and 7 show the achievable resolution at various disturbance force levels as a function of suspension stiffness and bandwidth, respectively. The disturbance force represented is modeled as a broad band disturbance over the entire frequency range of interest. For the simple control system considered, the bandwidth and stiffness requirements are related by bandwidth = (stiffness/mass)$^{1/2}$ x 2Pi.

Position Measurement

There are four principal sensor systems that need to be designed for the ARMM:

(1) Environmental. Temperature, pressure, and humidity all need to be monitored to enable the environment to be

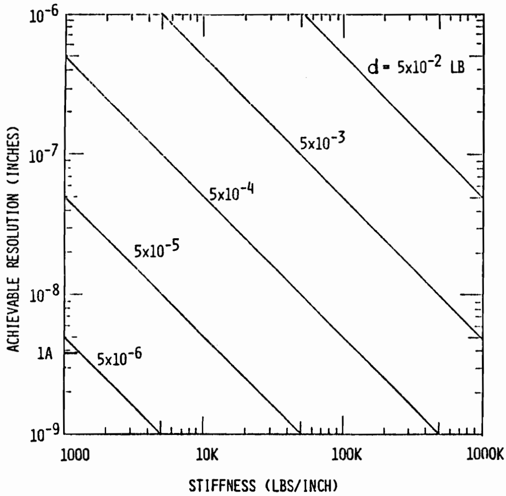

Fig.6. Achievable suspension resolution vs. suspension stiffness

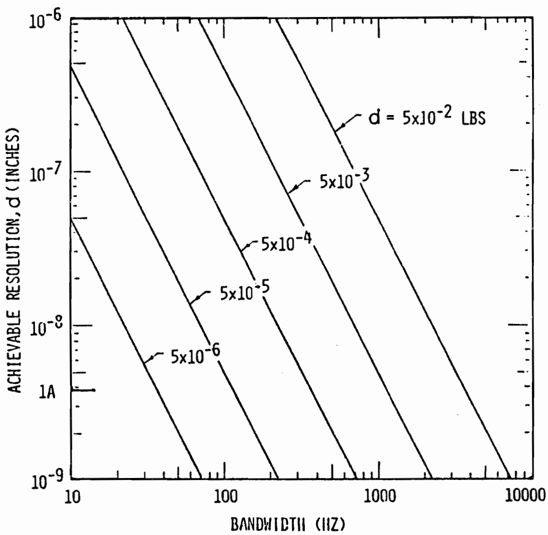

Fig.7. Achievable suspension resolution vs. suspension bandwidth

controlled to ensure accuracy of the machine. It is anticipated that temperature control good to 0.01-0.001°C/cm will be required for the ARMM. In order to achieve such high resolution and accuracy, a Mach-Zehnder interferometer will probably be used.

(2) Large range of motion, high resolution. For example, the axial position of the platen has to be measured with a resolution on the order of 1.0-0.1A over a range of motion on the order of 50 mm. Differential plane mirror interferometers will probably be used for this application. Existing technology allows for resolution to $\lambda/512$ (about 10 Angstroms).

(3) Small range of motion, ultra-high resolution. For example, the lateral position of the platen, the magnetic bearing gap, needs to be measured with a resolution of 0.1-0.01A over a range of motion on the order of 1μm. A Fabry-Perot interferometer with the capability to resolve to $\lambda/10^6$ could even be used for this type of application where one of the reference optics is moving orthogonal to the distance being measured.

(4) Measuring location of atoms. For example, scanning tunneling probes need to be adapted for use on the ARMM. Existing technology developed for the STM could be used; however, a single probe would take many thousands of years to map a 50 mm diameter specimen. Thus multiple probe techniques would be needed.

Capacitance probes or laser interferometers can be used to make ultra precision measurements of the bearing gap. Regardless of the system used, however, a through the bearing measurement method must be used. This maintains accuracy of the kinematic model and provides for checking measurement closure should direct measurement of the position and orientation of a region of the slide also be made.

If a laser interferometer system is used as shown in Figure 8, then the slide itself must be polished to optical quality. The cost of a laser interferometric measurement system is on the order of $10,000 per measurement axis. It is envisioned that in the near future the resolution of differential plane mirror interferometers will exceed the one Angstrom level. Thus a single magnetic bearing supported slide would require $50,000 worth of laser interferometers.

For substantially less cost, on the order of $2,500 per axis, capacitance probes, also shown in Figure 8, can be used for through the bearing sensor. They have the advantage of not

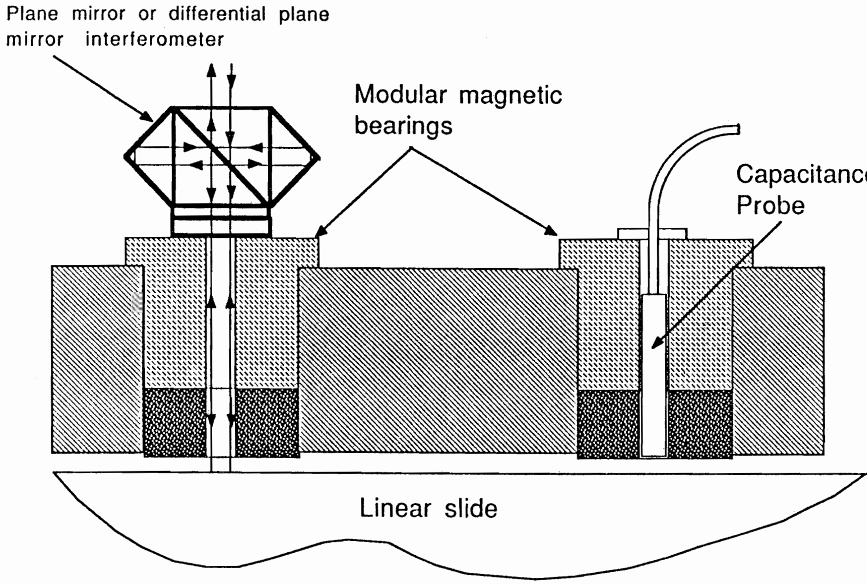

Fig.8. Sensor arrangements for through the bearing measurement

requiring the surface of the slide to be optically polished. The finite area of their measuring tips creates an averaging effect which reduces the effect of surface finish errors on the gap measurement. However, long-term drift problems may render the probes inadequate for continuous operation of the system over a period of days.

All measurement systems, as well as the machine itself, are very sensitive to thermal effects. Thus control of the overall temperature and of temperature gradients is extremely important. A detailed discussion of temperature control methods is beyond the scope of this paper, but some general comments on the effects of magnetic bearings on the overall system thermal budget are in order:

(1) Magnetic bearings with copper windings do dissipate heat; however, power dissipated can be minimized with a proper balance of permanent magnets to support 98% of the weight of the slide. Copper windings would then be used to provide servoing capability.

(2) Resistance heaters can be used to make the bearings constant power devices, thereby minimizing the effect of

transients on the system. The system could then be more easily operated at its thermal equilibrium.

(3) The availability of "warm" superconductors could dramatically change the way magnetic bearings are designed and used, and is thus a research area that required serious attention.

Disturbance Forces

The principle disturbance forces acting on the slide in a laboratory environment are due to air current, acoustic disturbances, and ground plane motion. The forces were modeled to have a broad frequency content over the range of interest. Figures 9 and 10 show the disturbance forces for impinging air flow and acoustic disturbances, respectively. Figure 11 shows the disturbance forces as a function of base motion for various suspension gaps. A comparison of Figures 9 through 11 shows that base motion is the largest single contributor to slide disturbance force. If necessary, the sensitivity to base motion could be reduced by one order of magnitude by incorporating magnetic flux feedback in the control loop and by two orders of magnitude by employing voice coil actuators. Even without these changes the total disturbance force level

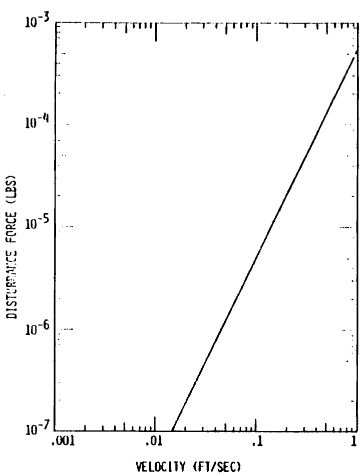

Fig.9. Slide disturbance force as a function of impinging air flow

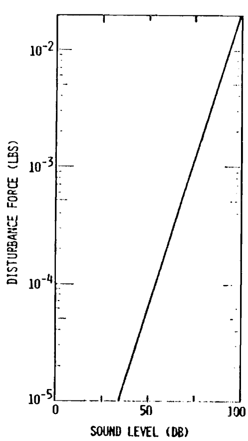

Fig.10. Slide disturbance force vs. acoustic noise level

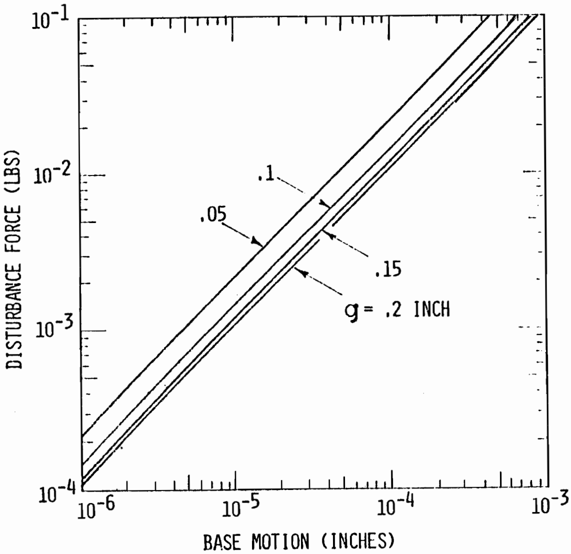

Fig.11. Slide disturbance force as a function of base plane motion

could be kept below 5 x 10^{-3} pounds. This is based on the MIT experience with expected base motions, air velocity, and acoustic effects in a well-controlled laboratory environment.

Conclusions

The factors that determine achievable resolution for a magnetically suspended slide are position measurement accuracy, controller bandwidth, controller gain, and disturbance forces. Laser interferometers are expected to be available in the near future with resolutions exceeding one Angstrom and adequate accuracy for a one Angstrom resolution slide suspension. At the expected disturbance force level of 5 x 10^{-3} pounds, the suspension would be required to have a bandwidth of 1,000 Hz and a stiffness of 1,000,000 pounds per inch to maintain a slide resolution of one Angstrom. These suspension characteristics are achievable with state-of-the-art magnetic and electronic components. Based on these considerations, the authors believe that a magnetically suspended slide having a resolution better than one Angstrom could be developed using state-of-the-art and near-state-of-the-art technology.

Bibliography

1. Binnig, G. and H. Rohrer: Scanning Electron Microscopy. Helvitica Physica Acta, Vol. 55 (1982) 726-735.

2. Lindsey, K. and P. Steuart: NPL Nanosurf 2: A Sub-nanometer Accuracy Stylus-based Surface Texture and Profile Measuring System with a Wide Range and Low Environmental Susceptibility. 4th Int. Precision Engr. Sem. Cransfield Inst. of Tech., U.K. (11-14 May 1987) 15.

3. Donaldson, R. and S. Patterson: Design and Construction of a Large Vertical-Axis Diamond Turning Machine. SPIE's 27th Annual International Technical Symposium and Instrument Display (21-26 August 1983).

4. Moore, W.: Foundations of Mechanical Accuracy. The Moore Special Tool Company. Bridgeport, Connecticut (1970) 24-28.

5. Biesterbos, J., et al: A Submicron I-Line Wafer Stepper. Solid State Technology (February 1987) 73-76.

6. Nuhn, M.; Yao, S.; Avrit, B.: I-Line Wafer Stepper Used for Low Volume Production of 0.5 Micrometer GaAs Integrated Circuits. Solid State Technology (February 1987) 81-84.

7. Berthold, J.; Jacobs, S.; Norton, M.: Dimensional Stability of Fused Silica, Invar, and Several Ultra-low Thermal Expansion Materials. Metrologia 13 (1977) 9-16.

Applications in Robotics