Magnetic Actuator Characterization for Nanometer-level Positioning

Todd N. Hinnerichs and Hy D. Tran[*]
Department of Mechanical Engineering
University of New Mexico
Albuquerque, NM 87131

Abstract

A kinematically coupled magnetic-bearing calibration fixture was designed based on the previous work of Poovey[1] and Groom[2], which provides the ability to experimentally explore some of the issues of concern in magnetic bearing technology. Since magnetic levitation requires the controlled production of force from an electrical signal and the dynamics of the magnetic bearing are inherently nonlinear, force characteristics (i.e., force as a function of coil current and air gap) are often developed to linearize the response of the bearing for typical precision positioning applications. The magnetic actuator characterization curves are most often implemented in a 2-D or 3-D type lookup table and can greatly enhance the bandwidth of the levitation system. Often, these curves are developed using classical magnetic circuit theory, which is accurate only at low flux densities. This linearization technique works quite well until ferromagnetic core saturation, which results in force hysteresis.

To properly understand the resulting force hysteresis, a reluctance type magnetic actuator was analyzed using the kinematically coupled calibration fixture. The maximum force of this actuator was designed to be approximately 150 N at saturation. The nominal air gap for this experimental analysis was 300 micrometers with a range of the nominal gap plus or minus 200 micrometers. To minimize the mechanical hysteresis in the system, the kinematic coupling was designed to have both high stiffness through high preload and minimal contact surface interaction. Experimental results using this calibration fixture are compared to a linear magnetic circuit model. In addition, effects of actuator/target angular misalignments on force production are presented.

Future research will include experimental testing of hysteresis force production after core saturation. The end goal of this analysis is to expand on the current understanding of reluctance based magnetic actuators and to present a more thorough model of reluctance magnetic actuators, which will aid in the future development of control systems for magnetic levitation.

Introduction

As today’s semiconductor technologies demand smaller and smaller feature sizes, an attractive bearing mechanism for semiconductor lithography applications is magnetic bearings, which provide essentially frictionless, lubrication-free motion in up to six degrees of freedom with resolution limited only by the sensors and control system. Although magnetic bearings are attractive for these reasons, their inherent dynamic instability, nonlinearity (hysteresis and ferromagnetic core saturation), and damping characteristics make it necessary to fully characterize this type of bearing. However, if a complete understanding of magnetic bearings can be developed, nanometer-level positioning with high throughput is possible with a properly designed bearing.

To get a more thorough understanding of magnetic bearings, experiments were carried out using a reluctance-type magnetic actuator. The first phase of the analysis was to compare experimental data obtained from testing to a linear magnetic circuit model at the exact conditions (i.e., gap and current). From this comparison, a direct understanding of the limitations of linear magnetic circuit theory was found and will be described. In addition, experiments were run to compare target/actuator angular misalignments

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[*] Address inquiries to Hy D. Tran; tran@me.unm.edu

Theory

Linear magnetic circuits were developed to model the magnetic actuator at small air gaps and low flux densities[3]. The models allow for the variation of current input, angular misalignments between the actuator and target, and number of incremental area units of the pole faces. The last parameter allows for very accurate calculation of iron core saturation (if the number of incremental areas is large), which in turn lets the user of the model know the bounds of the linear model (mainly useful for angular misalignment calculations).

In the first model, shown in Figure 1, the reluctance of the actuator and target's iron core is ignored. This simplification greatly reduces the complexity of the calculation by removing the necessity to find the permeability of the iron core, which varies as a function of the operating flux density. Using the electrical analogy on the magnetic circuit shown in Figure 1, the following two equations describe the magnetic circuit:

$$\Phi_{left} \cdot R_{air,left} + \Phi_{left} \cdot R_{air,mid} - MMF = 0 \qquad (1)$$

$$\Phi_{right} \cdot R_{air,rightt} + \Phi_{right} \cdot R_{air,mid} + MMF = 0 \qquad (2)$$

where

Φ_{left} is the magnetic flux through the left air gap

Φ_{right} is the magnetic flux through the right air gap

$R_{air,left}$ is the reluctance of the left air gap

$R_{air,rightt}$ is the reluctance of the right air gap

$R_{air,mid}$ is the reluctance of the middle air gap

MMF is the magnetomotive force

We solve for the magnetic flux through each area gap. The force developed at each pole face can then be found using:

$$F_{poleface,X} = \frac{\Phi^2}{2 \cdot m_0 \cdot A} \qquad (3)$$

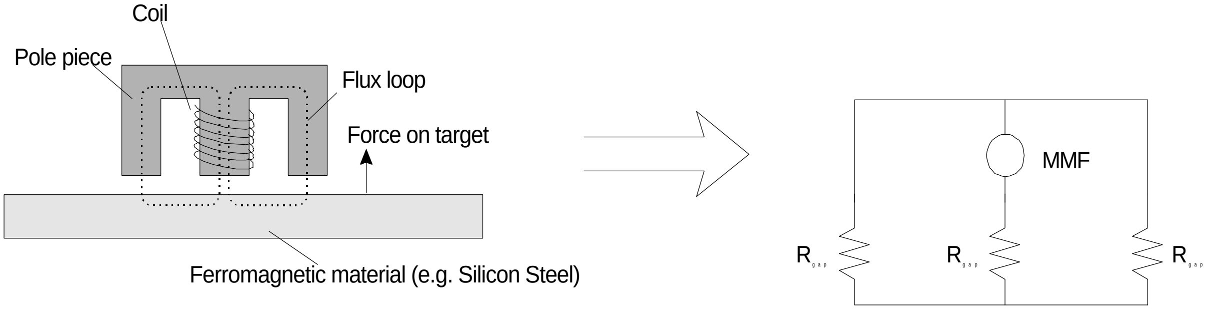

Figure 1. A typical "E-core" actuator, and its simplified magnetic circuit model for Equations (1-3).

The reluctance R of a gap is generally approximated by $R \approx \dfrac{l}{A \cdot m_R \cdot m_0}$, where l is the distance across the gap; *A* is the area of the gap, μ_R is the relative permeability of the material, and μ_0 is the permeability of free space ($4\pi\times10^{-7}$ H/m).

This simplified linear analysis can be extended; first, by including the reluctance of the E-core and of the target in the magnetic circuit model; next, by modeling the effects of geometric misalignments, as shown in Figure 2.

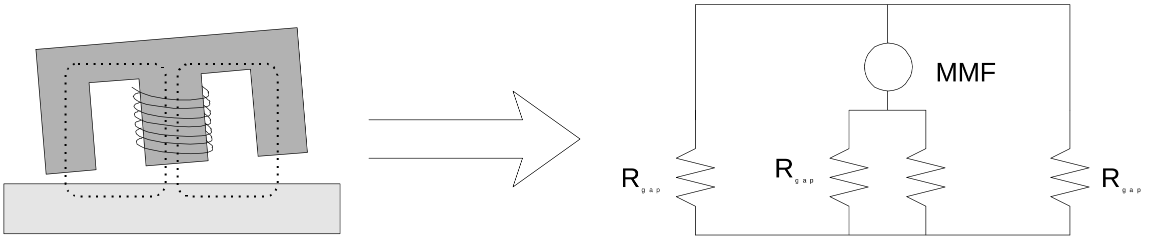

Figure 2. Effect of misalignment of the actuator on the magnetic circuit model.

We subdivide the actuator into individual area increments, and calculate the reluctance across the gap for each increment; then, we apply the magnetomotive force to obtain flux across each gap element. Force can then be calculated from Equation (3). A MATLAB program has been written to perform these calculations. The MATLAB model predicts the force at each pole face of the E-core actuator, based on current, gap, and misalignment. Furthermore, it is easy to incorporate the permeability of the core and target into this MATLAB model.

Experiments

We designed and built a calibration fixture based on the designs of Trumper and his students[1]. A solid model of this fixture is shown in Figure 3. The kinematic coupling between base and top plate is based

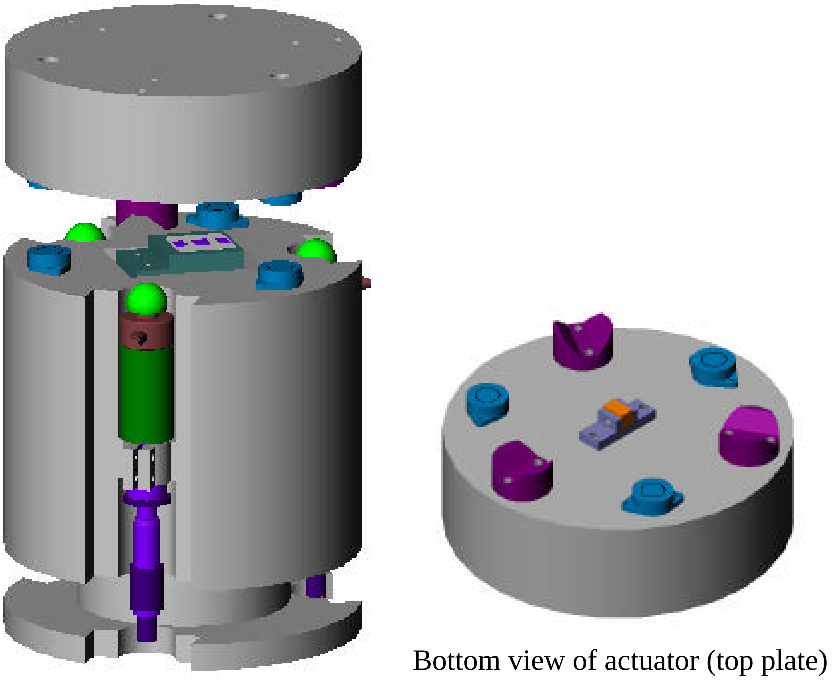

Figure 3. Solid model of kinematic actuator calibration fixture.

on the 3 balls/3 vees configuration (see, for instance, [4,5]). Micrometers are used to adjust the height of the balls (based on 3 balls/3 vees coupling between the base and the top plate). The actual spacing between the base and top plate are measured with capacitive gauges, and the forces are measured with load cells placed between the micrometer adjusters and the balls. Data from the capacitive gauges, the actuator current amplifier, and the load cells is collected via a National Instruments PCMIO-16 16-bit resolution A/D board. The system is calibrated by placing dead weights on the top plate and removing the deadweights.

Results and models will be presented at the conference.

References

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Acknowledgments

This work was supported in part by Sandia National Laboratory University Research Program grant BE-0226, and by the NASA PURSUE undergraduate research support program grant NCC5-350 from NASA MURED.