A COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS FOR MAGNETIC BEARINGS[*]

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ABSTRACT

A comprehensive program was undertaken to experimentally characterize the static and dynamic characteristics of a heteropolar magnetic bearing and to develop nonlinear theoretical models capable of accurately predicting magnetic bearing performance. This paper presents the results for the static characteristics of the magnetic bearing and a comparison with the predictions from the analytical model. The results indicate that the nonlinear theoretical model can accurately predict the static characteristics of the magnetic bearing.

SYMBOLS AND ABBREVIATIONS

A - magnetic vector potential
B - flux density
F - force
H - field intensity
I - current
J - current density
ν - reluctivity of the material
σ - conductivity of the material

subscripts
x,y,z - spatial coordinates

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INTRODUCTION

The magnetic bearing holds great promise for product lubricated and non-lubricated rotating machinery. Although the potential benefits in terms of bearing friction losses, condition monitoring, and active control are many, there is a great price to be paid in terms of increased complexity. The complexity and lack of fundamental understanding of magnetic bearing static and dynamic performance characteristics have limited its application in both aerospace and industrial machinery.

One important application where detailed knowledge of magnetic bearing force characteristics is required is their use as force measurement devices in rotordynamic test rigs[1,2,3,4,5]. Scharrer et al.[1] showed that use of magnetic bearings for this application requires accurate calibration of the magnetic bearing's static characteristics and transfer function in order to obtain acceptable measurement uncertainty. Without such a calibration, the data from the test apparatus will be questionable at best.

To better understand magnetic journal bearing technology, a number of researchers have attempted to characterize them both analytically and experimentally. Hibbs and Scharrer[6] and Scharrer and Powers[7] review previous efforts in magnetic bearing actuator analysis and rotordynamic analysis, respectively.

There are basically two experimental approaches to the characterization of journal bearings (magnetic or otherwise), rotor model-matching and direct component measurement. Rotor model matching involves the building of a test rotor with somewhat known properties and mounting the rotor in a housing with two of the bearings of interest. Test data for rotor displacement is measured and through comparison with rotor static and dynamic analysis predictions, journal bearing performance is inferred. This technique has been utilized in the past with many kinds of fluid film and mechanical bearings with the same result: large uncertainty and misleading results. This technique has also recently been utilized for magnetic bearings[8,9]. No attempt at predicting the uncertainty was made in either case.

Accurate results for journal bearing characteristics are best obtained through direct component measurement. This technique requires the complete isolation of the test bearing so that all forces are reacted through the test bearing and measured directly. Imlach et al.[10] reported the first component measurements of static force characteristics for a heteropolar magnetic bearing. A closed loop controller was employed. The measurements were somewhat indirect in that a load was applied at the end of the shaft and analytically corrected to adjust for the offset relative to the bearing's actual position. The authors reported stiffness as a function of shaft eccentricity. No experimental uncertainty was reported.

Knight et al.[11] tested a heteropolar magnetic journal bearing without a controller. Loads were applied to one actuator at a time. The authors reported force of the single actuator as a function of position. Experimental uncertainty was reported.

The present effort is focused on measurement of the force versus current characteristics of a full heteropolar bearing with closed loop control.

ANALYTIC MODEL

The current model[6] is focused on the actuator design and characterizes the following nonlinearities of magnetic bearings.

- Nonlinear stator/rotor core permeability
- Nonlinear force/ flux relationship
- Magnetic leakage and fringing effects
- Air gap non-uniformity (eccentricity)
- Eddy current effects - rotational and control current frequency

Slew rate and other controller dependent effects are modeled separately as discussed by Scharrer and Powers[7]. The two dimensional magnetic bearing analysis solves the harmonic vector potential equation. Derivation continues from Maxwell's field equations:

$$\partial/\partial x\left(\nu_z \frac{\partial A_z}{\partial x}\right) + \partial/\partial y\left(\nu_y \frac{\partial A_y}{\partial y}\right) = \sigma \frac{\partial A_z}{\partial t} - J_z \quad (1)$$

The transient term is further split into a rotational and control current term. The control current is assumed to harmonically vary so that $J_z = J_z e^{j\omega t}$ that requires the magnetic vector potential to vary similarly, $A_z = A_z e^{j\omega t}$. A novel approach is used to solve for the vector potential.

Nonlinear magnetic flux - magnetomotive force relationship is included in the analysis by allowing the reluctivity to vary with the magnetic flux such that $\nu = \nu(B)$. The medium is assumed to be isotropic ($\nu_x = \nu_y$). The periodic boundary condition was used between the actuators on the magnetic bearing, and zero vector potential was set at the inner radius of the rotor and the outer radius boundary.

TEST APPARATUS

The test apparatus employed for this effort is shown in figure 1. The test rig can support the test article either horizontally or vertically. For this effort, the test article was supported vertically in order to eliminate gravity effects and difficulties associated with determination of the zero position control current[10].

In the vertical position, the test article is supported by four flexures that connect to the test article through a ring attached at the mid-plane. The stiffness of the flexures was small. Calibration of the flexure stiffness was accomplished to account for its contribution to the measurement uncertainty. For this test the shaft was nonrotating and hard mounted to the support structure. Four SKF proximity probes were mounted at each end of the test article. The proximity probes had a range of 1.3 mm and were specially calibrated for this application to insure that the magnetic field would not interfere with the measurement accuracy. SKF had the only product found to be suitable for this application. The load was applied through a loading rod connected on one end to the mounting ring and at the other end to a strain-gauged load bolt from A. L. Design. The capacity of the load bolt was 9200 N. All displacement, current, and load data was acquired using a Pemtech data acquisition system. The sample rate used was 100 Hz.

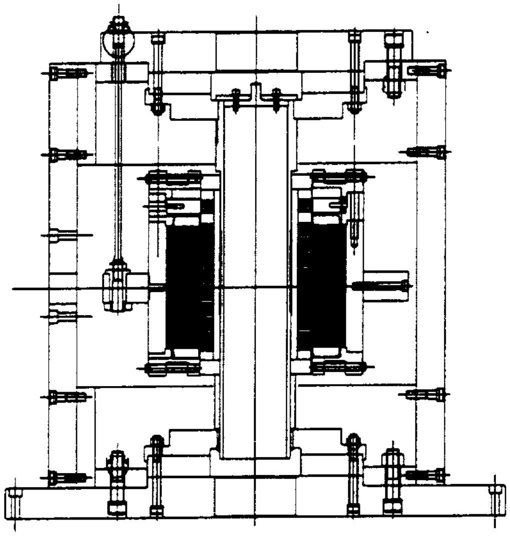

Figure 1. Magnetic bearing test rig

TEST BEARING

The test bearing was a four pole, E-sector heteropolar magnetic bearing from Revolve Technologies. The bearing geometry and material properties are given in Tables 1 and 2, respectively. A representative magnetization curve for Hiperco 50 with a rotor anneal is shown in figure 2.

Table 1. Bearing Geometry

Stator Stack Length (mm)	152.400
Stator OD (mm)	226.081
Stator ID (mm)	140.716
Rotor OD (mm)	139.700
Rotor Lamination ID (mm)	105.973
Nominal Gap (mm)	0.508
Small Pole Width (mm)	16.060
Pole Height (mm)	25.819
Slot Width (at ID) (mm)	15.277
Pole Centerline Angle (radians)	0.224

Table 2. Material Properties

Rotor Material	Hiperco 50
Stator Material	Hiperco 50
Sat. Flux Density, Tesla	1.80
Rotor Lam. Thickness (mm)	0.3556
Stator Lam. Thickness (mm)	0.3556
Mat. Resistivity (μohm.mm)	48.0
Density (N/cu.cm)	0.07

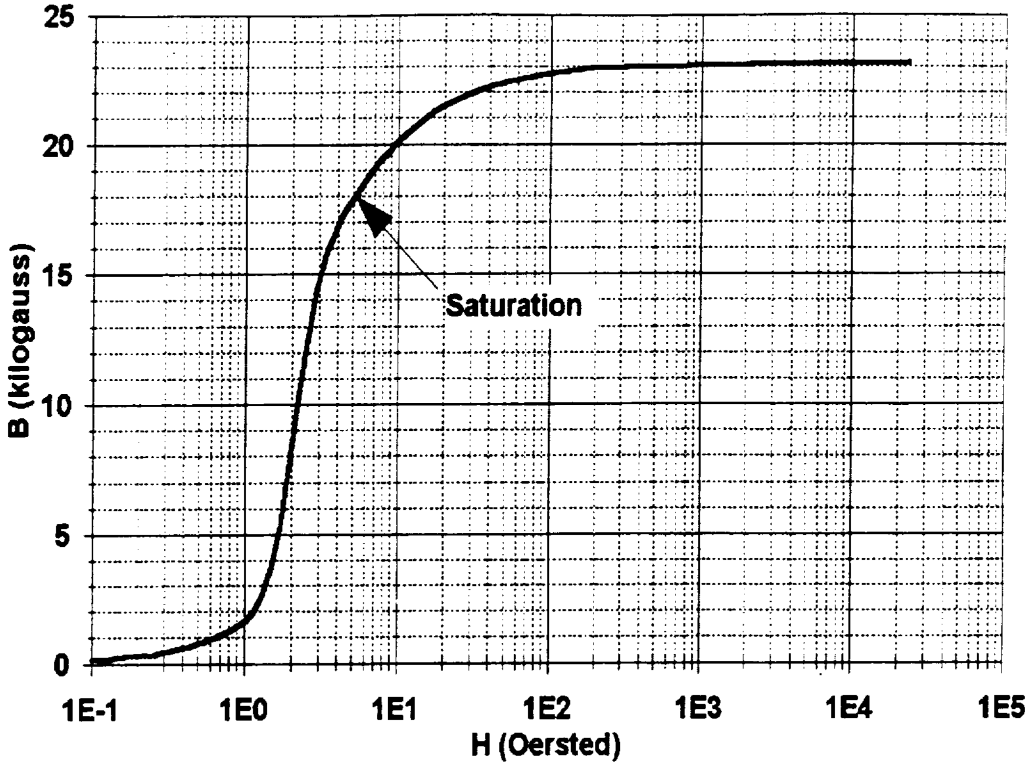

Figure 2. Magnetization curve for Hiperco 50

UNCERTAINTY ANALYSIS

The uncertainty analysis was performed using the methods outlined by Coleman and Steele[12]. End to end calibration of the entire system (i.e., transducer to D/A) was conducted to obtain the necessary inputs to the uncertainty analysis. The calculated uncertainties in the force and current measurements were 10.5 N and 0.25 mA, respectively.

RESULTS AND COMPARISON

Using the loading rod, the bearing was incrementally loaded over the range 0-8000 N. The bearing load was increased in 222 N increments. Data was taken continuously as the load was increased and decreased over the complete range. The loading was applied through the center of the actuator pole and between actuator poles. The bearing maintained a centered position for all load points. The results of the on pole loading are shown in figure 3. The figure shows that the nonlinear predictions are much closer to the test data and have the same characteristic curvature as the test data. The linear predictions are in error as much as 20% when compared to the test data. Figure 4 shows the load between pole data. Again, the nonlinear predictions are much closer to the test data than the linear predictions. The curvature in the data and the nonlinear prediction is much less pronounced.

The current shown in the graphs is twice the control current. Beyond around 5 amps on the graphs, the loaded actuator becomes saturated. Bias current in the actuator gives a maximum magnetic flux around 17 kG which is in the upper part of the linear range of the magnetization curve (see figure 2). This indicates that the bearing is operating in the nonlinear range of material properties.

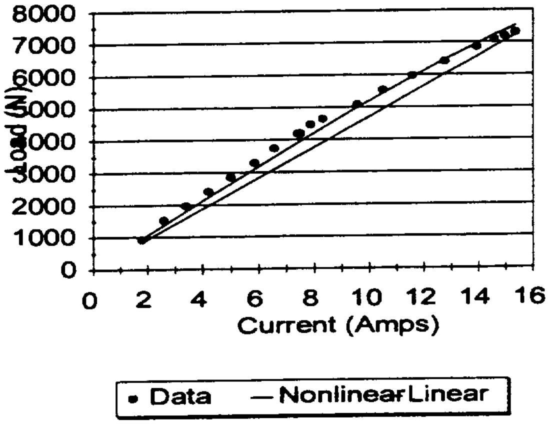

Figure 3. Load on pole data

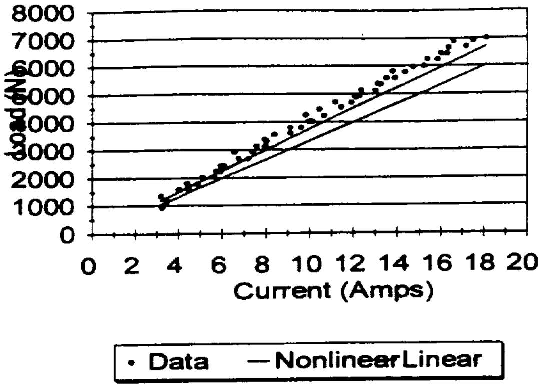

Figure 4. Load between poles data

CONCLUSIONS

New experimental data for the force versus current characteristics of a heteropolar magnetic bearing were presented. The data indicate that the force characteristics are nonlinear. Results from a previously developed nonlinear analysis technique were compared to the test data. The agreement between theory and experiment was good.

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