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MEASUREMENT and CALCULATION of FORCES in a MAGNETIC JOURNAL BEARING ACTUATOR

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Abstract

Numerical calculations and experimental measurements of forces from an actuator of the type used in active magnetic journal bearings are presented. The calculations are based on solution of the scalar magnetic potential field in and near the gap regions. The predicted forces from a single magnet with steady current are compared with experimental measurements in the same geometry. The measured forces are smaller than calculated ones in the principal direction but are larger than calculated in the normal direction. This combination of results indicates that material and spatial effects other than saturation play roles in determining the force available from an actuator.

1. Introduction

Recently, there has been much interest in the use of active magnetic bearings to replace or augment traditional bearings in turbomachinery. Magnetic bearings offer a number of potential advantages, including low power loss, suitability for harsh environments, and the ability to change the bearing characteristics to minimize vibration.

This paper presents data on calculation and measurement of forces from a magnetic actuator similar to those that are used in magnetic journal bearings. The data are for open-loop, steady conditions only and are part of the development of models for active bearings.

Much research has recently been devoted to magnetic bearings. No extensive literature survey is attempted in this paper, but from a sampling of the published papers on the topic [1-9], and the proceedings of the two international symposia on magnetic bearings [10,11], it is clear that the concentration is on control aspects. Although the development of robust control strategies is important in optimizing magnetic bearing characteristics, particularly stability characteristics, it is also necessary to understand the forces arising from actuators in order to optimize fully a magnetic bearing system. This is expected to become increasingly important when the requirements for peak force and for force to weight ratio are stringent, which may be expected in aerospace applications. Better understanding of the characteristics of the journal bearing actuator is necessary in order to take advantage of all available parameters, including gap size, shape and material selection in a system optimization. This paper presents preliminary results of work toward this goal.

2. Theory

A computer program has been written that calculates the force exerted on the journal by a magnet having a steady current in its coils. The force is found by calculating the energy stored in the air gaps between the magnet and the journal, then performing a numerical perturbation to obtain a central difference of the energy change per unit position change. This gives the force in the direction of the perturbation. The force for a magnet at an arbitrary location can be calculated.

The algorithm includes the following assumptions:

i. The permeability of the metal is infinite compared to that of the gaps, which is assumed equal to that of free space. This implies that all the energy is stored in the gaps.

ii. All magnetic flux closes the path through both metal parts. Expansion or fringing of the field near the gaps is allowed, however.

iii. The coil current, therefore the MMF, is constant over a perturbation.

In an isotropic domain not containing currents, where time variations are only of low frequency, the magnetic field can be represented as the gradient of a scalar field $\phi(x,y)$.

The energy contained in the domain is

$$\sigma = \int_V \bar{B} \cdot \bar{B} dV \tag{1}$$

where the flux density B is given by

$$\bar{B} = -\nabla\phi \tag{2}$$

and the potential ϕ satisfies the governing equation

$$\nabla^2\phi = 0 \tag{3}$$

with the boundary conditions

$$\frac{\partial\phi}{\partial n} = 0 \text{ on free boundaries} \tag{4}$$

and, because of assumption (i) above

$$\begin{aligned} \phi &= \Phi_1 \text{ on pole face 1} \\ \phi &= \Phi_2 \text{ on pole face 2} \\ \phi &= 0 \text{ on journal surface,} \end{aligned} \tag{5}$$

as shown in Figure 1.

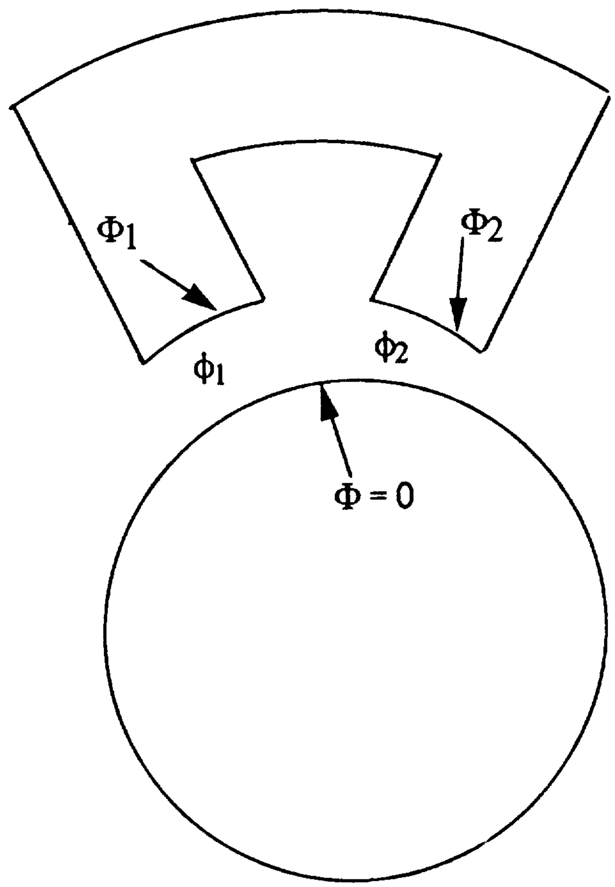
Initially the boundary values of ϕ on the pole faces, Φ_1 and Φ_2, are not known, but must be determined in relation to the datum of $\phi=0$ on the journal surface. The problem is made tractable by the fact that the governing equation is a linear one, so that the values of ϕ internally are determined within a multiplicative constant even for an arbitrary choice of boundary condition values. The fact that the flux must be the same through the two gaps allows the ratio

$$\kappa = \frac{\Phi_2}{\Phi_1} \tag{6}$$

to be determined. Then the fact that the difference between the two potentials is the magnetomotive force,

$$\Phi_1 - \Phi_2 = \zeta \tag{7}$$

allows determination of the actual surface potentials.



ϕ scalar potential field

Φ boundary value of scalar potential

Figure 1. Boundary conditions for solution of magnetic scalar potential.

2.1. Computer Program

The algorithm above is embodied in a FORTRAN computer program, GAPFOR1, which uses the finite element method for calculating the magnetic potential in two dimensions. For a given journal position the program calculates the gap height as a function of angular location and generates a finite element mesh for each gap. Flux fringing is allowed by extending the finite element domain beyond the edges of each pole face. Then the journal position is perturbed four times, first with positive dx and negative dx, then with positive dy and negative dy. At each step the mesh is regenerated and the energies are recalculated. The central difference analog to the derivative of energy is then computed, which is equal to the force in the perturbation direction.

To achieve rapid computational speed and efficiency, a dedicated finite element program was written for this application. It includes a grid generation routine as well as a banded gauss elimination solver for the assembled equations.

Forces from one magnet of a bearing

The computer program has been used to predict the forces from one magnet acting on the journal at various positions of the journal within the clearance space. The geometry corresponds to that of the experimental apparatus described in Section 3. Half of the entire clearance space is mapped, since all positions of the journal with respect to a single magnet can be represented in terms of positions in this half plane. Figures 2 and 3 show a map of force versus x,y position. The magnet is the upper vertical magnet, and a steady current of 1 ampere through the coils is used. The dimensions and other parameters are the same as those of the experimental apparatus described below. The figure indicates that the force in the y-direction (the principal force) varies between 6 and 180 N as the journal is moved along the y axis between $-0.7 < y/c < 0.7$. When the journal is also given an x-direction eccentricity, the y-force increases somewhat.

Except at x=0, there is also an x, or normal, component to the force, as shown in Figure 3. This normal force increases rapidy as x is made larger. At $x/c = 0.7$ it is 12% of the principal force.

3. Experiment

3.1 Design of Apparatus

The apparatus for force measurement is shown in an exploded view in Figure 4. Each magnet is independent and is wound with 400 turns capable of carrying current of 2.0 A in the steady state. In the steady force measurement mode, the rotor is held stationary by

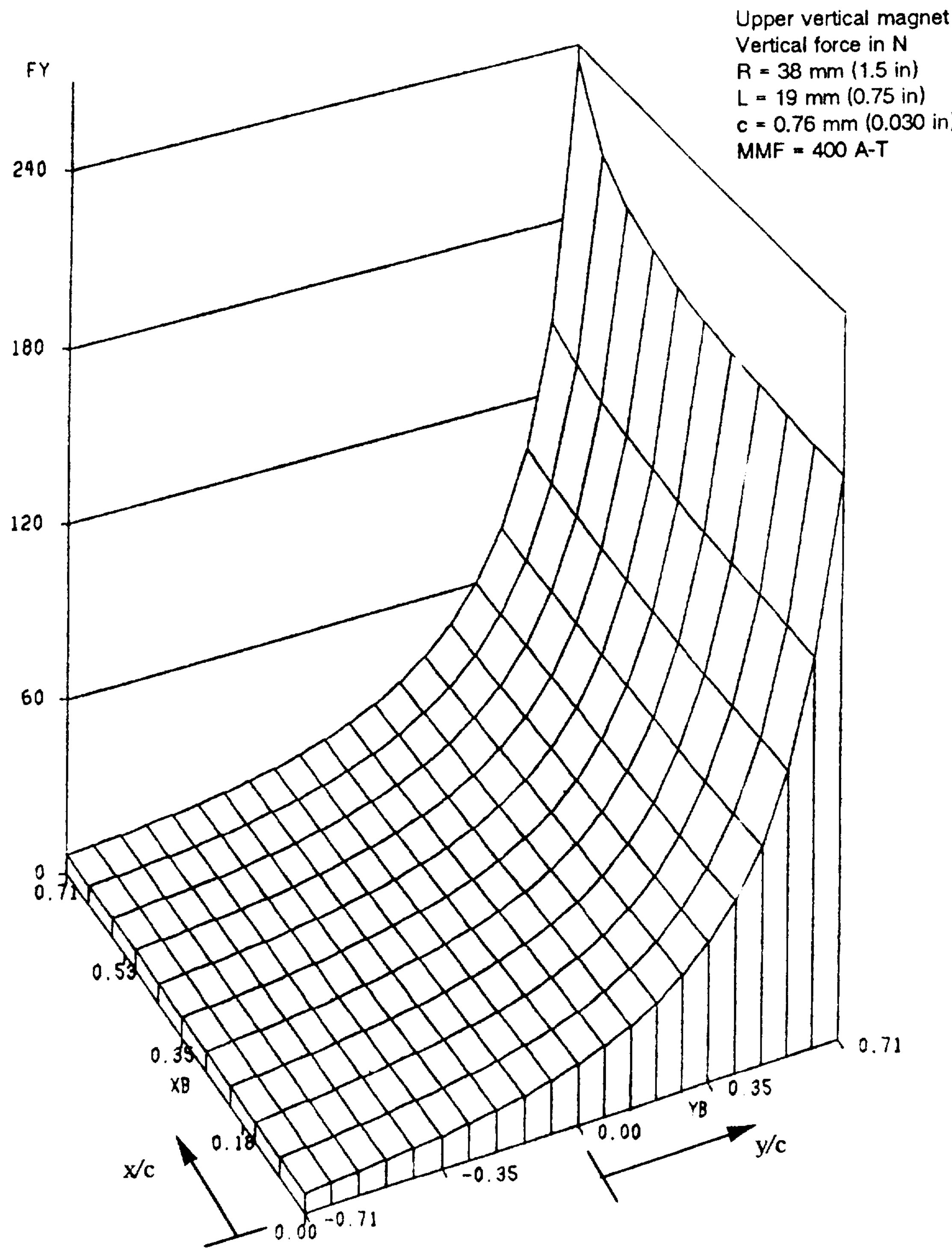


Figure 2. Attractive force from one magnet in principal direction.

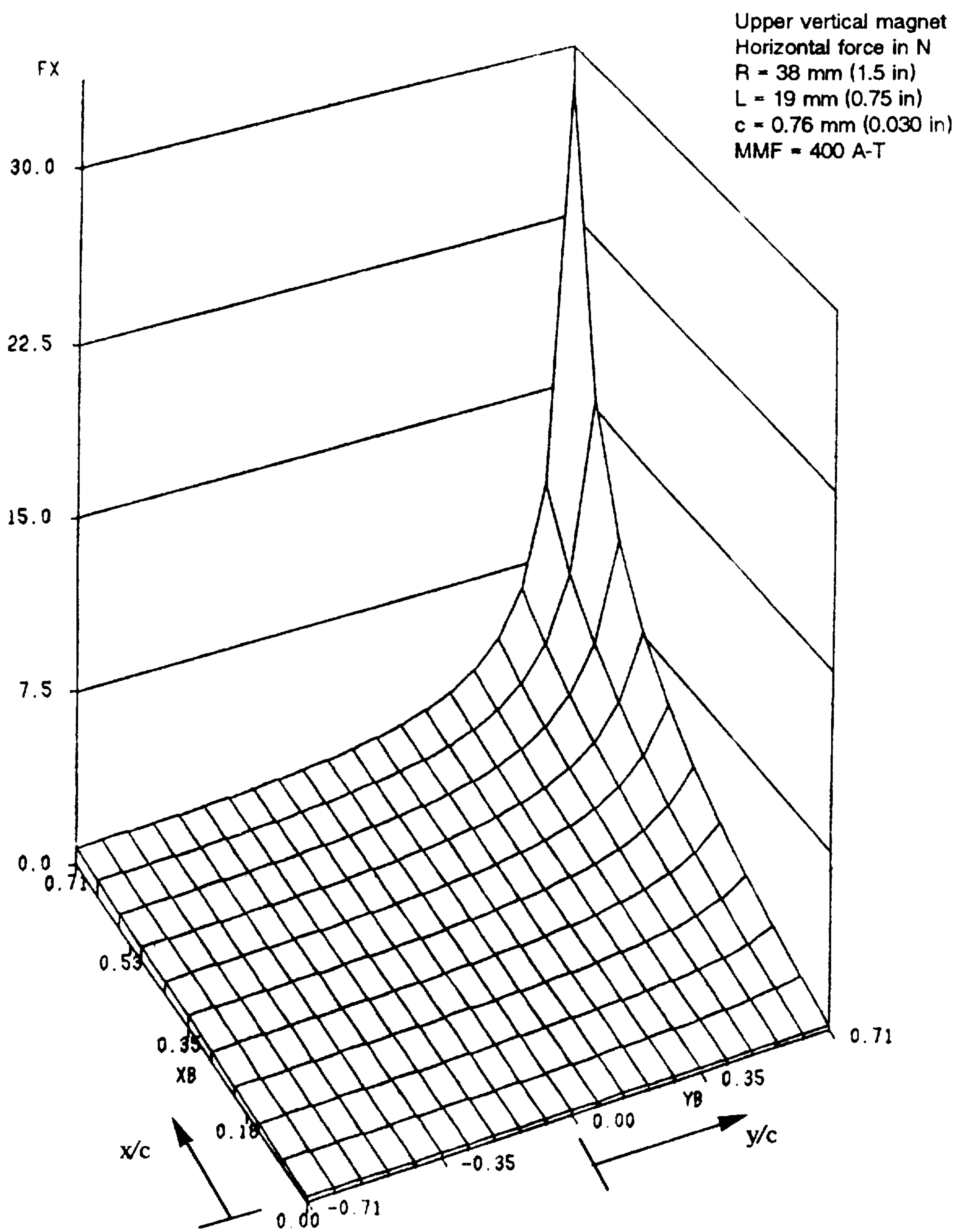


Figure 3. Attractive force from one magnet in normal direction.

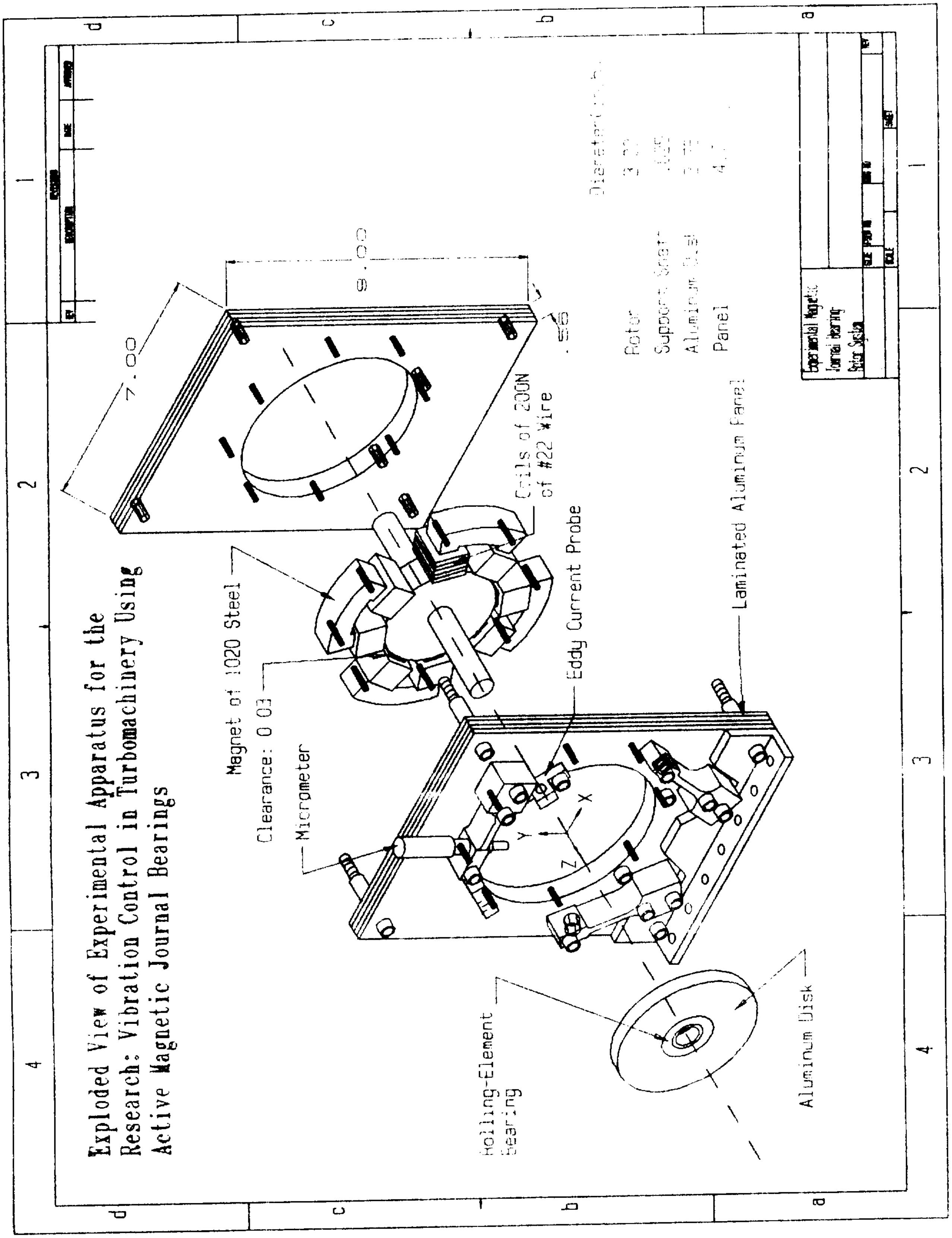


Figure 4. Assembly drawing of force measurement apparatus.

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pressure from six micrometer heads (three on each end) that are in turn held by cantilever arms instrumented with strain guage bridges. Thus all mechanical force on the rotor passes through the micrometer pushers and the strain guage arm transducers To minimize any tangential force on the pusher ends Teflon ball sockets with steel spheres were used between the pusher micrometers and the support disks. A full assessment of the uncertainty due to friction has not been completed.

3.2 Results of Measurements

Forces were measured at several locations and for several values of steady current. The figures referred to below display dimensional data as measured, with forces in Newtons plotted against y/c, the eccentricity ratio in the vertical direction. All of the forces presented are from the lower vertical magnet, so the vertical forces are in the negative y-direction. The eccentricites in the x-direction are all positive. Three traverses of the y-direction were made, at x/c positions of approximately 0.0, 0.24, and 0.45. Assessments of the errors in measurement are not complete; however, it is expected that the error in position measurement is no greater than plus or minus 0.05 in y/c and x/c, and that the error in force measurement is no greater that plus or minus 5 N. Errors in current level control are within 0.1 A. A larger series of measurements that were made before the addition of the ball/socket contacts was eventually discarded because the measurement error due to friction appeared to be significant.

The data support some of the anticipated relationships among the position, current and force variables but appear to disagree with other aspects of the present theory. Figure 5 shows the vertical force as a function of y/c for several values of current. The force tends to increase roughly as the inverse square of the gap. The magnitudes of the forces, however, are considerably lower than those predicted either by the linear finite element theory or by the traditional theory based on assumption of uniform gaps, and the ratio between measured and predicted forces is not constant. Figure 6 is a comparison of the measured forces with those predicted by the finite element calculation. The results indicate that at large gap and/or small current the ratio between the measured and predicted forces is about 1.5, but at smaller gaps and/or higher currents this ratio increases, eventually exceeding 2.0 for all the three values of current that are plotted.

Several mechanisms may be operating to cause these discrepancies, including flux leakage, non-uniform permeability of the materials and magnetic saturation. Some part of the disagreement is likely the result of measurement errors, but the differences appear to be significant even after allowing for reasonable experimental error. These disagreements reinforce the need for additional work, already planned, on force calculation.

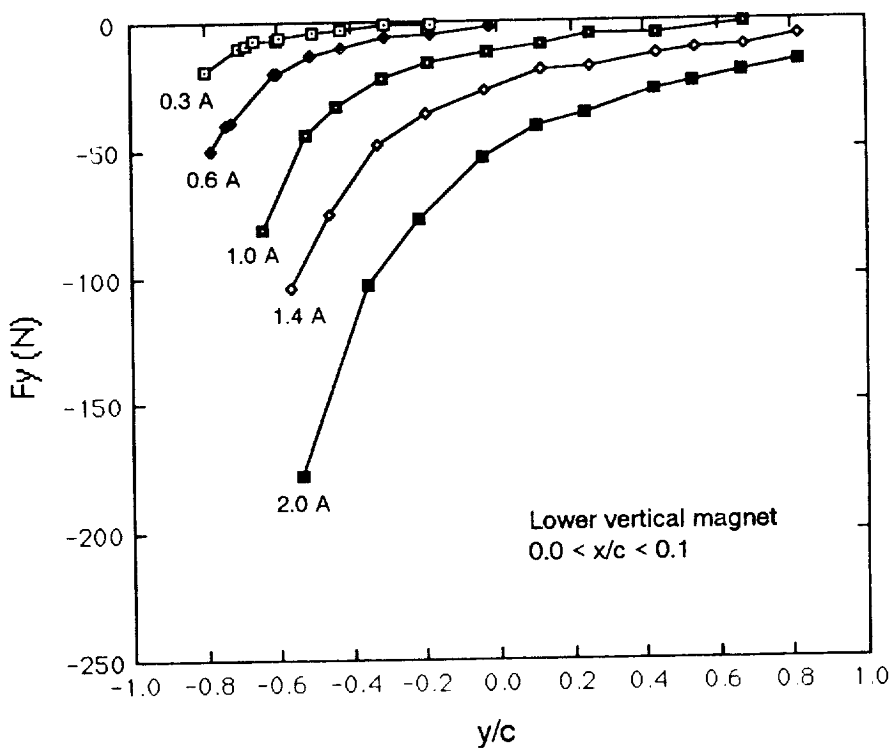

Figure 5. Vertical force from lower vertical magnet at different values of current.

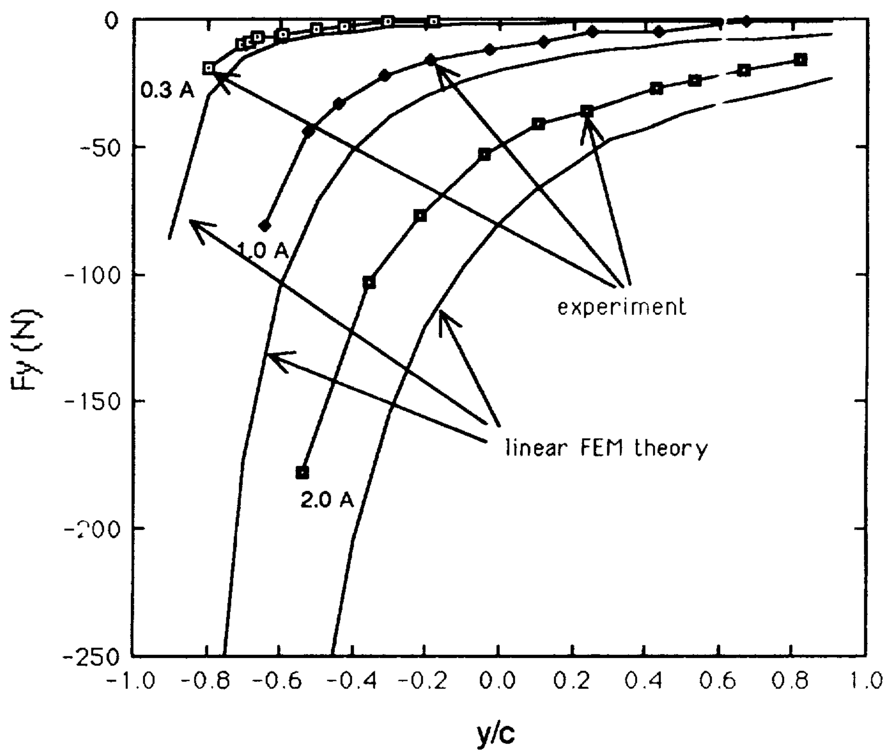

Figure 6. Measured forces and forces predicted by linear FEM calculation.

The linear finite element theory predicts the existence of forces from a magnet that are normal to its axis of symmetry when the rotor is displaced from this symmetry axis, but the forces that are measured are considerably stronger than those predicted by calculation. Figure 7 shows the x component of force when the rotor is placed as closely as possible on the y-axis. The normal force appears to be somewhat stronger at higher current levels but all these forces are small, on the order of 5 % or less of the principal force, so it is difficult to attribute much significance to this ratio in view of the experimental uncertainty. At higher values of x/c, however, the normal force becomes much more significant. Figures 8 through 11 show the vertical and horizontal components of force when the x/c value is 0.24 or 0.45, and Figure 12 shows the value of the x force as a function of position for several values of x/c while the current is held constant at 1.0 A. In general it appears that the normal force increases significantly with increasing x/c, and at x/c = 0.24 and 0.45 the horizontal force is about 10 % of the principal force. Theory predicts a ratio of about 2 % to 4 %.

Figure 13 indicates that within measurement uncertainty there are not significant differences in the y-components of force at the three different values of x/c. This is in general agreement with the theoretical predictions, which show some increase in the y-component of force as the x-eccentricity is increased.

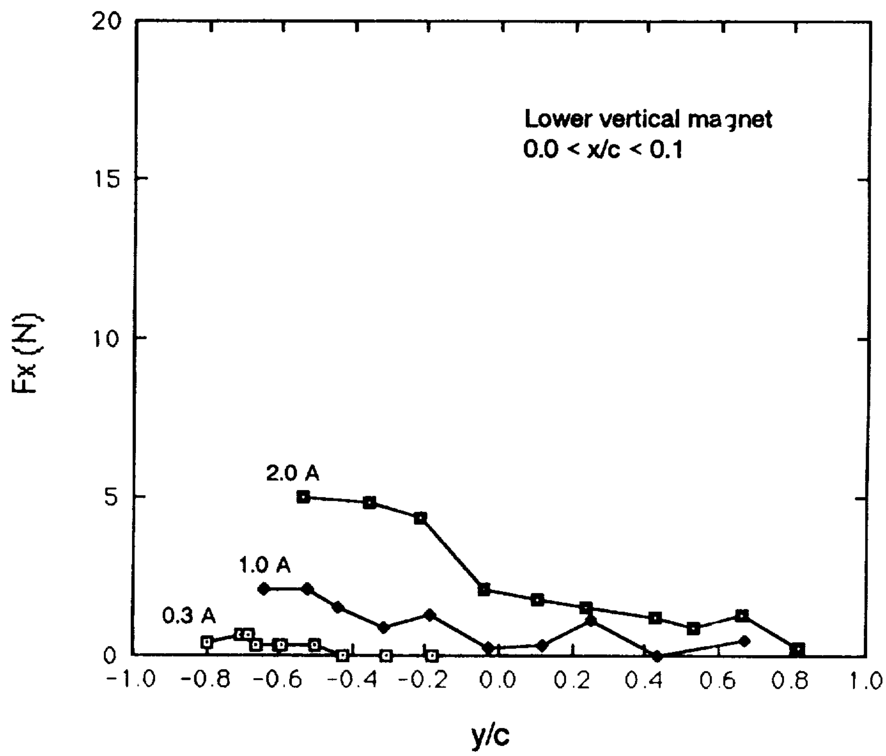

Figure 7. Horizontal force from lower vertical magnet at different values of current.

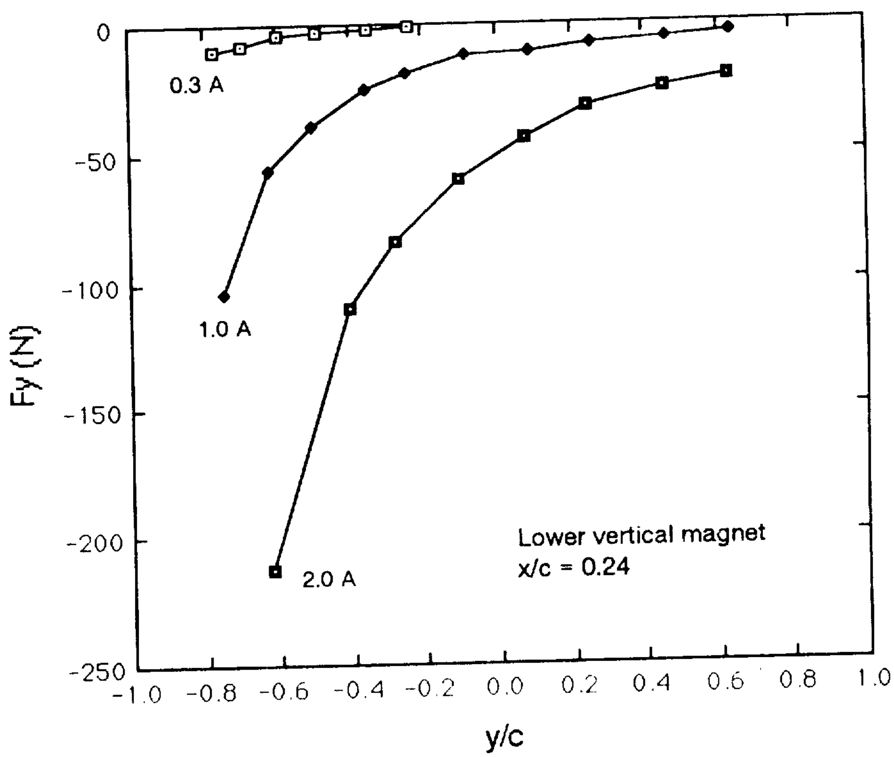

Figure 8. Vertical force from lower vertical magnet when x/c = 0.24.

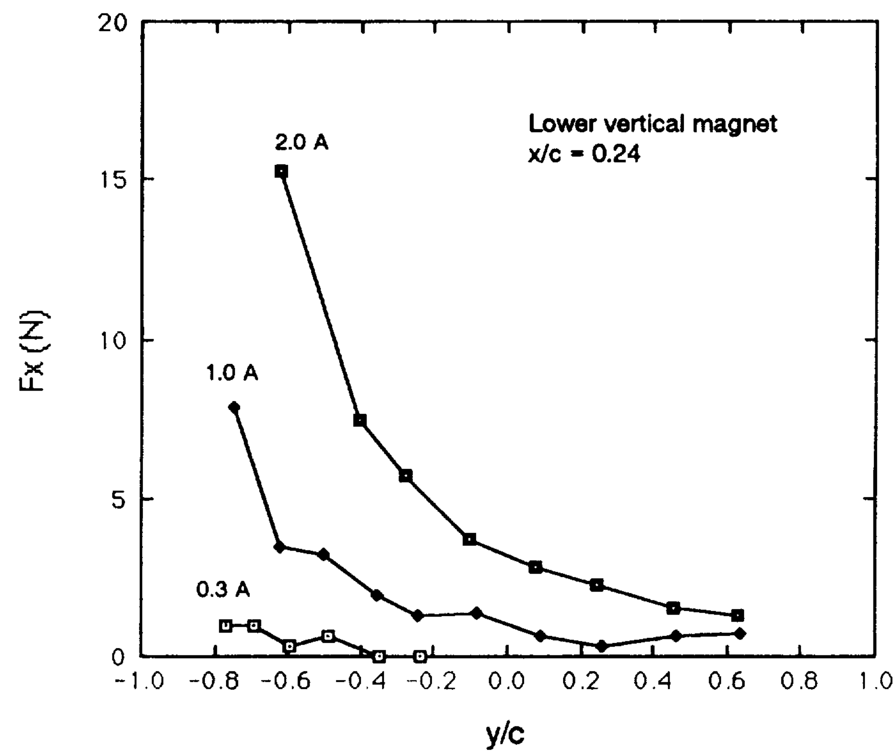

Figure 9. Horizontal force from lower vertical magnet when x/c = 0.24.

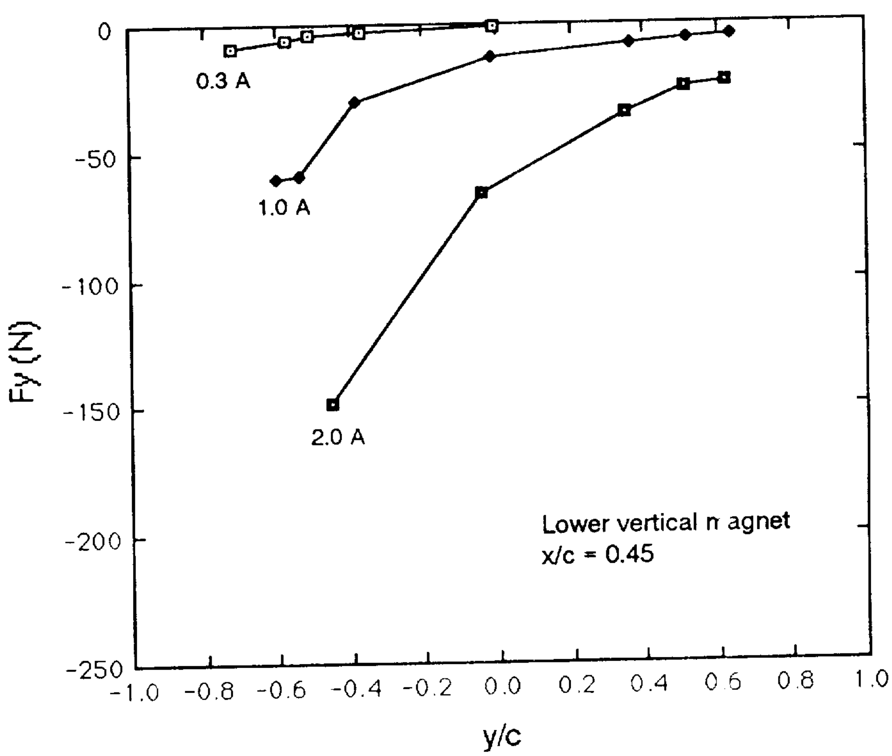

Figure 10. Vertical force from lower vertical magnet when x/c = 0.45.

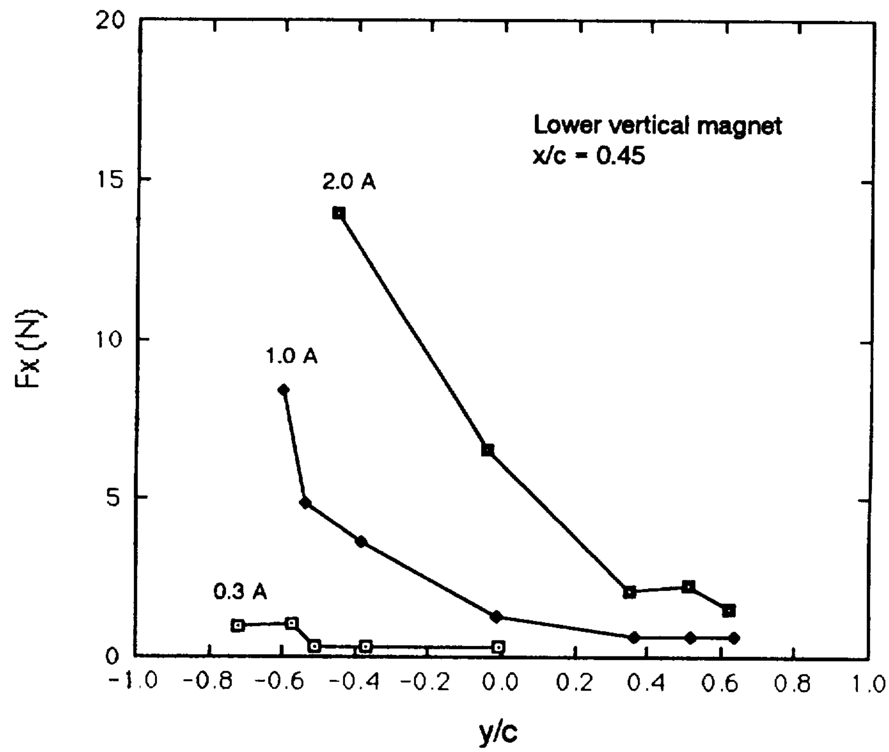

Figure 11. Horizontal force from lower vertical magnet when x/c = 0.45.

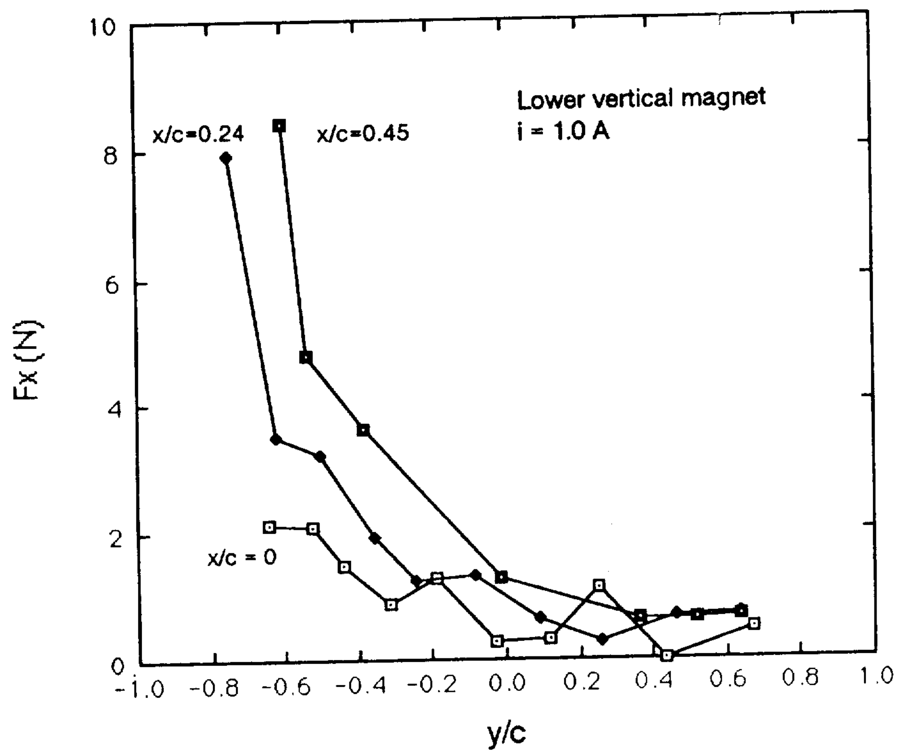

Figure 12. Horizontal force at different x positions with 1.0 A current.

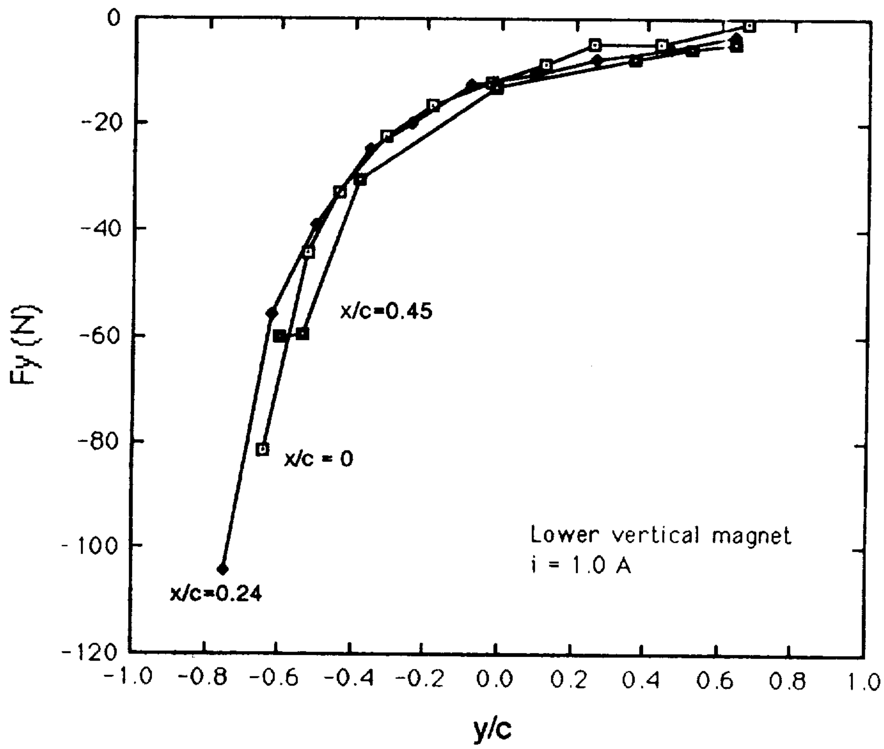

Figure 13. Vertical force at different x positions with 1.0 A current.

4. Conclusion

Numerical calculations and experimental measurements of forces in a magnetic journal bearing actuator are presented.

In summary, the general trends of the measured principal forces agree with the predictions of the theory while the magnitudes of forces are somewhat smaller than those predicted. The measured forces in the normal direction appear to be significantly larger than those predicted by theory when the rotor has an x eccentricity. The accuracy of the measured results has not been firmly established, and these conclusions should be reexamined as later measurements are made. It appears, however, that these effects will be significant even after considering experimental uncertainty, and both of these phenomena warrant further study.

Additional work is planned that will include force calculations considering the finite permeability of metals, and further force measurements using other materials. A new apparatus is being constructed that will allow more precise position control and force measurement.

5. Acknowledgments

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