Magnetic Thrust Bearing Concepts: Tests and Analyses

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ABSTRACT: The rotor/stator configurations considered are washer-shaped laminate stack (WL), tape-wound laminate stack (TL), U-shaped laminate stack (UL), solid metal (S), and solid wedge pieces. Since preloading reduces rotor vibration, the effects of preloading a WL rotor and TL stator system on the flux density/input current transfer function magnitude and phase are determined from tests. Since eddy currents result in power loss and phase lag, tests are performed on four rotor/stator pairs, i.e., WL/TL, TL/TL, TL/UL, and S/S, to find the one with minimal eddy currents. For S/S, the test results are compared with those obtained from a two-dimensional finite element analysis, for Silicon-Iron and Hiperco-27. Since overhanging the rotor beyond the stator is a common practice, the effect of this on the fringing of magnetic flux is studied using finite element analysis.

INTRODUCTION

ACTIVE magnetic bearings levitate a rotor by the attractive forces generated in a magnetic field due to the electromagnets. The magnetic bearings are electromechanical systems with their stiffness and damping properties dependent on both electronic and mechanical components. Thus, the stiffness and damping of the rotor/bearing system can be easily controlled. Hence, the magnetic bearings are finding increasing number of applications in rotating machinery. Magnetic bearings are used in both the radial directions and axial (thrust) direction. The thrust bearings can be either single-acting or double-acting depending on the number of stators. In this paper, a single-acting thrust bearing is studied.

Preload refers to a compressive force applied in the axial direction to prevent vibration of the rotor with respect to the stator. The force is applied with free weights. The effects of varying the preload on the flux density/input current transfer function's magnitude and phase have not been investigated in the past. These are determined from tests in this paper.

The eddy currents that arise in a thrust bearing result in a power loss (decrease in magnetic force) and phase lag between stator coil current and magnetic force (DeWeese, 1996). Increase in eddy currents result in increase in power loss and phase lag. Increase in phase lag worsens the system's stability.

The load capacity of an experimental double acting thrust bearing was reported by Allaire et al. (1989). The eddy currents for a magnetic bearing were first studied by Yoshimoto (1983). For an unlaminated radial magnetic bearing, eddy currents cause Hopf bifurcation of rotor equilibrium position (Hebbale, 1985). For laminated stator/rotors, the eddy currents decrease as an inverse square function of the number of laminates the rotor has (Smith and Oliver, 1994). The rotational losses of a thrust magnetic bearing were studied by Mizuno and Higuchi (1994). The power losses due to eddy currents increase as the square of the frequency (Kasarda et al., 1994). When a powdered metal is used for a double acting thrust bearing, the actuator bandwidth is 700 Hz (Baun, Fittro, and Maslen, 1994). The actuator performance differs significantly from a linear model due to eddy current and hysteresis nonlinearities (Allaire et al., 1994). The drag forces due to eddy currents including the skin depth was studied by Simon and Tichy (1994). The time lag due to eddy currents is modeled theoretically by a first order transfer function by Zmood, Anand, and Kirk (1987), Malone (1993), and was found experimentally by Fukata et al. (1991).

From the literature review given above it is seen that different rotor/stator configurations were not studied for their eddy currents. The present paper reports experimental and numerical findings on different rotor/stator configurations to find the one with minimal eddy currents.

Since overhanging the rotor beyond the stator is common practice, the effect of this on the flux fringing that it results in is investigated using finite element analysis for various "percentages" of overhang.

TESTS

An exploded view of the test setup for a single-acting magnetic thrust bearing is shown in Figure 1. The rotor, stator,

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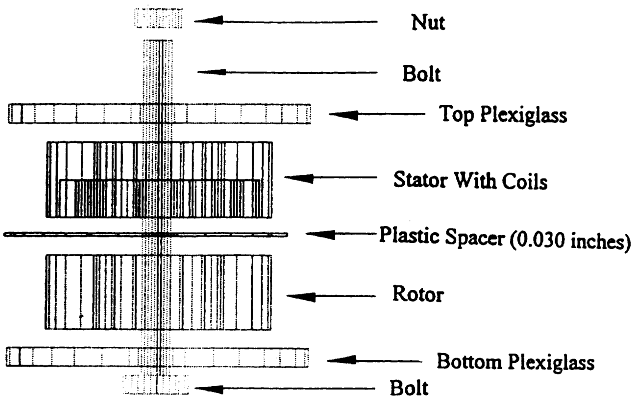

Figure 1. *Assembly view of magnetic bearing system.*

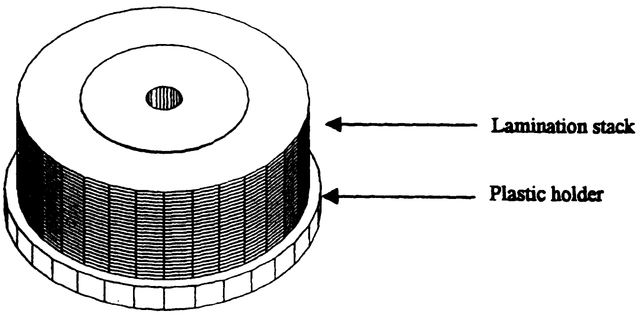

Figure 2. *Washer-shaped laminated rotor with plastic holder.*

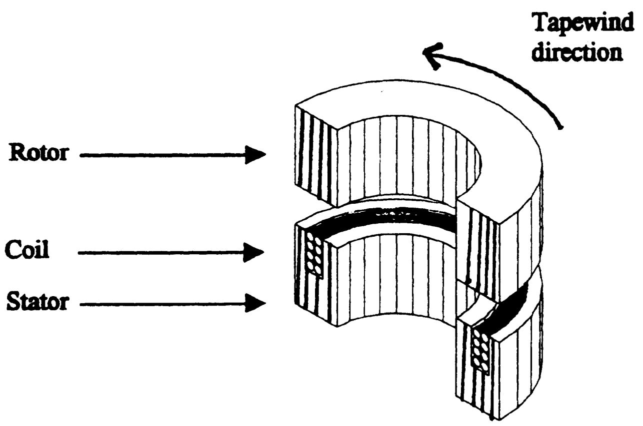

Figure 3. *Exploded cut view of tapewound laminated rotor, stator, and coil.*

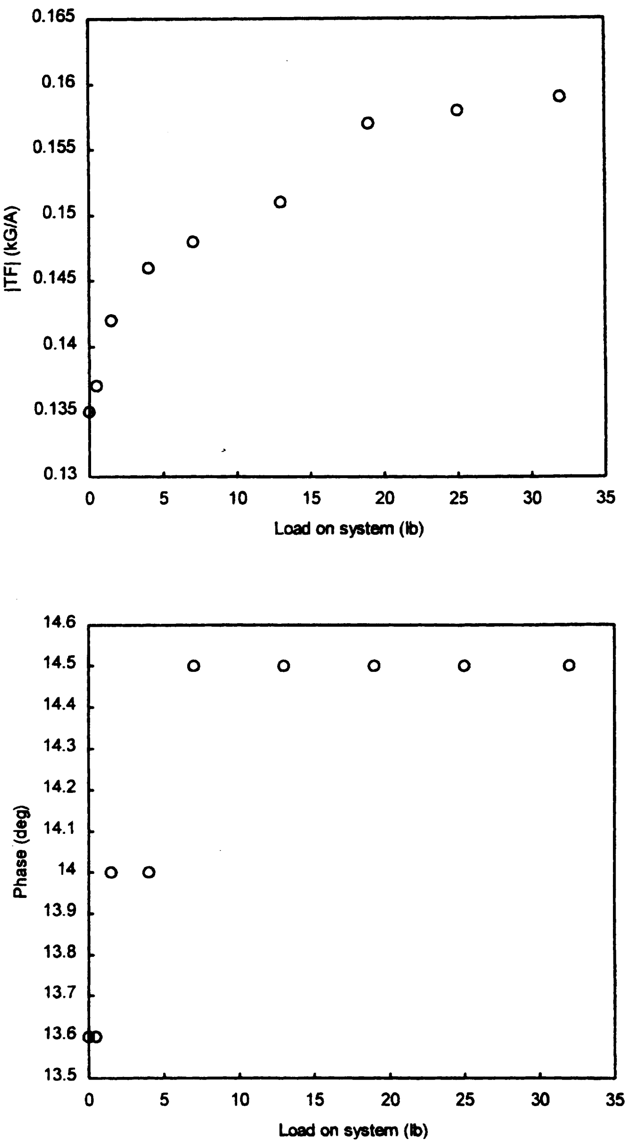

Figure 4. *Transfer function magnitude and phase of washer laminated rotor and tapewound laminated stator.*

and top plexiglass parts are changeable so that all rotor/stator configurations could use the same setup. The 30 mil (0.76 mm) plastic space provides the gap between the stator and rotor. A function generator generates a sinusoidal current (input) that is then passed through a power amplifier before passing through stator coil. A Hall probe measures the flux density, B (output) in the gap between the stator and rotor. The input coil current and the output flux density are fed to a two-channel signal analyzer to obtain the flux density transfer function, with flux density as numerator and coil current as denominator.

Effects of Preload

The preload is applied with free weights. Note that the stator weight acts on the rotor in all cases. So zero load means that no external weight is put on top of the system. Tests are performed to study the effects of preloading a washer-shaped laminated (WL) rotor shown in Figure 2, and a tapewound laminated (TL) stator shown in Figure 3. The tapewound component resembles a roll of tape for its wind direction. Note that WL laminations are not held together with an adhesive.

Figure 4 shows how the magnitude and absolute phase angle of the transfer function increase when the preload is increased. When the preload is greater than 20 lb (89 N) there is very little change in the transfer function magnitude and no change in phase. Hence this preload would be used in the following tests.

Eddy Currents for Nonwedged Configurations

In addition to the WL and TL rotor/stator configurations used in the preceding tests, the other configurations that would be tested for eddy currents are U-shaped laminated stator (UL) (Figure 5), and solid metal (S) stator and rotor.

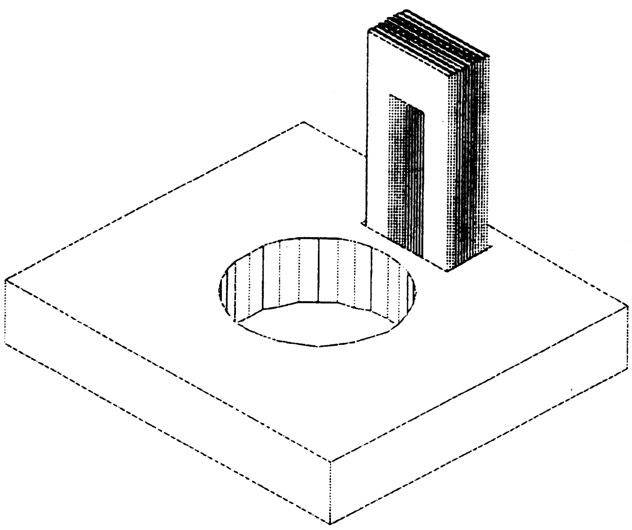

Figure 5. U-shaped Si-Fe laminates with wooden holder.

Table 1. Summary of transfer function magnitude and phase angle at 100 Hz for silicon iron configurations (compensated for circuit capacitance).

System Configuration	$\|TF\|$ kG/A	Phase Angle, Degrees	NI Static, Amp-Turns	NI Dynamic Amp (RMS)-Turns
Lam/Lam	0.154	−19.4	164.16	109.08
Washer/Lam	0.227	−14.9	163.62	109.08
Solid/Solid'	0.428	−9.75	162.00	109.50
Lam/ U shape	1.290	−7.96	159.90	110.25

The solid metal stator and rotor resemble a tapewound laminated stator shown in Figure 3.

The four rotor/stator pairs tested are WL/TL, TL/TL, TL/UL, and S/S. All parts are made of heat treated silicon iron. In all cases, the preload is 20 lb (89 N), and the operating frequency is 100 Hz. In testing, the static NI product is kept within 5% of 160 ampere-turns, and the dynamic NI product within 5% of 109 ampere-turns. This ensures almost equal conditions for all configurations, and for a sinusoidal current input results in a sinusoidal magnetic flux.

The transfer function magnitude and phase results are summarized in Table 1. It is seen that TL/UL configuration had the smallest phase angle (8°), which is 60% less than the worst case of 19.4° for a TL/TL. While the transfer function for the TL/UL is much higher than the others tested, the TL/UL also had a smaller pole area than the others tested. Table 2 shows the number of UL sets for stator required to provide the same force as the TL/TL and S/S. Six UL sets could be installed on the test article.

Eddy Currents for Wedge Stator

Cutting grooves on the stator is found to have almost no effect on the transfer function magnitude or phase. So the Hiperco-27 solid stator is machined into eight equal wedges, which are separated by 30 mil (0.76 mm) plastic spacers. Each spacer serves to take up the gap caused by machining the pieces and to provide electrical insulation between adjacent wedges. The latter should cause the eddy currents to break up into smaller paths, and reduce the phase lag caused by the eddy currents. The results and comparison with solid stator case is shown in Table 3. The phase lag decreased by 19%, which is good, but the transfer function magnitude also

Table 2. U-shaped laminated sets required to produce equivalent forces.

Comparison Configuration	Frequency of 10 Hz	Frequency of 50 Hz	Frequency of 100 Hz
Lam/Lam	1.76	1.57	1.27
Solid/Solid	5.70	5.45	5.16

Table 3. Solid and wedged stator results for Co-Fe at 100 Hz.

Stator Configuration	|*TF*| (kG/A)	Phase Angle (degrees)
Solid	0.430	−23.50
Wedged	0.372	−19.00

decreased by 13.5%, which is bad. The latter is perhaps due to the fringing of the magnetic field into the side (cut) faces of the wedges. So if it is possible to make up for the loss in the magnetic force, by increasing the current, then cutting the stator into wedges will increase the system's stability.

TESTS VERSUS FEA

The comparison is made only for the solid rotor solid stator (S/S) configuration. A two-dimensional axisymmetric model of solid rotor and solid stator, made using the finite element software ANSYS, is shown in Figure 6. As a static solution is sought, a symmetric mesh is chosen in the vertical direction. In the analysis, the magnetic flux density and phase lag are obtained by averaging the values across a pole face. A linear material assumption is made since the tests are performed with bias and control fluxes selected to ensure operation in the linear portion of the material B-H (flux density–flux intensity) curve.

The transfer function's magnitude and phase for Silicon-Iron are shown in Figure 7. For the transfer function magnitude, the theoretical (FEA) values are lower than the experimental ones at all frequencies. The theoretical phase lag is within ten percent of the experimental values at all frequencies except at 400 Hz.

The transfer function's magnitude and phase for Hiperco-27 (Co-Fe) are shown in Figure 8. For the transfer function magnitude, the theoretical values are within 5% below 200 Hz, 15% between 200 and 300 Hz. The theoretical phase lags are within 10% of the experimental values at all

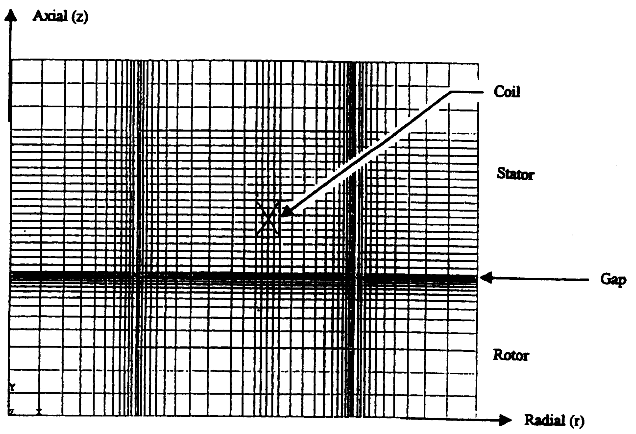

Figure 6. *Axisymmetric FEA model with equal rotor and stator.*

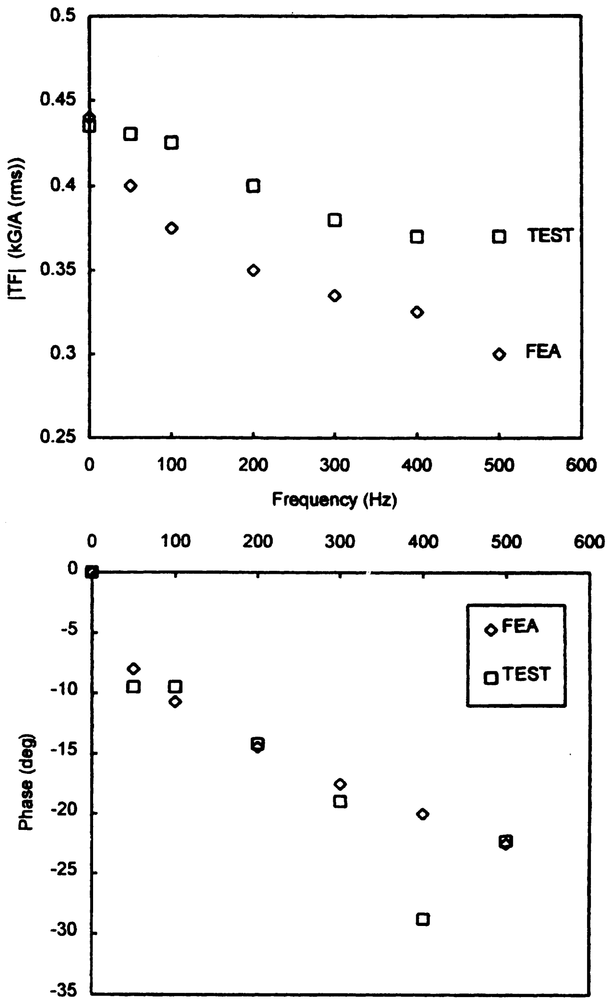

Figure 7. *Transfer function magnitude and phase for S/S Si-Fe.*

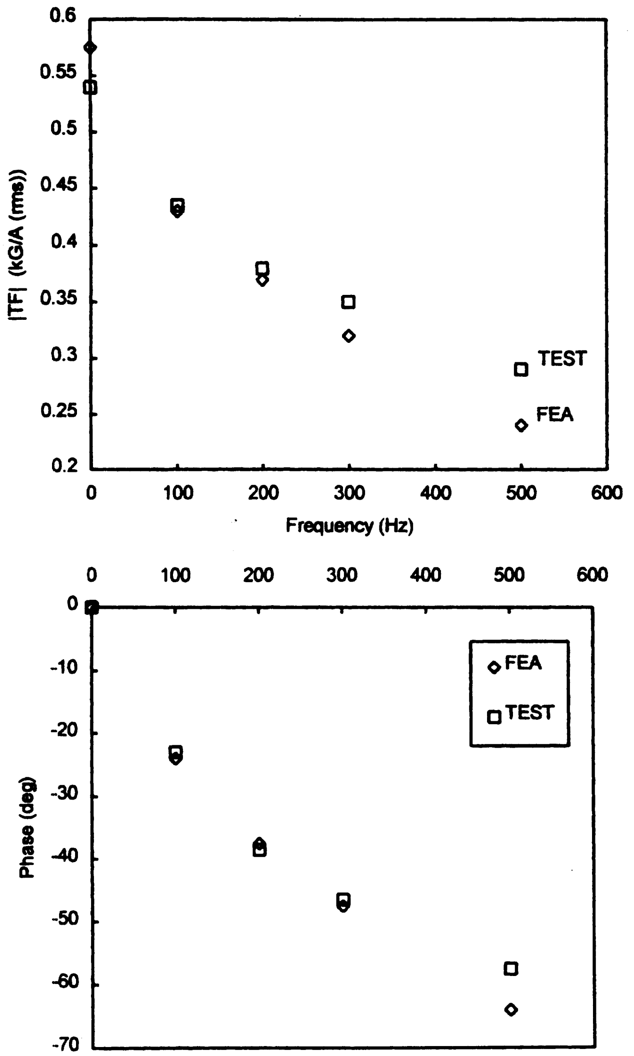

Figure 8. *Transfer function magnitude and phase for S/S Hiperco-27.*

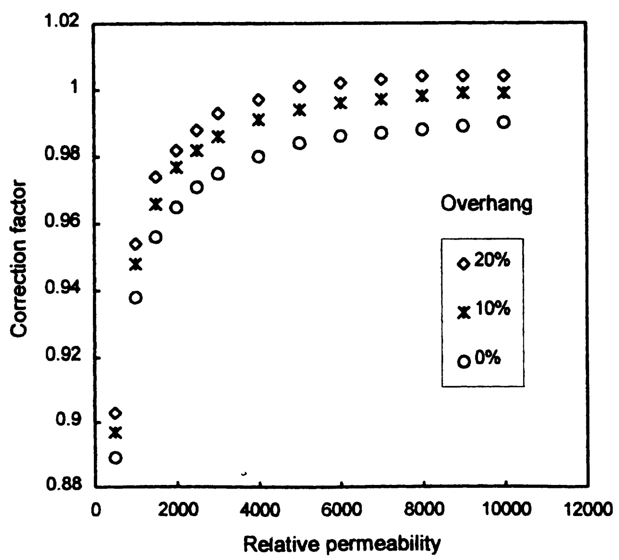

Figure 9. *Variation of fringe factor with overhang.*

frequencies measured up to 500 Hz. However, the theoretical values are greater than the experimental values below 150 Hz, and vice versa above 150 Hz.

FLUX FRINGING

This is determined using finite element analysis. The overhang of the rotor beyond the stator is determined as a percentage difference between the inside and outside radii of the stator. Defining the fringe factor as

$$\beta = \sqrt{\frac{F_{ANSYS}}{F_{1D}}} \tag{1}$$

For the one-dimensional calculation, the stator area is used in estimating the force, F_{1D}, from the flux density, B. Figure 9 shows how the fringe factors approach 1 for increasing amounts of overhang and relative permeability. Even at $\mu_r = 1250$, the fringe factor is above 0.948 (Baun, Fittro, and Maslen, 1994).

CONCLUSIONS

The effect of preloading the washer-shaped laminate stack was found to be an increase in the transfer function magnitude and phase angle up to 20 lb, above which there was no change. In studying the effects of eddy currents, the tape-wound laminated rotor with U-shaped laminated stator (TL/UL) gave the smallest lag (8°) which was 60% less than the worst case of 19.4° for a tapewound laminated rotor and stator (TL/TL). Cutting the stator into wedges resulted in a 19% decrease in phase lag and a 13.5% decrease in the magnitude of transfer function. The latter is perhaps due to flux fringing. The results from FEA for the solid rotor solid stator (S/S) case were less than those obtained from tests. If the rotor is overhung beyond the stator, and for large relative permeabilities, the fringe factors approach unity.

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