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**FLUX DENSITY AND AIR GAP EFFECTS ON ROTOR POWER LOSS MEASUREMENTS IN PLANAR RADIAL MAGNETIC BEARINGS**

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**ABSTRACT**

The rotor power losses in magnetic bearings are due to eddy currents, hysteresis, and windage. The influence of air gap magnetic flux density and air gap thickness is not well understood at this time. This paper presents measured results in two magnetic bearing radial configurations with a laminated rotor. The rotor power losses were evaluated by measuring the rundown speed of the rotor, in air, after the rotor was spun up to speeds of approximately 30,000 rpm in atmospheric air. The kinetic energy of the rotor is converted to heat by magnetic and air drag power loss mechanisms during the run down. A method of separating the hysteresis, eddy current and windage losses is presented. Eddy current effects were found to be the most important loss mechanism in the data analysis. Hysteresis and windage effects did not change much from one configuration to the other. The measured rotor power loss increased significantly as the magnetic flux density increased and also increased significantly as the air gap thickness decreased.

**NOMENCLATURE**

- b = Loss Coefficient
- C = Loss Coefficient
- d = Lamination Thickness (mm)
- f = Frequency
- J = Polar Moment of Inertia ( $N-s^2-m$ )

- N = Rotor Speed (rpm)
- $P_t$  = Power Loss (watts)
- V = Volume
- $\omega$  = Rotor Speed (rad/sec)

**INTRODUCTION**

The effect of rotor power losses in magnetic bearings are very important for many applications. In some cases, these losses must be minimized to maximize the length of time the rotating machine can operate on a fixed energy or power supply. Examples include aircraft gas turbines, space devices, or energy storage flywheels. In other applications, the heating caused by the magnetic bearing must be removed. Excessive heating can be a significant problem in machines as diverse as large compressors, electric motors, textile spindles, and artificial heart pumps.

Power loss studies in magnetic bearings published in the open literature have been very limited. Matsuura, et al [1988] discussed magnetic bearing losses including a partial Fourier analysis of magnetic flux as seen by the rotor as it passes the poles in the bearing. Higuchi, et al. [1986] presented some experimental rotating loss data in magnetic bearings. Ueyama and Fujimoto [1990] gave power loss results for an eight pole radial bearing. Matsuura and Hatake [1992] discussed a Fourier analysis of fringing and leakage effects on eddy current losses, indicating

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that pole edge effects may be the most important consideration. Kasarda et al. [1993,1996a] conducted loss measurements in a low speed test rig, operating up to approximately 2800 rpm (DN = 175,000), in air.

Kasarda, et al. [1994] discussed the design of the present high speed test rig in some detail and gave a sensitivity analysis of the loss modeling based upon the theoretical parameters involved. Kasarda, et al. [1996b] presented high speed loss results, using the same test rig employed for the work in this paper, for an 8 pole radial bearing constructed of silicon iron laminated materials. The rotor operated at a top speed of about 32,000 rpm, corresponding to a DN value of  $2.9 \times 10^6$  mm rpm. Variations in pole winding configuration and bias flux were examined. Bias flux was found to be very significant while pole winding was found to be not very significant. An analytical/empirical model was then applied to the loss measurements by Kasarda, et al. [1996c].

This paper reports the first results where rotor power losses were directly measured in the same stator with different bias flux densities and air gaps. A preliminary report of the test results was presented in Allaire et al. [1996]. A power loss model is then employed to evaluate the component hysteresis, eddy current, and windage losses.

#### TEST RIG

The test rig consists of a shaft with two magnetic bearings and two induction motors located at the shaft ends, as shown in Fig. 1. It has been designed to measure the power losses in magnetic bearings by accurately measuring the conversion of the rotor's kinetic energy into heat. This is done by measuring the time it takes for the rotor to run down from one speed to another. The rotor kinetic energy due to rotation is

$$E_k = \frac{1}{2} J \omega^2 \quad (1)$$

where  $\omega$  is the rotational speed in rad/s. The power loss is the time derivative of the kinetic energy

$$P_k = \frac{dE_k}{dt} = J \omega \frac{d\omega}{dt} + \frac{\omega^2}{2} \frac{dJ}{dt} \quad (2)$$

The second term is small for this test because the rotor does not have large dimensional changes so this expression reduces to

$$P_k = J \omega \frac{d\omega}{dt} = \left( \frac{\pi}{30} \right)^2 J N \frac{dN}{dt} \quad (3)$$

$$= P_h + P_e + P_w$$

where the polar moment of inertia is easily determined from a calculation and  $N(t)$  is easily measured from the rundown tests. On the right hand side of this equation, the power loss is written as the sum of the power loss due to hysteresis,  $P_h$ , the power loss due to eddy currents,  $P_e$ , and the power loss due to windage,  $P_w$ .

It has been shown in previous work by Kasarda et al. [1996a,1996b, 1996c] that the power loss can be written in terms of frequency dependent parameters as

$$P_k = C_h \omega + C_e \omega^2 + C_w \omega^{2.8} \quad (4)$$

based upon analytical/empirical models. In this formula, the skin effects are neglected [Kasarda, 1996b]. Analytical/empirical modeling results including skin effects for the data presented in this paper are not available at this time.

The test rig has been designed so that the only significant loss mechanisms come from the magnetic bearings: eddy current losses, hysteresis losses, and air drag. The two electric motors drive the rotor up to peak operating speed and then they are shut off. The motor stators have been shown to not have any significant residual magnetic drag during run down [1996b].

The outer diameter of the bearing journals is approximately 89.0 mm (3.5 in) and the test rig is designed to operate up to 50,000 rpm resulting in a DN of  $4.5 \times 10^6$  mm-rpm. However, the yield strength of the current silicon iron bearing limits

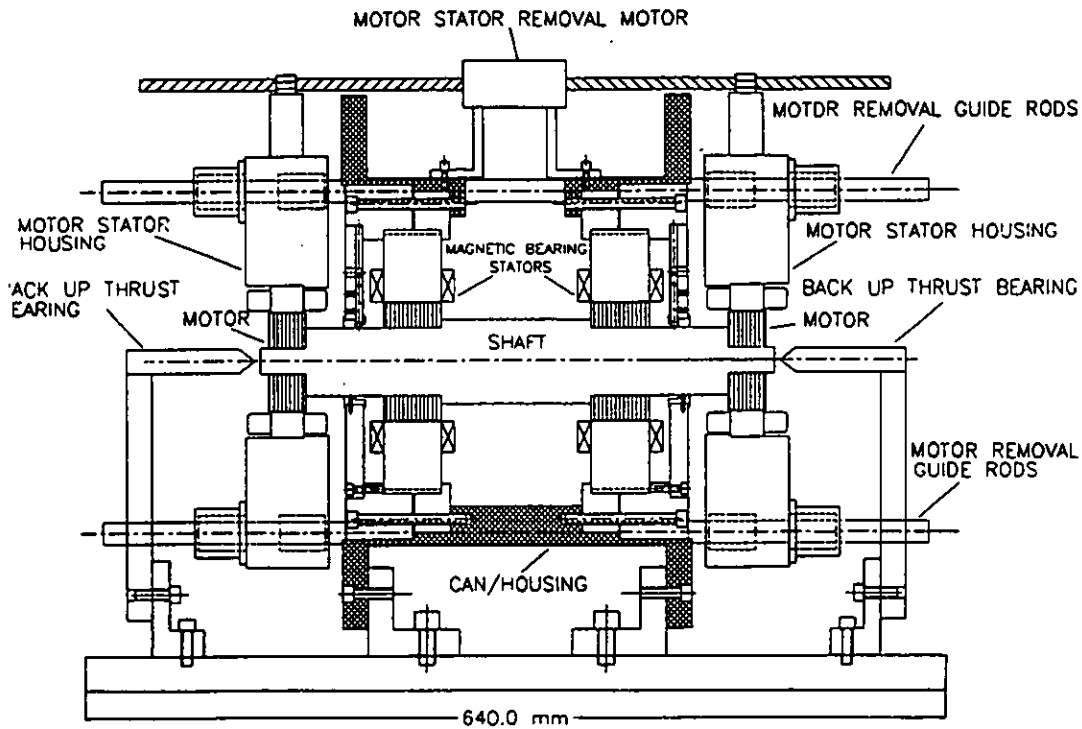


Figure 1. Diagram of Magnetic Bearing Loss Test Rig

the peak speed to 32,000 rpm. The rotor first critical speed is at approximately 84,000 rpm so the rotor is considered rigid. Additional details of the test rig design are given in [Kasarda, 1994].

gap of 0.762 mm (0.030 in) while

#### MAGNETIC BEARING PROPERTIES

One magnetic bearing stator has been used in these tests: an 8 pole radial planar (heteropolar) bearing. Stator dimensions were OD = 196.2 mm (7.726 in) and axial length of the bearing  $L = 43.6$  mm (1.715 in) (without coils). The radial length of each leg is 31.8 mm (1.253 in) and the circumferential width of each leg is 21.1 mm (0.79 in). Each pole has a coil winding of 94 turns. The stators were constructed of 0.356 mm (0.014 in) 3% silicon iron laminations. The stator has a total pole face area which covers 53% of the journal surface area. The radial bearing geometry is shown in Fig. 2.

Two rotors, with mass moments of inertia  $J_1$  and  $J_2$ , were employed. The bearing lamination stack diameters, shrunk fit onto the rotors, were approximately OD = 89.0 mm (3.50 in), shaft OD = 50.8 mm (2.0 in). Both were constructed of 3% silicon iron lamination thickness of 0.356 mm (0.014 in). The laminations are stacked axially along the shaft to restrict the development of eddy currents moving in the axial direction. The two rotors had two different air gaps; Rotor R1 had an air

Radial (Heteropolar)

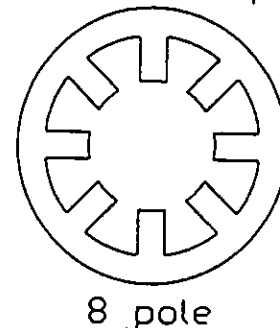


Figure 2. Radial Bearing Geometry

rotor R2 had an air gap of 0.381 mm (0.015 in). The different gap thicknesses were obtained by using two different rotors with different rotor lamination OD. The polar moment of inertia of the first rotor is  $J_1 = 8.10 \text{ N-s}^2\text{-mm}$  ( $7.02 \times 10^{-2} \text{ lbf-s}^2\text{-in}$ ) and for the second rotor  $J_2 = 8.16 \text{ N-s}^2\text{-mm}$  ( $7.08 \times 10^{-2} \text{ lbf-s}^2\text{-in}$ ). The difference is primarily due to the addition of a small collar in Rotor R2 to prevent the laminations from separating. The relative permeability of the rotor and stator material is estimated at 3,000.

#### MEASURED ROTOR POWER LOSSES

Measured power loss data was obtained for the radial bearing with the two different air gaps at three different values of bias flux density, 0.4 T, 0.5 T, and 0.6 T. The speed range was 0 to 30,000 rpm. Rundown plots are not shown for these cases but some example rundown plots are shown in [Kasarda, 1996b].

#### DATA REDUCTION

The measured data was recorded as speed (in rpm) vs. time (in seconds). The rundown data  $dN/dt$  was evaluated using the following model

$$\frac{dN}{dt} = b_1 + b_2 N + b_3 N^{1.8} \quad (5)$$

where the coefficients are defined as

$$b_1 = \frac{C_h}{J(\pi/30)^2}$$

$$b_2 = \frac{C_e}{J(\pi/30)^2} \quad (6)$$

$$b_3 = \frac{C_w}{J(\pi/30)^2}$$

from (3) and (4). An analytical expression for the actual speed curve was determined for each case and minimized using a simplex search method [Kasarda, 1996a]. The calculated power loss components were then determined from (4) and (6).

Six measured power loss curves are given in Fig. 3. They cover: bearing No. 1 (rotor R1 with air gap of 0.762 mm (0.030 in)) for static flux levels of 0.4, 0.5 and 0.6 T and bearing No. 2 (rotor R2 with air gap of 0.381 mm (0.015 in)) for static flux levels of 0.4, 0.5 and 0.6 T vs. rotational speed from 0 to 28,000 rpm. Some example power loss values are given in Table 1 for both of the bearings.

The coefficients  $b_1$ ,  $b_2$  and  $b_3$  are given in Table 2 for the data in Fig. 3 with the air gap of 0.76 mm (0.030 in) and for the air gap of 0.38 mm (0.015 in). The effect of various mechanisms for power loss are indicated by the coefficients in Table 2

and the specific loss values for each component are given in Table 3 at 28,000 rpm.

Table 1. Example Measured Rotor Power Loss vs. Bias Current and Nomial Bias Flux Density For Two Air-Gap Thicknesses at 28,000 rpm.

Magnetic Flux Density (T)	Bearing 1 (watts) Gap = 0.762 mm	Bearing 2 (watts) Gap = 0.381 mm
B = 0.4	580	929
B = 0.5	683	1385
B = 0.6	795	1497

The hysteresis coefficients are nearly the same for both bearings at a given value of flux density indicating that the hysteresis effects are nearly the same for each bearing. The eddy current coefficients are much larger, by a factor of 2 to 3, for the case with the smaller gap of 0.381 mm (0.015 in). Thus the eddy currents are the major difference in the larger losses at lower gap thickness.

The windage coefficients are nearly the same for the two bearings when the bias flux density is the same. There is a difference in the bias flux density of 0.6 T for the small gap configuration which is not well explained at this time.

#### STATIC MAGNETIC FLUX DENSITY MEASUREMENTS

The static magnetic flux density was measured in the air gaps for all cases to serve as an independent check on the magnetic flux density in the air gaps. A Hall probe of thickness 0.254 mm (0.010 in) was inserted into each of the eight air gaps in the bearing and the measured flux noted and found to be nearly constant in the air gap. The shaft was not rotating during the measurements.

Example measured static values are given in Table 4 for a nominal bias flux density of 0.6 T. The bias current in the bearing coils corresponding to the data in Table 4 was 3.50 A for bearing No. 1 and 1.94 A for bearing No. 2. The difference in the air gaps is due to the load on the bearing and experimental variability on using the flux probe. The average value for both bearings is approximately 0.62 T.

NASA Highspeed Power Loss Test Rig

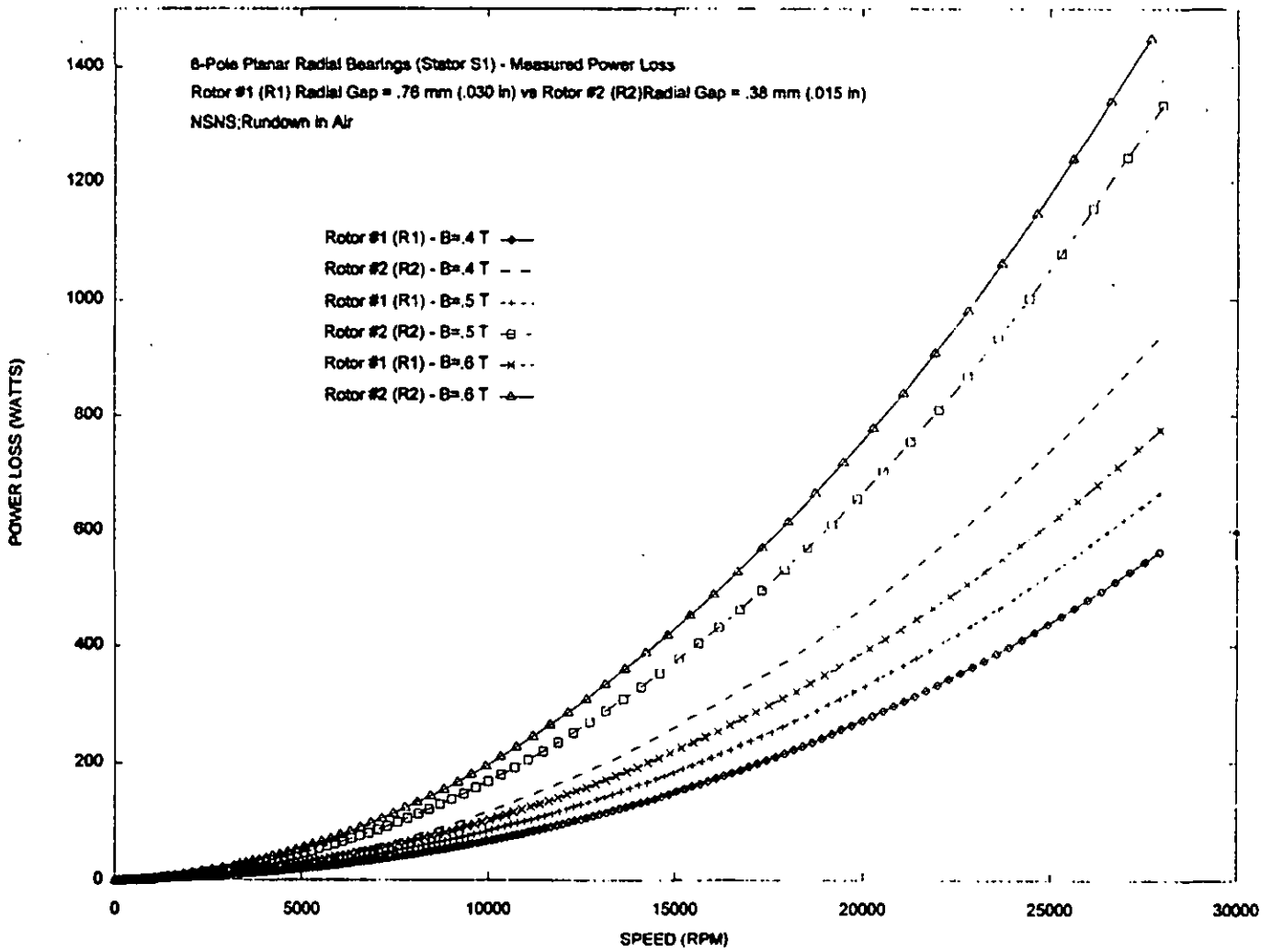


Figure 3. Measured Magnetic Bearing Power Loss vs. Speed at Three Bias Flux Density Values for Two Air Gap Thicknesses.

Table 2. Power Loss Coefficients For Magnetic Bearings Data Presented in Fig. 3 For Three Bias Flux Density Values and Two Air Gap Thicknesses.

Loss Coefficient	Air Gap Thickness=0.76 mm			Air Gap Thickness=0.38 mm		
	B=0.4 T	B=0.5 T	B=0.6 T	B=0.4 T	B=0.5 T	B=0.6 T
Hysteresis Coefficient $b_1$ (rpm/s)	-17.6	-22.1	-26.8	-16.0	-22.2	-25.2
Eddy Current Coefficient $b_2$ (1/s)	$-4.6 \times 10^{-3}$	$-6.2 \times 10^{-3}$	$-7.9 \times 10^{-3}$	$-1.0 \times 10^{-2}$	$-1.6 \times 10^{-2}$	$-1.9 \times 10^{-2}$
Windage Coefficient $b_3$ (1/rpm <sup>0.5</sup> s)	$-8.6 \times 10^{-7}$	$-7.8 \times 10^{-7}$	$-7.1 \times 10^{-7}$	$-7.4 \times 10^{-7}$	$-8.2 \times 10^{-7}$	$-4.0 \times 10^{-7}$

Table 3. Calculated Power Loss Components in Magnetic Bearing No. 1 with Three Bias Flux

Values and Two Air Gap Thicknesses at 28,000 rpm.

	Air Gap Thickness=0.76 mm			Air Gap Thickness=0.38 mm		
	B=0.4 T	B=0.5 T	B=0.6 T	B=0.4 T	B=0.5 T	B=0.6 T
Hysteresis Loss (watts)	44	55	67	40	56	63
Eddy Current Loss (watts)	320	432	550	701	1122	1333
Windage Loss (watts)	216	196	179	187	208	101

Table 4. Measured Static Air Gap Flux Levels in Bearings No. 1 and No. 2.

Pole No.	Stator No.1 Magnetic Flux Density (T)	Stator No. 2 Magnetic Flux Density (T)
1	0.71	0.68
2	0.60	0.62
3	0.66	0.66
4	0.59	0.57
5	0.62	0.63
6	0.56	0.52
7	0.67	0.70
8	0.56	0.59

ANALYTICAL/EMPIRICAL MODEL

It is of great interest to be able to calculate the power losses for other magnetic bearing configurations. Since the eddy current losses are the largest, these are considered first. The most commonly employed formula for the eddy current losses is

$$P_e = \frac{\pi^2 d^2 B_{max}^2 f_{eff}^2 V_{eff}}{6\rho} \quad (7)$$

where  $d$  is the lamination thickness,  $B_{max}$  is the maximum flux density in the rotor,  $f_{eff}$  is the effective frequency,  $V_{eff}$  is the effective volume of the rotor, and  $\rho$  is the resistivity of the material.

The effect of the flux density can be

determined by evaluating the eddy current coefficients vs. nominal air gap flux. Table 5 gives the ratio of the eddy current coefficient divided by the nominal air gap flux density squared. The values are close to one another, for a particular air gap thickness, indicating that the flux density squared model is reasonable. The values decrease somewhat with increasing flux density, which shows that other factors, not yet understood, are entering into the formula. However, most of the flux density effect is predicted by this classical eddy current power loss formula.

Table 5. Ratio of Eddy Current Coefficient to Flux Density Squared For Both Magnetic Bearings

Magnetic Flux Density	$b_2/B^2 (1/T^2)$	
	Air Gap =0.76 mm	Air Gap =0.38 mm
B=0.4 T	$-29 \times 10^{-3}$	$-62 \times 10^{-3}$
B=0.5 T	$-25 \times 10^{-3}$	$-64 \times 10^{-3}$
B=0.6 T	$-22 \times 10^{-3}$	$-53 \times 10^{-3}$

The effect of the air gap thickness on the eddy power loss is not directly predicted by the above formula at all. The nominal air gap flux density is the same in both measurements so it is likely that the value of  $B_{max}$  is not radically different. Thus, the only parameter in the power loss formula which is expected to change significantly between the two cases is  $V_{eff}$ . It is difficult to predict this effect without full numerical modeling such as finite elements. An alternative formula will have to be developed if it is desired to have a simple eddy current

power loss formula.

A two dimensional finite element model of the bearing was developed for the eddy current losses. The details of the finite element model are given in Rockwell et al [1997]. Figure 4 shows the comparison for the air gap thickness of 0.76 mm while Fig. 5 shows the results for the air gap thickness of 0.38. The rotor eddy current power losses are accurately modeled for a wide range of speed for three flux levels and two air gap thicknesses.

The hysteresis coefficients given in Table 2 and the power losses indicated in Table 3 show that the power loss increases with bias flux but does not change with air gap when the bias flux is the same.

Trends in the windage loss terms are not completely consistent. The windage power losses should be independent of the bias flux but the method employed in this paper does not produce this effect. More work needs to be done in this area and will be reported in future work.

#### CONCLUSIONS

Magnetic bearing rotor power loss variations with speed, bias flux density and air gap thickness were studied. The variation of rotor power loss vs. speed was evaluated for two different bearings. In each case, the total power loss varied approximately with  $\omega^2$  over the entire operating range tested.

A power loss model including hysteresis, eddy current and windage losses was applied to the data. Examples of power loss estimates were obtained for the two bearings at 28,000 rpm as illustrations of the values of hysteresis, eddy current, and windage losses. Eddy current effects were found to be the largest loss component. The power loss model fits the data reasonably well, except for the windage loss in Rotor No. 2 for a flux level of 0.6 T. A more detailed analysis of these and other test results using statistical modeling is in progress. It will be reported in future work.

As a general rule, the overall power increases significantly when the bias flux density increases. This is primarily due to the strong role of eddy current effects at high rotational speeds. The air gap effect is significant. A reduction in air gap by a factor of 2 yields a significant increase in power loss, nearly by a factor

of 2, as seen in Table 1. Again, this increase in the power loss is primarily due to higher eddy current losses.

Simple eddy current models predict the bias flux squared effect on eddy current losses in magnetic bearings but do not predict the effect of the air gap. A finite element model correlated well with the experimentally measured eddy current power loss.

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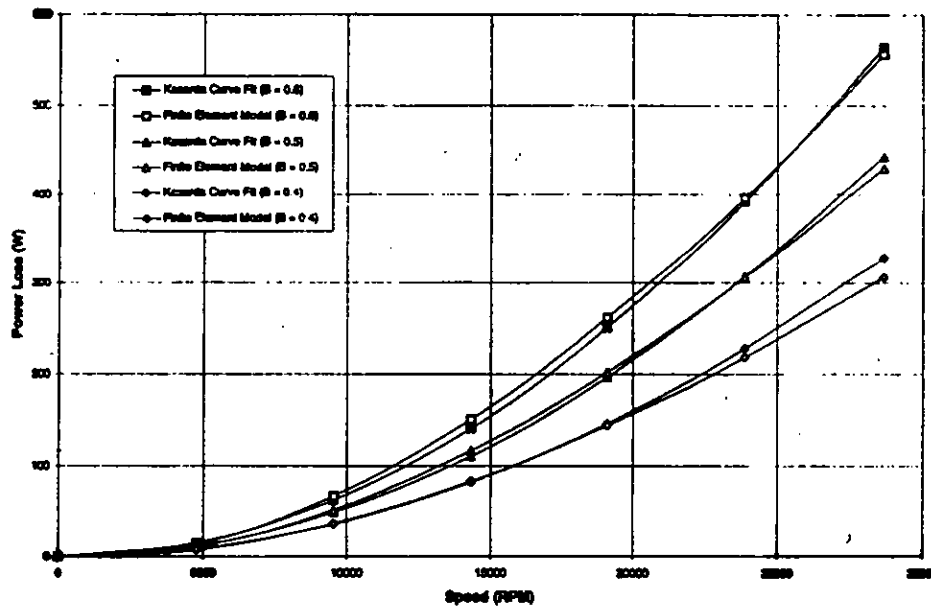


Figure 4. Rotor Eddy Current Power Loss vs. Rotor Speed at Air Gap 0.76 mm - Comparison of Finite Element vs. Experimental Results

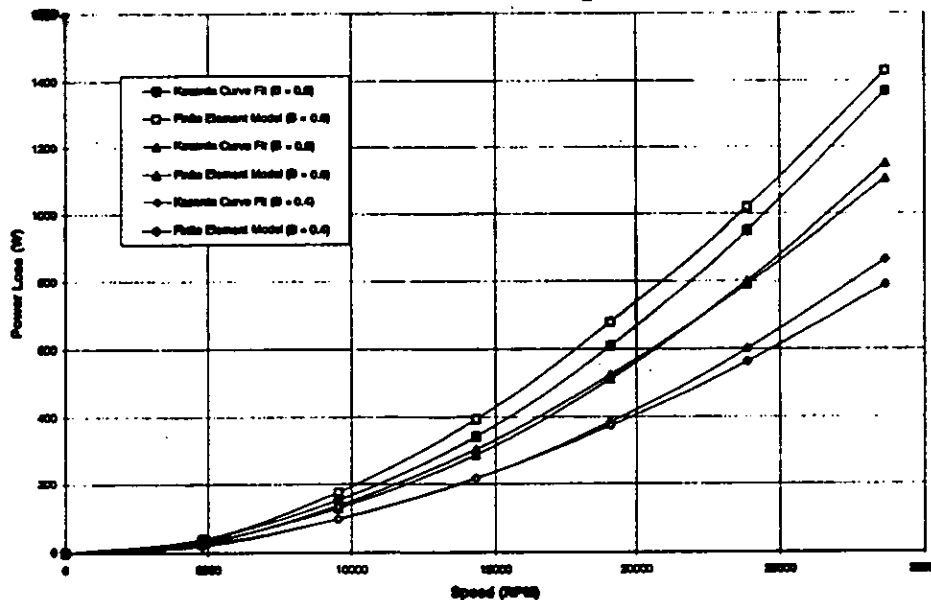


Figure 5. Rotor Eddy Current Power Loss vs. Rotor Speed at Air Gap 0.76 mm - Comparison of Finite Element vs. Experimental Results

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