ROTOR POWER LOSSES IN PLANAR RADIAL MAGNETIC BEARINGS—EFFECTS OF NUMBER OF STATOR POLES, AIR GAP THICKNESS, AND MAGNETIC FLUX DENSITY

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ABSTRACT

Rotor power losses in magnetic bearings cannot be accurately calculated at this time because of the complexity of the magnetic field distribution and several other effects. The losses are due to eddy currents, hysteresis, and windage. This paper presents measured results in radial magnetic bearing configurations with 8 pole and 16 pole stators and two laminated rotors. Two different air gaps were tested. The rotor power losses were determined by measuring the rundown speed of the rotor after the rotor was spun up to speeds of approximately 30,000 rpm, DN = 2,670,000 mm-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. Given past publications and the opinions of researchers in the field, the results were quite unexpected. The measured power losses were found to be nearly independent of the number of poles in the bearing. Also, the overall 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_k = Power Loss (watts)
V = Volume
ω = Rotor Speed (rad/sec)

INTRODUCTION

Rotor power losses in magnetic bearings are very important for many applications but are not well understood. Recently there have been a number of power loss studies in magnetic bearings published in the open literature. Some of the indications in the literature of how iron power losses should vary in different stator configurations appear to be directly contradicted by the results of the measurements in this paper. The purpose of this study is to provide fundamental information of critical importance on rotor iron power losses to the magnetic bearing industry.

A primary concept in the previous literature was that the rotor iron power losses (eddy current and hysteresis) were expected to be roughly proportional to the number

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approximately proportional to the number of poles in the bearing. Another implication of the Fourier analysis presented in this work is that the shape of the pole edge may be very important in the rotor iron power loss. Matsumura and Hatake [1992] discussed a Fourier analysis of fringing and leakage effects on eddy current losses, indicating that pole edge effects may be the most important consideration. Kasarda et al. [1996a,c] discussed power loss measurements in an 8 pole bearing and an analytical/empirical model which used a frequency dependent effect based upon the number of poles passed by the rotor.

Allaire et al. [1997] presented results on an 8 pole magnetic bearing for the power loss variation with respect to air gap flux density and air gap thickness. It was found that, overall, the power loss varied with the rotational speed squared. Also, the power loss is approximately proportional to the air gap flux squared and inversely proportional to the air gap thickness. The effect of the air gap thickness was not predicted by previous studies reported in the literature. Rockwell et al. [1997] presented a finite element model of the same bearing to calculate the eddy current loss component of these losses.

This paper reports the first results where rotor power losses were directly measured in both an 8 pole and 16 pole stator with the same pole face area, and with other geometric parameters kept as compatible as possible. The tests were run with different bias flux densities and air gaps using the same rotor. Most unexpectedly, the power loss measurements for the 8 pole and 16 pole bearings were nearly identical, when other parameters were held constant. This contradicts the expectations of all previous publications in regard to the effect of the number of stator poles on the iron losses.

TEST RIG

Figure 1 shows a schematic of the test rig. It consists of a shaft with two magnetic bearings and two induction motors located at the shaft ends. The two electric motors drive the rotor up to peak operating speed and then they are shut off. Kasarda, et al. [1994] discussed the design of the high speed test rig in some detail and gave a sensitivity analysis of the loss modeling based upon the theoretical parameters involved. The test rig 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 $E_k = J\omega^2/2$ where ω is the rotational speed of the rotor in rad/s. PID control was used.

The power loss is the time derivative of the kinetic energy

$$P_k = J\omega\frac{d\omega}{dt} = \left(\frac{\pi}{30}\right)^2 JN\frac{dN}{dt} \qquad (1)$$
$$= P_h + P_e + P_w$$

Here 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,b,c] that the power loss can be written in terms of frequency dependent parameters as

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

based upon analytical/empirical models. In this formula, the skin effects are neglected [Kasarda, 1996b].

The outer diameter of the bearing journals is approximately 89.0 mm (3.5 in) and the test rig is

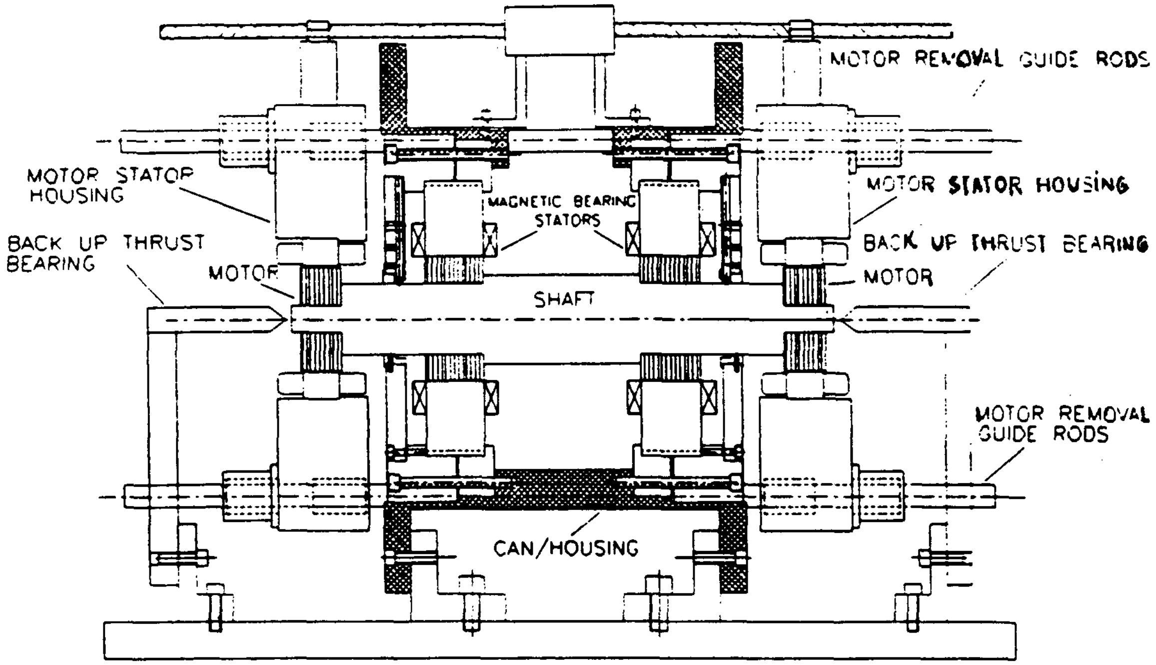

Figure 1. Diagram of Magnetic Bearing Loss Test Rig

designed to operate up to 50,000 rpm resulting in a DN of $4.5x10^6$ mm-rpm. However, the yield strength of the current silicon iron bearing limits the peak speed to 32,000 rpm. The rotor first bending 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].

MAGNETIC BEARING PROPERTIES

Two magnetic bearing stators have been used in these tests: S1 - an 8 pole radial planar (heteropolar) bearing stator and S2 - a 16 pole bearing stator. Stator dimensions for both designs have an OD = 196.2 mm (7.726 in) and axial length L = 43.6 mm (1.715 in) (without coils). In the 8 pole bearing stator, 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). In the 16 pole bearing stator, the circumferential width of each leg is 10.6 mm (0.395 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. Each of the two stators has a total pole face area which covers 53% of the journal surface area. The 8 pole radial bearing geometry is shown in Fig. 2 and the 16 pole bearing geometry is shown in Fig. 3. It should be noted that these bearings were designed to be comparable to one another to provide an "apples to apples" comparison between bearings but are not designed to be low loss bearings.

The bearing rotor lamination stack diameters have an approximate OD = 89.0 mm (3.50 in), shaft OD = 50.8 mm (2.0 in), and axial length of 4.36 mm (1.72 in) and are shrunk fit onto a 50.8 mm (2.0 in) diameter shaft. They are constructed of 3% silicon iron laminations with a 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. Two test rotor assemblies have been built with two different air gaps at the bearings; Rotor R1 had an air gap of 0.762 mm (0.030 in) and Rotor R2 had an air gap of 0.381 mm (0.015 in). The different gap thicknesses were obtained by using two different rotor lamination outer diameters. The polar moment of inertia of the first rotor is J_1=8.10 N-s^2-mm ($7.02x10^{-2}$ lbf-s^2-in) and for the second rotor J_2=8.16 N-s^2-mm ($7.08x10^{-2}$ lbf-s^2-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.

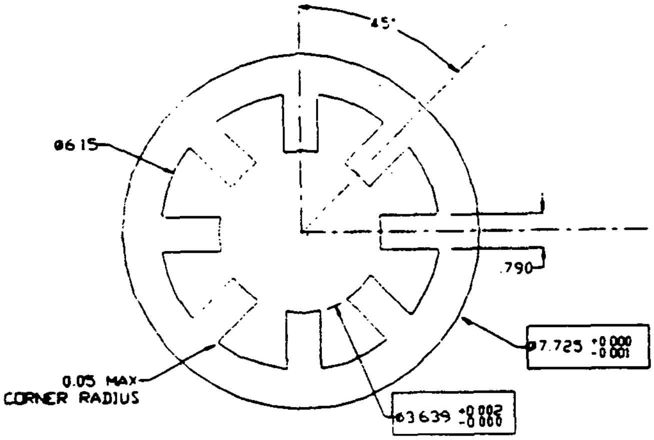

Fig. 2 8 Pole Radial Bearing Stator S1 Geometry

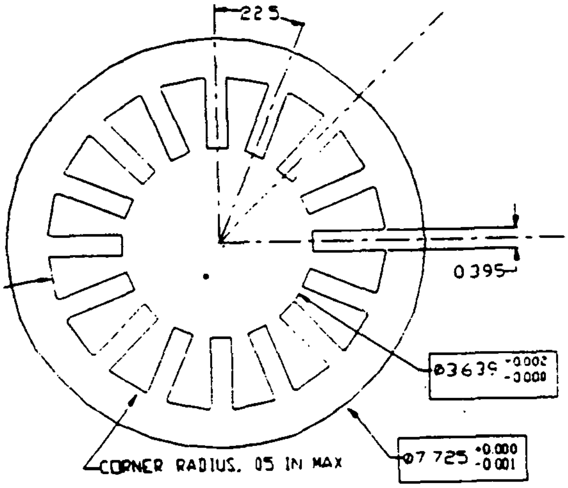

Fig. 3 16 Pole Radial Bearing Stator S2 Geometry

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

$$\frac{dN}{dt} = b_1 + b_2 N + b_3 N^{1.8} \tag{3}$$

where the coefficients are defined as

$$\begin{aligned} b_1 &= \frac{C_h}{J(\pi/30)^2} \\ b_2 &= \frac{C_e}{J(\pi/30)^2} \\ b_3 &= \frac{C_w}{J(\pi/30)^2} \end{aligned} \tag{4}$$

from (1) and (2). An analytical expression for the actual speed curve was determined for each case and minimized using a simplex search method [Kasarda, 1997]. The calculated power loss components were then determined from (1) and (4).

MEASURED POWER LOSSES FOR AIR GAP = 0.381 mm (0.015 in)

Figure 4 gives six measured power loss curves for two bearings. Three curves are for bearing No. HE-8-15 (8 pole stator S1 and rotor R2 with air gap of 0.381 mm (0.015 in)), for static flux levels of 0.32, 0.38 and 0.54 T, vs. speeds up to 28,000 rpm. The next three curves are for bearing No. HE-16-15 (16 pole stator S2 and rotor R2 with air gap of 0.381 mm (0.015 in)), for static flux levels of 0.31, 0.38 and 0.54 T, also vs. rotational speed from 0 to 28,000 rpm. In each case, there were numerous actual runs made to provide better statistical results. For example, for the HE-8-15 magnetic bearing, the number of runs for the bias flux levels of 0.32 T, 0.38 T, and 0.54 T were 4, 4, and 3 runs respectively. The runs were consistent to within a few percent in each data set [Kasarda, 1997].

The quite unexpected result is that the losses are nearly identical for each value of air gap magnetic flux density. The bearings have been designed to have exactly the same surface area under the poles, the same air gap length, and the static bias flux level [Kasarda, 1997]. Air gap flux levels were measured statically and were not expected to be significantly different at running speed although they were not measured due to the difficulties of

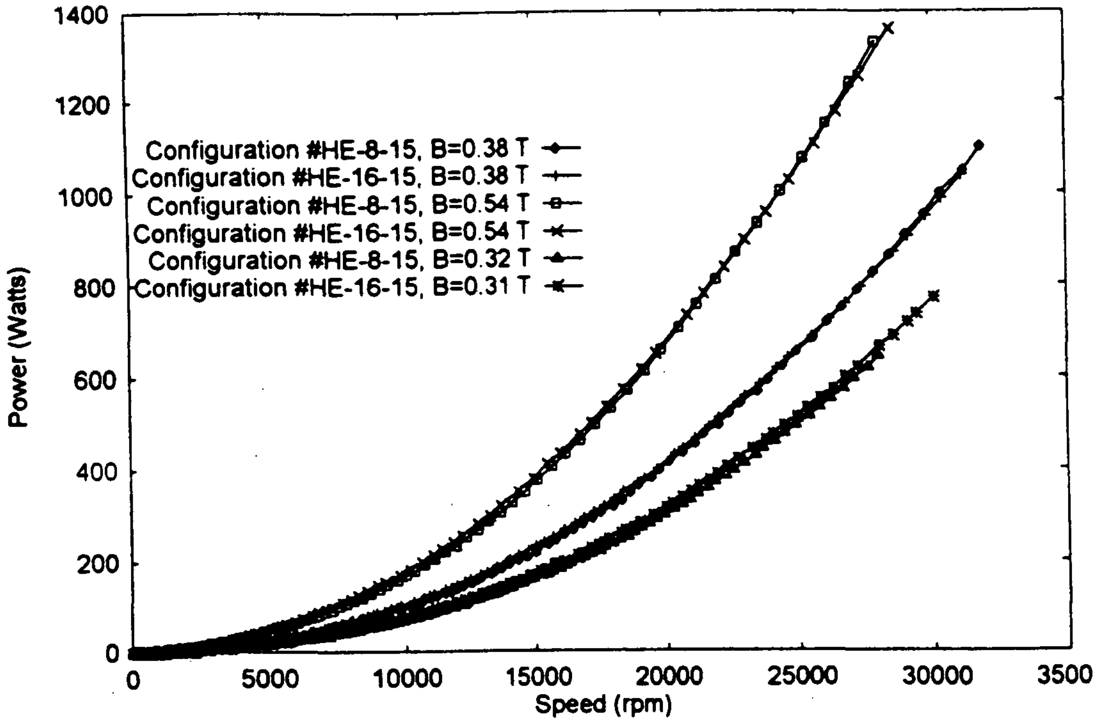

Figure 4. Measured Magnetic Bearing Power Loss vs. Speed at Three Bias Flux Density Values for HE-8-15 and HE-16-15.

working with Hall probes under rotating conditions [Kasarda, 1997]. The tip clearance to air gap thickness ratio is 22 for the 8 pole stator and 44 for the 16 pole stator but it is felt that the difference in these two numbers is not particularly important. Obviously the number of poles or edges differs by a factor of two in stator S1 vs. S2 but the measured power loss is nearly the same.

The coefficients b_1, b_2 and b_3 are given in Table 1 for some of the data in Fig. 4 for bearings HE-8-15 and HE-16-15. The effect of various mechanisms on power loss are indicated by the coefficients in Table 1 for some of the data in Fig. 4 and some other data at an air gap magnetic flux level of 0.44 T [Kasarda, 1997]. This model of the loss components is not perfect, implying that there is some error in the reduction process from the overall power loss measured values to the three components, but is the best that has been found to date.

The hysteresis coefficients are similar 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 also similar for both bearings. Figures 5 and 6 show the calculated loss components for the two bearings for a bias flux of 0.54 T based upon (2). In Fig. 5 for the HE-8-15 bearing, the results show that the eddy current losses are much larger than the hysteresis losses at all speeds. The eddy current losses are proportional to the square of the speed so they will be even larger as the speed continues to increase. Similar trends are seen in Fig. 6 for the HE-16-15 bearing, the where the eddy current losses are much larger than the other two components. Comparing the windage losses for both cases, the windage loss is quite a bit higher for the HE-8-15 bearing than the HE-16-15. This indicates that the model for separating the losses is not as accurate as desired.

Table 1. Power Loss Coefficients For Magnetic Bearings Data For Bearings HE-8-15 and HE-16-15.

	HE-8-15			HE-16-15		
Loss Coefficient	B= 0.32 T	B= 0.44 T	B= 0.54 T	B= 0.31 T	B= 0.46 T	B= 0.54 T
Hysteresis b_1 (rpm/s)	-10.0	-15.7	-21.8	-11.6	-21.5	-24.3
Eddy Current b_2 (1/s)	-5.5 x10^{-3}	-1.0 x10^{-2}	-1.6 x10^{-2}	-6.3 x10^{-3}	-1.3 x10^{-2}	-1.8 x10^{-2}
Windage b_3 (1/rpm$^{0.5}$s)	-9.2 x10^{-7}	-6.7 x10^{-7}	-6.4 x10^{-7}	-7.9 x10^{-7}	-5.5 x10^{-7}	-2.47 x10^{-7}

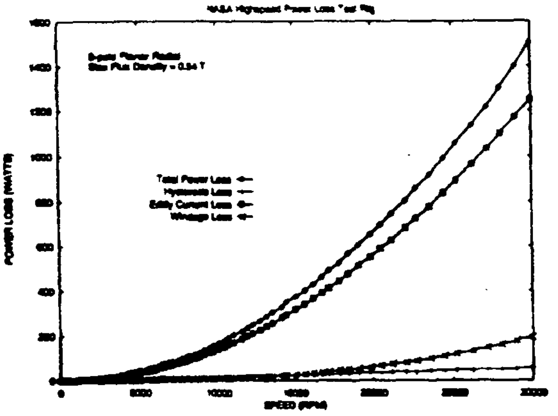

Figure 5. Eddy Current, Hysteresis, and Windage Loss Components in Bearing HE-8-15 For Flux Density 0.54 T.

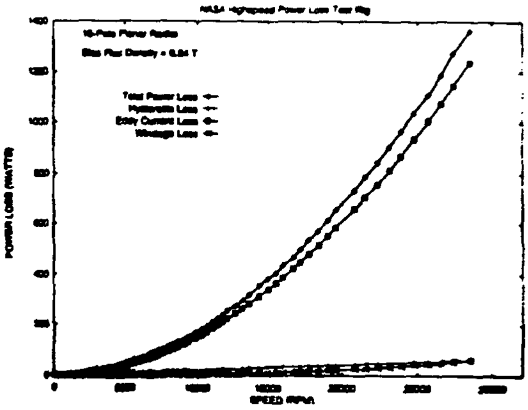

Figure 6. Eddy Current, Hysteresis, and Windage Loss Components in Bearing HE-16-15 For Flux Density 0.54 T.

The windage coefficients are comparable for the two bearings when the bias flux density is the same. Trends in the windage loss terms are not equal but are within approximately 28%. The windage power losses should be independent of the bias flux. More work needs to be done on a better statistical separation of losses into the components and will be reported in future work.

MEASURED POWER LOSSES FOR AIR GAP = 0.762 mm (0.030 in)

Measured power losses were also obtained for a different rotor with twice the air gap thickness. Figure 7 gives four measured power loss curves for bearing No. He-8-30 (8 pole stator S1 and rotor R1 with air gap of 0.762 mm (0.030 in)) for static flux levels of 0.44 and 0.54 T and bearing No. He-16-30 (16 pole stator S2 and rotor R1 with air gap of 0.762 mm (0.030 in)) for static flux levels of 0.44 and 0.50 T vs. rotational speed from 0 to 30,000 rpm.

Again, the result is that the losses are nearly identical for each comparable value of air gap flux. The stators are the same as in the cases plotted in Fig. 4 and the rotor is different only in the air gap thickness. The number of poles or edges differs by a factor of two in stator S1 vs. S2 but the measured

Table 2. Power Loss Coefficients For Magnetic Bearings Data Presented in Fig. 7 For Bearings HE-8-30 and HE-16-30.

	HE-8-30		HE-16-30	
Loss Coefficient	B= 0.44 T	B= 0.54 T	B= 0.42 T	B= 0.50 T
Hysteresis b_1 (rpm/s)	-17.9	-21.5	-18.6	-23.8
Eddy Current b_2 (1/s)	-4.5 $\times 10^{-3}$	-6.3 $\times 10^{-3}$	-5.3 $\times 10^{-3}$	-7.2 $\times 10^{-3}$
Windage b_3 ($1/rpm^{0.8}s$)	-9.1 $\times 10^{-7}$	-7.3 $\times 10^{-7}$	-7.1 $\times 10^{-7}$	-5.9 $\times 10^{-7}$

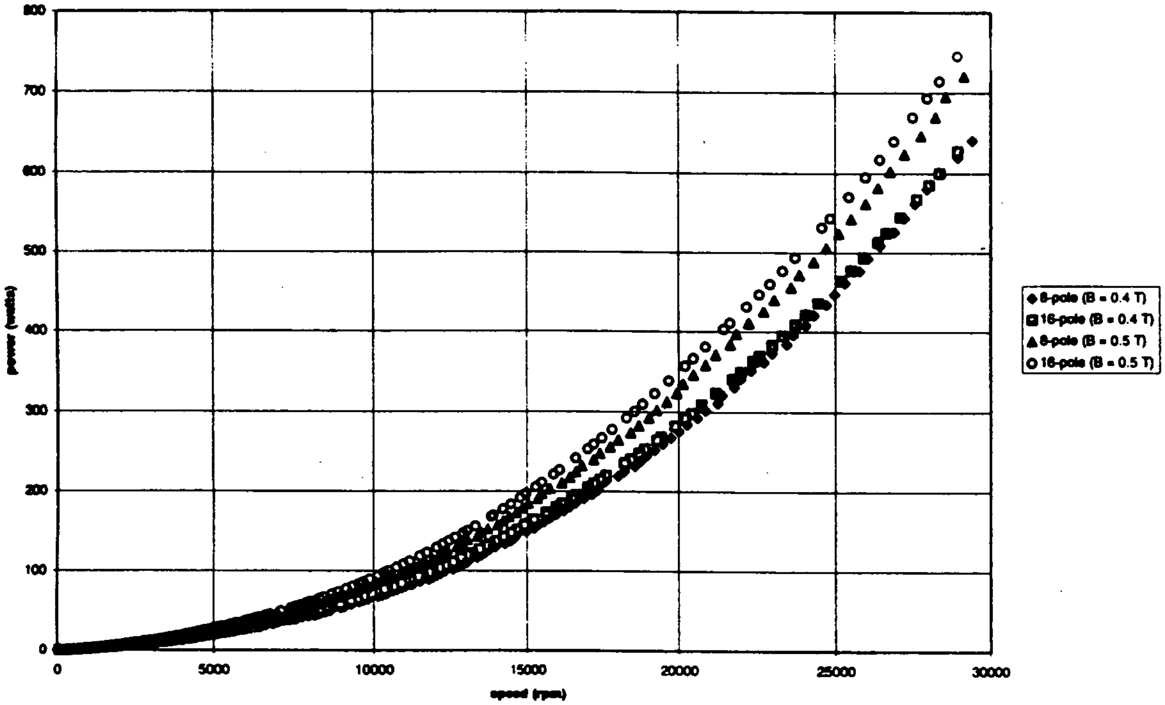

Figure 7. Measured Magnetic Bearing Power Loss vs. Speed at Three Bias Flux Density Values for HE-8-30 and HE-16-30.

power loss in Fig. 7 is nearly the same in each case confirming the results presented in Fig. 4.

The power losses were separated into components based upon (2). The numerical values of the coefficients are given in Table 2. The loss components are plotted in Fig. 8 and 9 for the two bearings for a bias flux level of 0.54 T for the HE-8-30 bearing and 0.50 for the HE-16-30 bearing. The flux levels for for these two plots are not exactly equal but the calculated values illustrate significant differences between the smaller clearance bearings in Fig. 5 and 6. In each of plots 8 and 9, the eddy current losses are clearly dominant over the hysteresis losses by a factor of approximately 2.5 to 4.0. If it is desired to design a low loss bearing, the air gap thickness will

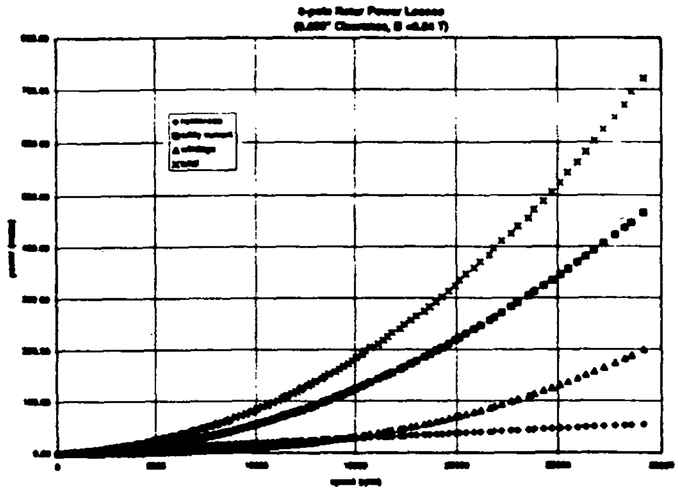

Figure 8. Eddy Current, Hysteresis, and Windage Loss Components in Bearing HE-8-30 For 0.54 T.

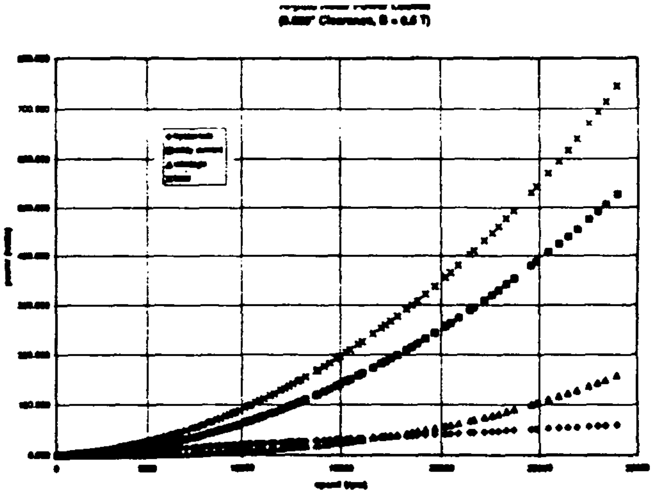

Figure 9. Eddy Current, Hysteresis, and Windage Loss Components in Bearing HE-16-30 For 0.50 T.

be selected as large as possible. The eddy currents will be the largest component of the iron losses by a large factor, unless greatly reduced by employing very thin laminations.

The windage losses in Figs. 8 and 9 are within approximately 15% of one another. This indicates that the windage loss model is acceptable but an improved formula is needed. Future work will be done with this test rig in a vacuum chamber to eliminate the windage term.

ANALYTICAL/EMPIRICAL MODEL

One approach to evaluating the eddy current losses, which are normally the highest of the loss components for high speed applications, is to use a formula adopted from transformer and motor loss models [Kasarda and Allaire, 1996]. The most commonly employed formula for the eddy current losses, without skin effects, is

$$P_e = \frac{\pi^2 d^2 B_{max}^2 f_{eff}^2 V_{eff}}{6\rho} \qquad (5)$$

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 ρ is the resistivity of the material. Previous calculation models have employed a factor for the effective frequency based upon the number of poles in the bearing stator. The measured power loss values presented in Figs. 4 and 7 indicates that the use of eddy current power and hysteresis loss formulas based upon this effective frequency factor are not accurate.

CONCLUSIONS

Magnetic bearing rotor power loss variations with speed, bias flux density, air gap thickness, and number of poles were studied for four different planar radial (heteropolar) bearing configurations. The unexpected result was that the measured rotor power losses for comparable bearings, with the same pole face area, air gap flux, and air gap thickness for both 8 and 16 pole stators were nearly identical. The windage losses in these bearings have been found to be largely independent of the number of poles indicating that the iron losses (eddy current and hysteresis) must be nearly identical. These measured results contradict expected results, that the power loss should be approximately proportional to the number of poles or edges seen in passing by the rotor material, as reported in the literature. While this result is clear for heteropolar bearing designs, it may or may not be true for homopolar designs. Only further testing will determine this.

This may also imply that, since the number of pole edges is not a major factor in heteropolar bearings, the shape of the pole edges is also not a critical factor.

A power loss model including hysteresis, eddy current and windage losses was applied to the data. Values of hysteresis, eddy current, and windage coefficients were obtained from the measured data. Eddy current effects were found to be the largest loss component.

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