EXPERIMENTAL MEASUREMENT OF ROTATIONAL LOSSES IN MAGNETIC BEARINGS

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ABSTRACT

Rotational losses in magnetic bearings are studied experimentally. The experimental setup was a totally active magnetic bearing system of vertical type. It had an axial bearing and two radial bearings. The radial magnetic bearing had eight poles. The arrangement of the magnetic poles was alternating pole arrangement (NSNSNSNS) or paired pole arrangement (NNSS-NNSS). The rotor was also one of the two types: laminated and solid (non-laminated). Rotational losses were estimated from run- down tests. Measurements were performed in a vacuum chamber. The experiments showed that (i)effects of pole arrangement for the laminated rotor were small, (ii)the rotational loss of the solid rotor was five to sixteen times larger than that of the laminated rotor, and (iii)the rotational loss in the paired pole arrangement was about 1.2 times larger than that in the alternating pole arrangement when the solid rotor was used.

INTRODUCTION

One of the most remarkable features of magnetic bearings is no mechanical friction. Some drag torque is, however, observed during rotation. This is due to iron losses in the radial bearings and windy losses. We measured rotational losses in magnetic bearings and reported some interesting phenomena that may be useful to minimize rotational losses [1]. Several papers treating this subject and referring our paper have been recently reported [2,3,4]. Our paper was, however, written in *Japanese* so that most *non-Japanese* people hardly read and understand it. Most of this paper is an *English* version of the paper [1].

Our approach to this topic is quite experimental. This work treats many factors determining rotational losses: bias currents, the arrangement of magnetic poles, and the lamination of a rotor. Windy losses are also studied.

EXPERIMENTAL EQUIPMENT

Figure 1 shows a magnetic bearing apparatus composed of units [5], which is used in this work. This apparatus is set vertically so that every electromagnet in the radial magnetic bearings has a same bias current as it keeps an identical distance (0.3mm) from the rotor. This is desirable to study the effects of bias current (flux) on rotational losses accurately. The bias current I_B is varied from 0.1A to 0.25A.

The radial magnetic bearing unit has eight poles as shown in **Fig.2**. The arrangement of these poles is one of the two types:

(a) **alternating** pole arrangement (NSNSNSNS)

(b) **paired** pole arrangement (NNSSNNSS)

as illustrated in **Fig.3**.

Figure 4 shows two rotors used in the experiments. Both have same mass m and polar moment of inertia J. Their values are:

$$m = 1.00\,\mathrm{kg}, \qquad J = 1.01 \times 10^{-4}\,\mathrm{kgm^2}$$

The difference between the rotors is the material of the parts on which electromagnetic forces act. One rotor is **laminated** and the other is **solid** (non-laminated). The thickness of laminated silicon steel is 0.15mm. The solid part is made of steel with **C** near 0.015% and **Si** near 3% in weight. Although most rotors used in AMBs are laminated to reduce the effects of eddy currents, much attention is paid to solid rotors in this work. One of the reasons is that they have advantages in economical production and strength. Another reason is a technical interest in how clearly the effects of eddy currents appear.

MEASUREMENT METHODS

Rotational losses are estimated from run down tests: the rotor is accelerated to a speed of 15000 rpm and then is allowed to rotate without any driving torque until it stops. Measurement is performed in a vacuum chamber. The pressure of air, P, is changed in studying windy losses while it is minimized in studying iron losses.

The rotational speed is detected with a photo sensor of reflective type, which generates a pulse per revolution. This signal is inputted to a computer for direct frequency measurement. The rotational loss at each moment, denoted by $W(t)$, is estimated based on the following equation:

$$\begin{aligned} W(t) &= T(t)\,\omega(t) \\ &= J\,\omega(t)\,\frac{d\,\omega(t)}{dt} \end{aligned} \tag{1}$$

where

$T(t)$: drag torque acting on the rotor
$\omega(t)$: angular velocity of the rotor

In calculating (1), $\omega(t)$ is approximated by a polynomial of order 5.

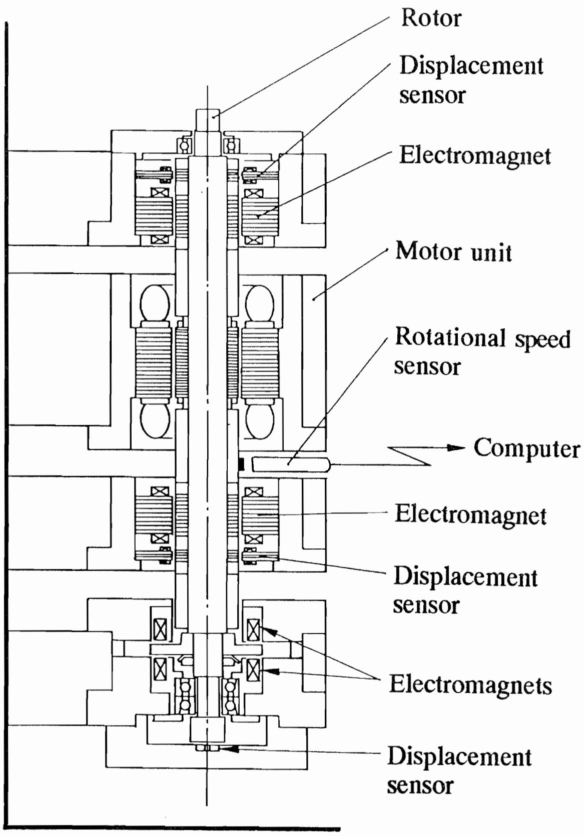


FIGURE 1: Experimental apparatus

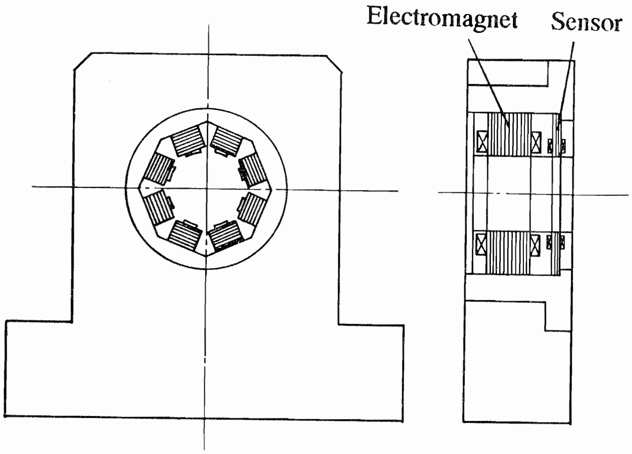
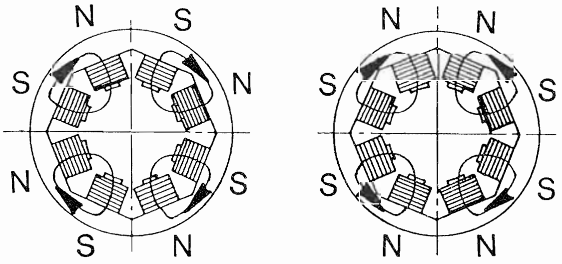
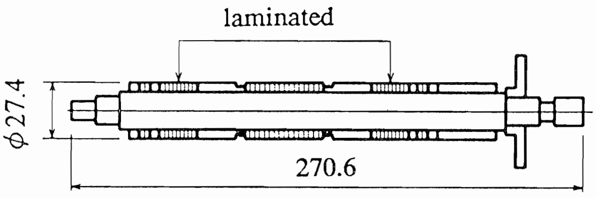


FIGURE 2: Radial magnetic bearing unit

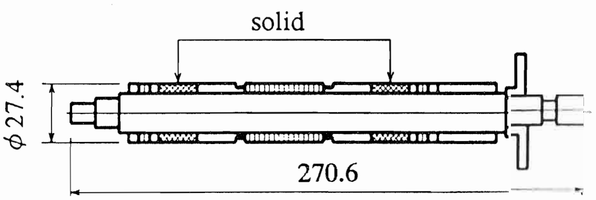


(a) Alternating poles (b) Paired poles

FIGURE 3: Arrangement of the magnetic poles in the radial magnetic bearing



(a) laminated



(b) solid

FIGURE 4: Test rotors

MEASUREMENT RESULTS

Windy Losses

Figure 5 shows the rotational loss as a function of speed. The pressure of air in the chamber is decreased from 1.01×10^{-1} MPa to 0.03×10^{-1} MPa[1]. The test conditions are (1) *laminated* rotor, (2) *alternating* pole arrangement and (3) $I_B=0.15$A. These results show that windy losses are not negligible at speeds higher than 6000rpm at the atmospheric pressure. For example, the rotational loss at $P = 1.01\times10^{-1}$ MPa is about twice the loss at $P = 0.03\times10^{-1}$ MPa when the rotational speed is 12000rpm. The pressure is, therefore, kept at around 0.03×10^{-1} MPa in the following experiments.

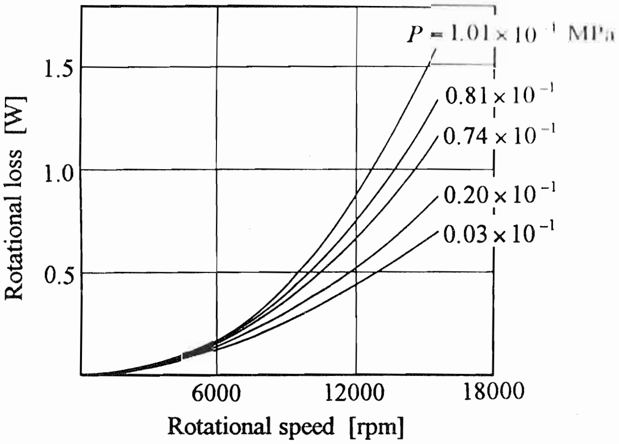


FIGURE 5: Effects of windy losses of the **laminated** rotor in the **alternating** pole arrangement with $I_B=0.15$A.

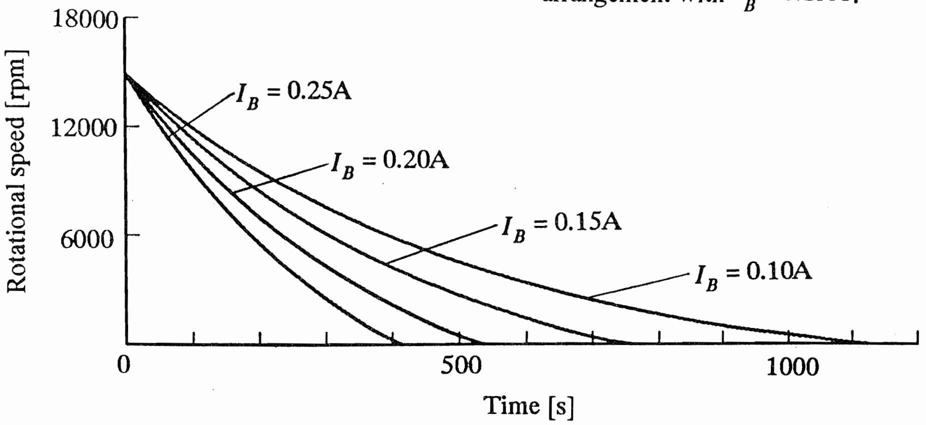


FIGURE 6: Results of run-down tests of the **laminated** rotor in the **alternating** pole arrangement

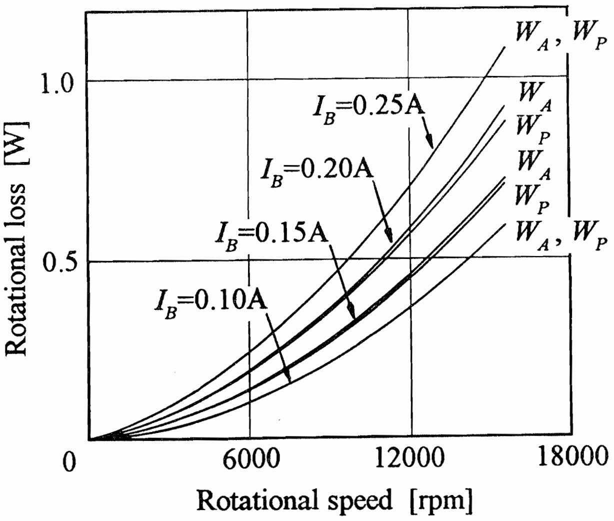


FIGURE 7: Rotational losses of the **laminated** rotor

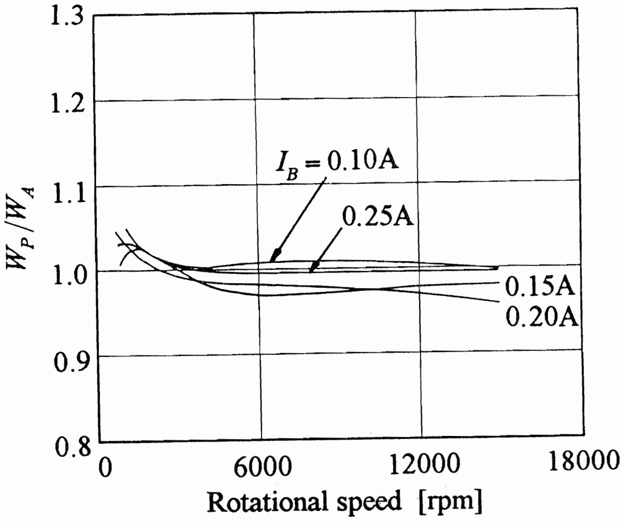


FIGURE 8: Comparison between the **alternating** and **paired** pole arrangements for the **laminated** rotor

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[1] The evacuation was not good because of some leakage through the cables connecting the setup and the controller.

Bias Current and Pole Arrangement

Decay times for the laminated rotor in the alternating pole configuration are shown in **Fig.6**. The bias current I_B ranges from 0.10A to 0.25A. It is clear that drag torque increases as the bias current, or the bias flux becomes larger. **Figure 7** compares the rotational loss in the alternating pole arrangement, W_A, with that in paired pole arrangement, W_P. There is not much difference. To see the difference clearly, the ratio of W_P to W_A at each speed is plotted in **Fig.8**. There is a tendency for W_P to be smaller than W_A. However, it depends on rotational speed and bias currents.

Solid Rotor

Decay times for the solid rotor are shown in **Fig.9**, and the rotational loss as a function of speed is shown in **Fig.10**. The solid rotor gets more drag torque than the laminated rotor, as expected. However, the effects of pole arrangement seem unexpected: *the paired pole arrangement produces more drag torque than the alternating pole arrangement.*

Figure 11 compares the rotational loss for the solid rotor, W_S, with that for the laminated rotor, W_L. This shows that W_S is five to sixteen times larger than W_L. The ratio depends on rotational speed, pole arrangement, and bias currents.

Effects of pole arrangement are remarkable for the solid rotor. **Figure 12** compares rotational loss in the alternating pole arrangement, W_A, with that in paired pole arrangement, W_P. It is observed that W_P is about 1.2 times larger than W_A. The deference tends to decrease according as the rotational speed becomes higher.

The measured results on effects of pole arrangement were opposed to our intuitive prediction: iron losses, especially eddy current loss, should increase as the number of alternation of magnetic polarity per revolution. This shows that accurate prediction of rotational losses is very difficult. This difficulty comes from the fact that eddy-current density at any point in

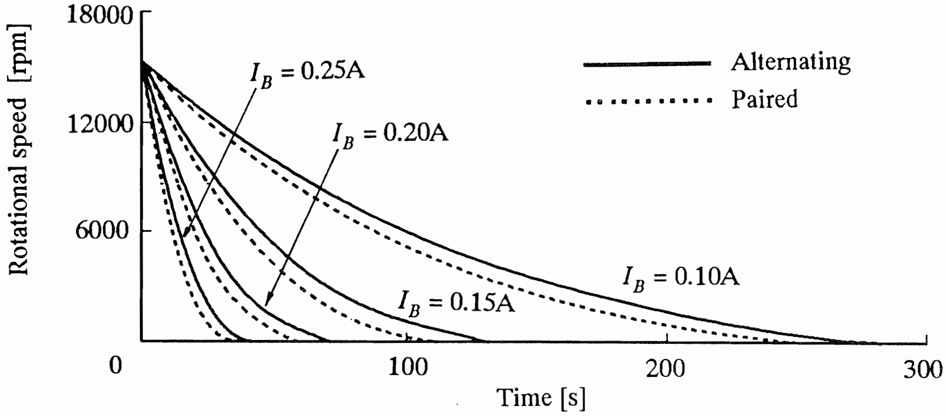

FIGURE 9: Results of run-down tests of the **solid** rotor

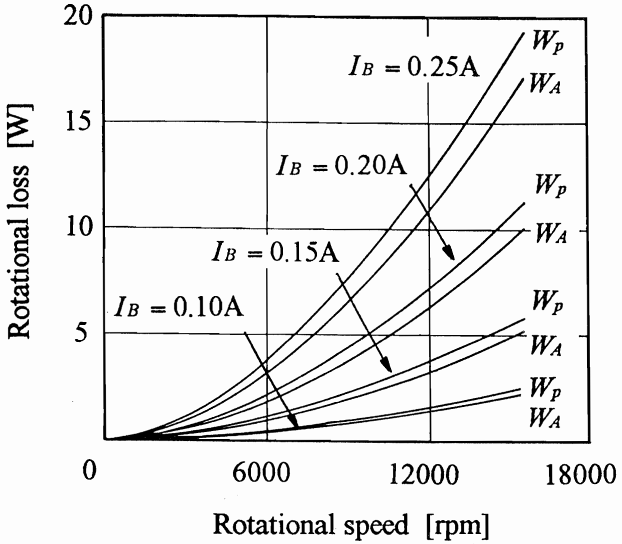

FIGURE 10: Rotational losses of the **solid** rotor

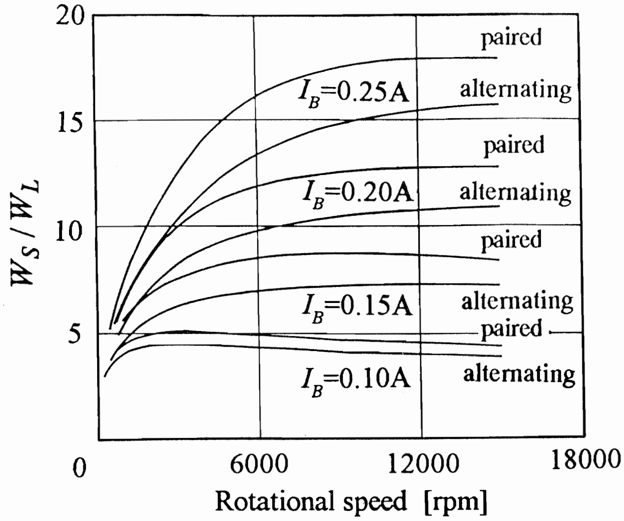

FIGURE 11: Comparison between the **laminated** and **solid** rotors

the rotor is a complicated time function of the iron resistivity, the permeablity, and the manner of distribution of the magnetic flux density.

CONCLUSIONS

Rotational losses were measured with a totally active magnetic bearing system of vertical type in a vacuum chamber. They were estimated based on run down test from 15000rpm. In measuring, pressure in the chamber, bias currents and pole arrangement in the radial berainga, and material of the rotor were varied. The main results of the experiments are summarized as follows.

(1) Effects of pole arrangement for the laminated rotor were small.

(2) The rotational loss of the solid rotor was five to sixteen times larger than that of the laminated rotor. The ratio depends on bias current and rotational speed.

(3) The rotational loss of the solid rotor in the paired pole arrangement was about 1.2 times larger than that in the alternating pole arrangement. The ratio depends on bias currents and rotational speed. It tends to decrease at high speeds.

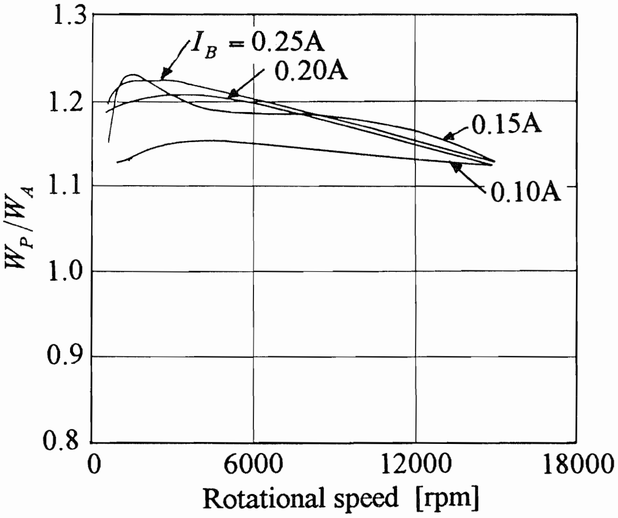

FIGURE 12: Comparison between the **alternating** and **paired** pole arrangements for the **solid** rotor

These results indicate that phenomena causing rotational losses are very complex. Elaborate modeling and analyses are necessary for predicting these losses accurately.

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