Relation between Magnetic Pole Arrangement and Magnetic Loss in Magnetic Bearing

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ABSTRACT

One of the most expected features of magnetic bearings may be little rotational loss. However, observing a rotational motion of the machine, we find out the existence of drag torque which cannot be neglected. In this paper, the relation between magnetic pole arrangements of the radial magnetic bearing and magnetic loss in 5-axis controlled magnetic bearing is studied with Fourier analysis on magnetic fields. A few experimental results are reported also.

INTRODUCTION

Magnetic bearings are bearings where the suspension forces are generated magnetically without any contact. Usually, the rotor is driven by a contactless electric motor. Hence they have many desirable features which can not be realized by rolling bearing or plain bearing in rotating machinery. One of the most expected features of magnetic bearings may be little rotational loss. However, observing a rotational motion of the machine, we find the existence of drag torque which cannot be neglected. In the usual plain bearing or rolling bearing, magnetic drag is hidden in the mechanical friction. However, magnetic drag can be observed only by suspension without contact.

The authors had made several experiments concerning magnetic drag by using three magnetic bearing systems, a magnetically levitated linear dc motor and a magnetically levitated iron ball. In these results, eddy current loss and the characteristics such as Coulomb friction have been investigated[1]. In this paper, the relation between magnetic pole arrangements of the radial magnetic bearing and magnetic loss in 5-axis controlled magnetic bearing is studied with Fourier analysis on magnetic fields. Finally, a few experimental results are reported.

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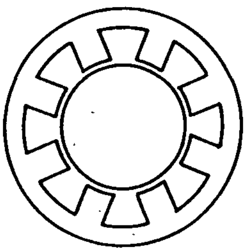


Figure 1 Standard structure of radial magnetic bearing.

(a) Type NSNS (b) Type NSSN

Figure 2 Two types of magnetic pole arrangement.

POLE ARRANGEMENTS OF RADIAL MAGNETIC BEARING

As to the structure of 2-axis (single side) radial magnetic bearing, there are various types[2]. The standard structure in these types is shown in Figure 1. There are two methods shown in Figure 2(a) and Figure 2(b) as a pole arrangement of radial magnetic bearing. That is, the magnetic poles can be arranged to NSNSNSNS (Type NSNS) or to NSSNNSSN (Type NSSN) in a revolution. Firstly, these two magnetic fields are analyzed by Fourier series based on the assumption of an approximation on leakage flux and fringing effect. Two types are not concerned in the characteristics of magnetic levitation. In this paper, the relation between two types of pole arrangement and eddy current loss is studied.

FOURIER ANALYSIS OF THE DISTRIBUTION OF MAGNETIC FIELD

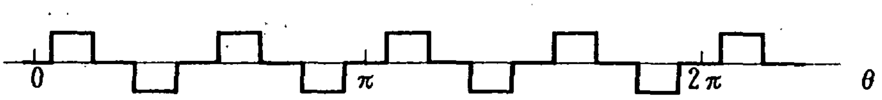
THE CASE THAT LEAKAGE FLUX AND FRINGING EFFECT ARE NOT CONSIDERED

The distribution of magnetic fields on the rotor of radial magnetic bearing are shown in Figure 3 (a),(b) as a linear expression in the ideal case that leakage flux and fringing effect are not considered. For the convenience, the origin of angle θ is defined as this waveform becomes odd function. The expanded figure in the part of $0 \leq \theta \leq \pi/2$ of Figure 3 are shown in Figure 4 (a),(b). As shown in these figures, there is the pole of N uniformly at $\alpha \leq \theta \leq (\pi/4)-\alpha$ in $0 \leq \theta \leq \pi/4$ and the magnetic field does not exist at any other place. Moreover, in the same way, poles S, N, S or poles N, S, S are continued sequentially.

We put the waveform of magnetic field $h(\theta)$ in the following expression.

$$h(\theta) = a_n \sin n\theta + b_0 + b_n \cos n\theta \qquad (1)$$

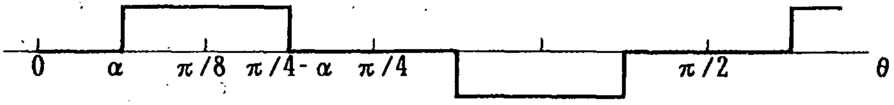
$$(n = 1,2,3, \cdots)$$



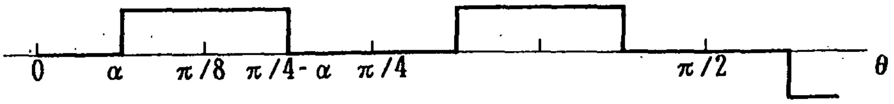
(a) Type NSNS

(b) Type NSSN

Figure 3 Distribution of magnetic field $(0 \leq \theta \leq 2\pi)$



(a) Type NSNS



(b) Type NSSN

Figure 4 Distribution of magnetic field $(0 \leq \theta \leq \pi/2)$

IN CASE OF TYPE NSNS

We calculate the Fourier coefficients over $0 \sim 2\pi$ in Figure 4 (a). Because the waveform is odd function, b_0 and b_n are 0. And Fourier coefficients have non zero value only in the case that n is 4× odd number because of symmetrization of the waveform. That is,

$$a_n = \frac{8}{\pi}\int_{\alpha}^{\pi/4-\alpha} \sin n\theta d\theta \qquad (2)$$

$$(n = 4k,\ k = 1,3,5, \cdots)$$

IN CASE OF TYPE NSSN

In the same manner, we calculate the Fourier coefficients over $0 \sim 2\pi$ in Figure 4 (b). In this case also, because the waveform is odd function, b_0 and b_n are 0. And Fourier coefficients have non zero value only in the case that n is 2× odd number because of symmetrization of the waveform. That is,

$$a_n = \frac{8}{\pi}\int_{\alpha}^{\pi/4-\alpha} \sin n\theta d\theta \qquad (3)$$

$$(n = 2k,\ k = 1,3,5, \cdots)$$

Calculating the Eq. (2),(3), we obtain the following Eq..

$$a_n = -\frac{16}{n\pi}\sin\left[\frac{n\pi}{8}\right]\sin n\left[\alpha-\frac{\pi}{8}\right] \qquad (4)$$

On the other hand, we used the symbol ξ in our previous report[2]. It is defined as the following Eq..

$$\xi = t/(t+s) \qquad (5)$$

t : width of teeth
s : width of slot

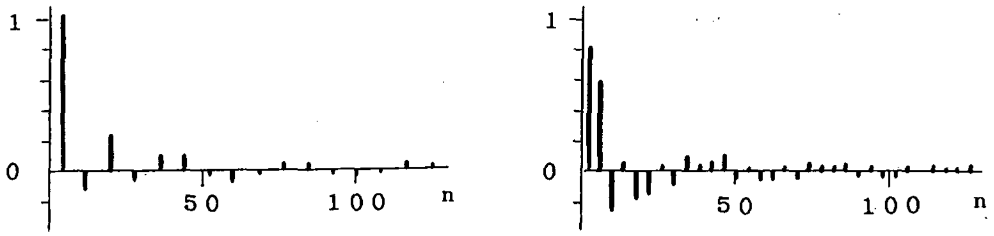
There is a following relation between ξ and α.

$$\alpha = (1-\xi)\pi/8 \qquad (6)$$

Eq. (4) becomes Eq. (7) with this relation.

$$a_n = \frac{16}{n\pi}\sin\left[\frac{n\pi}{8}\right]\sin\left[\frac{n\pi\xi}{8}\right] \qquad (7)$$

The results of calculation on the above Eq. are shown in Figures 5 (a),(b). As shown in these Figures, in type NSNS the 4th harmonics is maximum and the 20th harmonics follows. In type NSSN, the 2nd and 6th harmonics are large and 10th harmonics follows. There are considerably high components not to be ignored in these Figures. However, it seems to us that the waveforms of magnetic flux in the gap are



(a) type NSNS (b) type NSSN

Figure 5 Each harmonic component of magnetic fields.

not rectangular because of leakage flux and fringing effect. Therefore, we must consider that such high harmonics are small.

THE CASE THAT LEAKAGE FLUX AND FRINGING EFFECT ARE CONSIDERED

According to reflection of the previous section, considering leakage flux and fringing effect, we treat the dull shape as the magnetic flux distribution. As a proposal of waveforms, we consider the waveform that both sides can be expressed by cosine function (Figure 6). This figure shows only the region $0 \le \theta \le \pi/4$. Although there is not an exact basis in this idea, this waveform resembles to the supposed magnetic field and the idea of Hamming window or Hanning window in a signal processing technique. Therefore, we think this distribution as a reasonable idea.

Putting the angle 2β in this figure, the left side of the waveform is expressed by the following equation.

$$h(\theta) = \frac{1}{2} - \frac{1}{2}\cos\frac{\theta - \alpha + 2\beta}{2\beta}\pi \tag{8}$$

And the right side of the waveform is expressed by the following equation.

$$h(\theta) = \frac{1}{2} + \frac{1}{2}\cos\frac{\theta - \pi/4 + \alpha}{2\beta}\pi \tag{9}$$

In this case also, Fourier coefficients b_0 and b_n are 0 because of odd function. And a_n is expressed by

$$a_n = \frac{16}{\pi}\left\{\frac{1}{n} - \frac{1}{2(n+\pi/2\beta)} - \frac{1}{2(n-\pi/2\beta)}\right\}\sin\frac{n\pi}{8}\cdot\cos n\beta\cdot\sin\left[\frac{n\pi}{8} - \alpha + \beta\right] \tag{10}$$

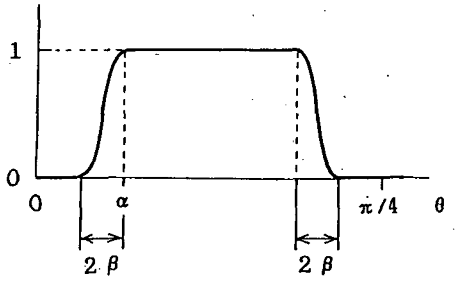
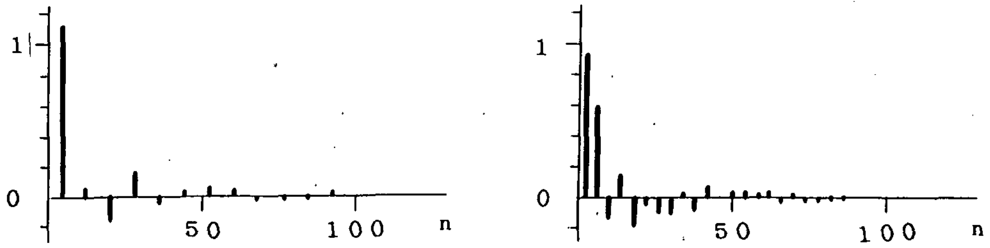


Figure 6 Modified distribution of magnetic field.



(a) type NSNS (b) type NSSN

Figure 7 Each harmonic component of magnetic field.

where,

$$n = 4k, \quad k = 1,3,5,... \qquad (\textit{in case of type NSNS})$$

$$n = 2k, \quad k = 1,3,5,... \qquad (\textit{in case of type NSSN})$$

When β is substitute to 0, this equation coincides with Eq. (4). Numerical examples in case of $\xi = 0.6$, $\delta = 0.1$ are shown in Figure 7. In this Eq., δ is a parameter which is shown in the following relation.

$$2\beta = (\pi/4)\delta \tag{11}$$

In type NSNS, 4th, 20th and 28th harmonics are large, on the contrary higher harmonics are decreased rapidly as was expected. In type NSSN, 2nd, 6th, 14th and 18th harmonics are large, on the contrary higher harmonics are decreased rapidly also.

COMPARISON OF EDDY CURRENT LOSSES

Let us compare eddy current losses between type NSNS and type NSSN in magnetic pole arrangement. Eddy current loss indicates the magnitude of drag torque namely.

Total magnetic loss caused by eddy current is estimated by the following assumptions.

(1) Linearity holds in magnetic circuit and portion in which eddy current flows. Therefore, the total loss is composed of the sum of each loss which is caused by each frequency component in the change of magnetic flux.

(2) Loss caused by each frequency component in a unit volume is proportional to the magnitude of the component (a_n) and to the square of frequency.

(3) The volume which cause a magnetic loss in material is proportional to $1/\sqrt{n}$ based on the consideration of skin effect on the surface of the rotor. (n: order of higher harmonics)

(4) Strictly speaking, when some eddy current flows in the rotor the original distribution of magnetic flux might be affected. But, this effect can be neglected here[4].

Putting together the above assumptions, we can obtain the result that the sum of eddy current loss is proportional to the following equation.

$$P = \sum_n (a_n^2 n^2/\sqrt{n}) = \sum_n (a_n^2 n^{1.5}) \tag{12}$$

Examples of P calculated are shown in Table 1.

As shown in this Table, the loss in type NSSN is slightly lower than that in type NSNS. The larger δ is, the smaller eddy current loss is. That is, the slower the change of magnetic flux density on the inlet and the outlet of the magnetic pole is, the smaller eddy current loss is.

TABLE 1. VALUE OF P (IN CASE OF $\xi = 0.6$)

δ	type NSNS	type NSSN
0.00	43.7	29.6
0.05	29.2	25.6
0.10	20.5	19.4
0.15	17.0	15.5
0.20	15.3	13.2

EXPERIMENTAL EXAMPLES

EXPERIMENTS BY HIGUCHI AND OTHERS[3]

Higuchi and others had made the experiments in cases of laminated rotor and solid rotor about a vertical 5-axis controlled magnetic bearing. And rotational loss had been investigated in cases of A type (type NSNS) and B type (type NSSN). Moreover, in order to decrease aerodynamic friction they had made the experiment in low pressure by sealing the apparatus in a vacuum tank. In these results, they reported that loss in the laminated rotor is much smaller than that in the solid rotor. Moreover, in the case of solid rotor, loss in type NSSN is 1.2 times large as that in type NSNS.

Their result is opposite to one of our estimation. It seems that the reason is caused by the difference of pole structures.

EXPERIMENTS BY US

We have made a few experiments about the loss in a horizontal type 5-axis controlled magnetic bearing. Parameters of experimental machine are shown in Table 2[5]. However, magnetic pole shape and manner of winding are not one shown in Figures 1, 2 but the coil which would be obtained by lap winding method in the iron core which have nine teeth and slot per 2-pole (N and S) is used. Moreover, the coil currents or strengths of magnetic field in each pole are different from each other due to the horizontal type.

First, the rotor is accelerated until 3,000 rpm by the motor, then the power supply of the motor is cut off. The speed decay characteristics in the latter process are shown in Figure 8. Solid line shows one in type NSNS and dotted line type NSSN. Because the speed decay characteristic is a straight line on the semilog graph paper, it is proved that friction torque is proportional to the rotational speed. When the rotational speed becomes low, experimental values are differ from the straight line.

TABLE 2 PARAMETERS OF EXPERIMENTAL MACHINE

Parameter	Numerical value
Mass of rotor	14.46 kg
Gap length	0.55 mm
Thickness of silicon steel	0.50 mm
Height of core	40 mm

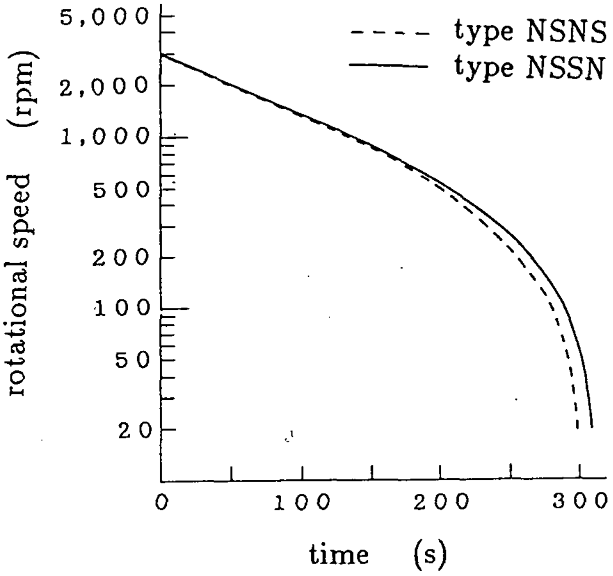


Figure 8 Characteristic of speed decay (semilog expression).

This reason is caused by the following facts. That is, at low speed, eddy current loss becomes small, therefore hysteresis loss becomes dominant in strength[1]. In this experimental result, eddy current loss of type NSSN is slightly smaller than that of type NSNS.

Comparison of hysteresis losses in both types could not been made, but it seems to us that loss in type NSSN is low on the basis of the both hysteresis loops.

CONCLUSION

The power loss or magnetic drag in magnetic bearing due to eddy current are small. In addition, aerodynamic drag exists. Therefore, magnetic drag in magnetic bearing is not important problem usually. However, when the magnetic bearing is used in vacuum, loss due to eddy current becomes most important. Temperature rise becomes large because there are no heat dissipation by conduction or convection. Therefore, it is hoped that magnetic loss is as small as possible.

The authors had forecasted that the loss of type NSSN is considerably smaller than that of type NSNS. But, by the analysis and results of experiments, it is clear that there is no remarkable distinction in both types. As shown in Table 2, leakage flux or fringing effect are more important for eddy current loss than pole arrangement. In other words, the shape of each magnetic pole and the relation between gap length and teeth width are more effective for magnetic loss.

A few studies on magnetic drag in magnetic bearing have been made. Much more experimental studies are needed for reduction of magnetic drag. For this reason, many presentations of experimental data are hoped.

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