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A Study on the Design Procedure of the Eight Pole Magnetic Bearings for the Inner-rotor and the Outer-rotor Type

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Abstract – This paper presents design procedure of the magnetic bearings used for high-speed electric machines and flywheel energy storage systems. Magnetic bearing can be categorized by inner-rotor type and outer-rotor type according to the position of the rotary disc. These two types are applicable based on application environments such as application space, required attraction force, and controllability. Magnetic bearing is generally designed based on the ratio (geometrical coefficient or geometrical efficiency) of pole width to rotor journal radius but proper ratio is only decided by the analysis. This is the difficulty of the magnetic bearing design. In this paper, proper design technology of the inner-rotor type and outer-rotor-type eight pole magnetic bearings is introduced and compared with the FEM analysis results, which verifies the proposed design procedure is suitable to be applied to the design of the magnetic bearings for the industrial applications and flywheel energy storage system

Keywords: Geometrical efficiency, Magnetic bearing, Inner-rotor type, Outer-rotor type

1. Introduction

As the magnetic bearing is a kind of ring support without any contact between rotor and stator, unlike conventional ball bearings which usually need lubricant, it has some merits such as very high speed RPM, low noise level, semi-permanent life expectancy, low maintenance cost, and environment-friendly. These advantages, especially, enable to maximize the ripple effect on very high speed rotor application industries [1-2].

For last three decades, researches on the magnetic bearing have been under active progress in USA, Europe and Japan such as ETH (Eidgenössische Technische Hochschule, Swiss Federal Institute of Technology(Swiss)), S2M(France), University of Virginia(USA), Texas A&M University(USA), NASA(USA), Chiba university(Japan) and National Defense Academy of Japan(Japan) [3-9]. From the researches, registration of patents are 183,192 in USA, 32,008 in Europe, 12,872 in Japan and 1,900 in China, respectively.

Magnetic bearing technology can be classified into three great divisions. One of them is pure active magnetic bearing method which is suitable to small rating applications because it should manage the load by itself without any support. Second method is hybrid bidirectional control which has some merits for controllability and power consumption points of view. This hybrid method is to support the load by the repulsive force of permanent magnet and the attraction force of magnetic bearing. Third method is hybrid unidirectional control which uses only unidirectional magnetic bearing for support. In general, first method is widely used because of excellent damping effect to external force but second method is also used in case power consumption is critical.

Therefore, proper magnetic bearing should be designed out of regard for various applicability and system requirement. As magnetic bearing is a non-contact bearing, it should have various uniform airgap according to applicable systems and this makes it difficult to standardize the design procedure of the magnetic bearing.

Magnetic bearing design has been researched by several researchers. Pang D dealt with the optimal design of the pancake type magnetic bearing for fly wheel energy storage devices. Pang focused on the pancake shape and suggested proper design variables. He focused on not the optimized geometrical dimensions but the comparison between different design procedures [10]. J Imlach et al dealt with the geometrical dimensions of the poles and electrical characteristics of the coils based on the seven design constraints for four radial magnetic bearings [11]. Nan-Chyuan Tsai et al dealt with the optimal bearing shape in order to minimize electrical energy consumption for fly wheel energy storage devices [12-14]. However, these design researches were limited in the inner-rotor type magnetic bearings and put forth a multilateral effort into solving a problem of design optimization which is very complicated.

This paper presents a design procedure of both inner-

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and outer-rotor type magnetic bearings and verifies usefulness of the proposed design procedure by comparing with the simulation results of numerical analysis and finite element method.

2. Fundamental Formula for Magnetic Bearing

Fig. 1 shows a basic schematic diagram of an inner-rotor type 8 pole magnetic bearing. Magnetic bearing basically controls the airgap by using the attraction force of the electromagnets and this attraction force is decided by the geometry of magnetic bearing. Magnet width W_p of a magnetic bearing as shown in Fig. 1, is related to the attraction force, and diameter D of the inner rotor of a magnetic bearing is related to the surface area which affect to the attraction force. Therefore, the attraction force of a magnetic bearing can be represented by the geometrical coefficient (geometrical efficiency), σ as in (1).

$$\sigma = \frac{2W_p}{D} = \frac{W_p}{R} = \frac{R\sin\theta}{R} = \sin\theta \tag{1}$$

here, $\theta = \frac{2\pi}{n_P}$ (n_p is number of pole).

(hence, $\sin 45^{\circ}$ is ideal for the 8 pole magnetic bearing)

The attraction force can be represented by Maxwell equation as in (2).

$$F = \frac{B^2 A_g}{\mu_o} \tag{2}$$

here, B is the magnetic flux density, A_g is the cross-sectional area of the airgap, μ_o is the permeability of the air.

In (2), A_g is the product of W_p and rotor journal length, L_j.

From (1) and (2), the attraction force can be represented by (3).

$$F = \frac{B^2}{\mu_o}\left(2W_p L_j\right) = \sigma\frac{B^2}{\mu_o}DL_j \tag{3}$$

$$B = \frac{\mu_o NI}{2g_o} \tag{4}$$

By inserting (4) into (3), the attraction force of a magnetic bearing including the geometrical coefficient (geometrical efficiency) can be represented in (5).

$$F = \sigma\frac{\mu_o N^2 I^2}{4g_o^2}DL_j \tag{5}$$

Maximum attraction force per 1 pole is obtained by the maximum available current, $I_{\max} = \frac{g_o B_{\max}}{N\mu_o}$.

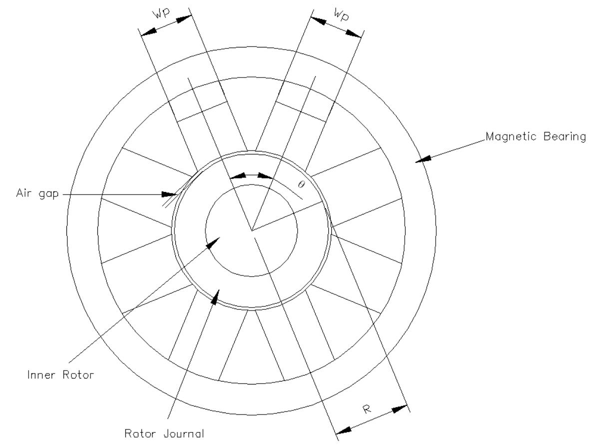

Fig. 1. Eight pole magnetic bearing

2.1 Inner-rotor type magnetic bearing

Design parameters for an inner-rotor type magnetic bearing is shown in Fig. 2. Decision of the winding areas is very important factor to secure the performance because the attraction force is proportional to the square of the currents and square of the number of turns. And decision of the outer diameters of the magnetic bearing and rotor which are determined by the system constraint, should be done at the very first beginning. In case a magnetic bearing is applied to a high-speed rotating machine, the outer diameter of the rotor can be decided by the standard of the backup bearing which is to prevent from any contact between rotor and stator.

In this paper, 70mm of inner diameter angular contact from NKS is chosen as the backup bearing (ball bearing) and 69.4mm of outer diameter for inner rotor is decided by considering the 0.6mm of airgap. The ratio of the sum of pole width to circumference of the inner rotor is defined as Iron ratio, r_i that is, $r_i = \frac{\theta n_p}{2\pi}$ which is 0.9 (40°) in this paper. The outer radius, R_1 should be decided by considering space constraint and outer radius of the rotor, which will be explained in the next section. From these constraints and (1), W_p is as in (6).

$$W_p = 2R_{3i}\sin\left(\frac{\theta}{2}\right) \tag{6}$$

In the Fig. 2, section shaded is the winding area which is product of t_c and l_c.

Here,

$$t_c = R_{3i}\tan\left(\frac{\theta}{2}\right) - \frac{W_p}{2} \tag{7}$$

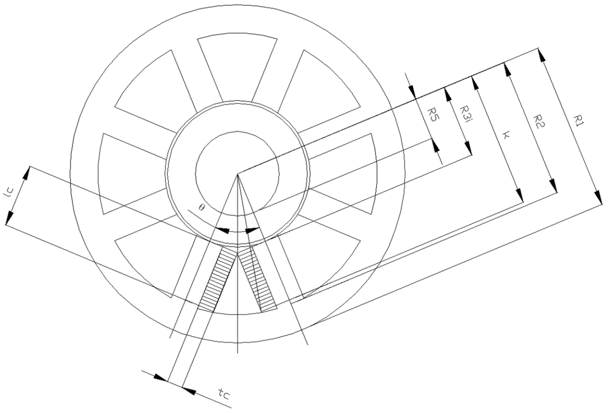

Fig. 2. Inner-rotor type magnetic bearing

$$l_c = \sqrt{R_2^2 - \left(\frac{W_p}{2} + t_c\right)^2} - R_{3i} \tag{8}$$

Number of winding can be calculated as in (9) by the winding area from (7) and (8).

$$N = \frac{t_c l_c}{A_{wi}} \beta \tag{9}$$

here, β is the packing factor.

2.2 Outer-rotor type magnetic bearing

Outer-rotor type magnetic bearing is shown in Fig. 3. Design procedure of the outer-rotor type is same as the inner-rotor type except winding area from different airgap location. That is, R_4 of the outer-rotor type is the inner radius of the rotor (R_4=D/2), while R_{3i} of the inner-rotor type is the inner radius of the rotor and airgap (R_{3i}=D/2+g_o). This difference affects to the calculation of t_c and l_c. Therefore, in case inner-rotor type and outer-rotor type have the same outer radius (R_1), followings are obtained.

$$R_2 = R_1 - W_p, \quad R_{3o} = R_1 - W_p - g_o, \quad R_{3i} = \frac{D}{2} + g_o, \quad R_4 = \frac{D}{2} \tag{10}$$

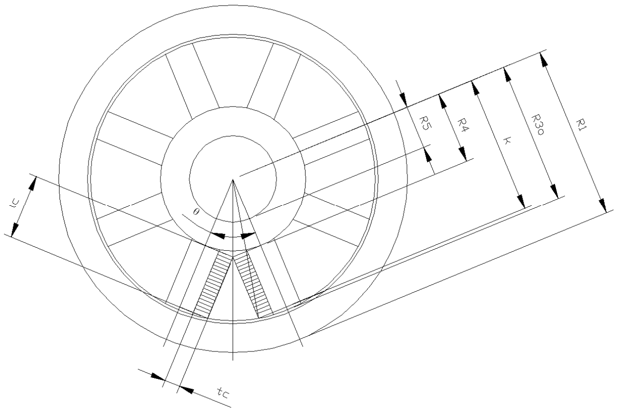

Fig. 3. Outer-rotor type magnetic bearing

As the final outcome, the performance of the inner-rotor type and outer-rotor type magnetic bearings becomes different from the different winding areas.

3. Simulation Results of the Finite Element Method

In this section the inner-rotor type and outer-rotor type magnetic bearing design is dealt with based on the design procedures mentioned in the previous section by using finite element method and also the comparison for the load capacity between the inner-rotor type and outer-rotor type is performed. Commercial magnetic field analysis program, Maxwell was employed for the finite element analysis. For the design of the two different types of the magnetic bearings, authors assume that the inner diameter of the rotor, D is 69.4mm, the air gap, g_o is 0.6mm, the journal length in the axial direction, L_j is 35mm. Three different kinds of dimensions for the outer radius (R_1=75mm, 88mm, 100mm) are selected arbitrary. Also authors assume that the geometrical efficiency, σ which presents the relation between the width of the magnetic bearing pole and the

Table 1. Design variables of the magnetic bearings

Variables	Values
Inner diameter of the rotor (D)	69.4 mm
Airgap (g_o)	0.6 mm
Pole-to-pole angle (θ)	45 deg
Journal length (L_j)	35 mm
Outer radius (R_1)	75, 88, 100 mm
Packing factor (β)	0.5
Coil diameter (A_{wi})	1.6 mm
Geometrical efficiency(σ)	0.01 ~ 0.7
Maximum flux density (B_{max})	1.2 T
Maximum current (I_{max})	10 A
Coil current density (J)	6 A/mm^2

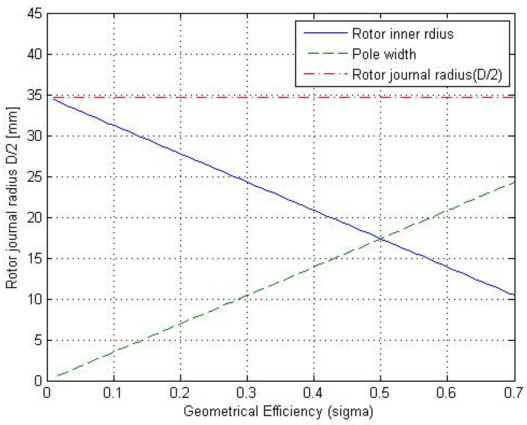

Fig. 4. The relations between geometrical efficiency and rotor inner radius and pole width of the magnetic bearings

rotor inner radius has 0.01 ~ 0.7. Table 1 shows the design parameters.

Fig. 4 presents the relation between geometrical efficiency and the width of the magnetic bearing pole when the rotor journal radius is pre-decided based on the design requirement. As seen in the figure when the geometrical efficiency is 0.5, the rotor inner radius and pole width of the magnetic bearing is same, which means that R_5 and W_p are decided based on the σ.

Fig. 5 shows the magnetic force produced from the magnetic bearings of the inner-rotor type and outer-rotor type. As seen in the figure if the magnetic saturation of the magnetic core is not considered the maximum magnetic force is around $\sigma = 0.2$.

Considering the magnetic saturation of the magnetic core, as seen in Fig. 6-7, the maximum magnetic force is at 0.33, 0.45, 0.55 of σ.

These results mean that when the magnetic saturation is not considered the narrower the pole width of the magnetic bearing the lower σ, instead the wider coil area the greater magnetic force.

However it is impossible that such magnetic force can be produced. When the magnetic saturation is considered the σ moves to around 0.5 (in this paper B_{max}=1.2T). This means that σ moves in the direction for W_p and R_5 to be same length, and means that in order to suppress the magnetic saturation W_p should be wider.

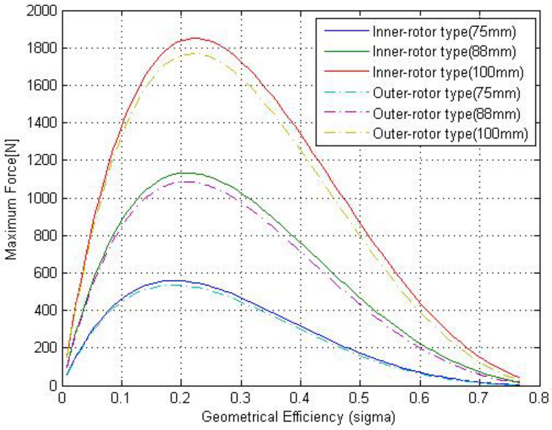

Fig. 5. Maximum magnetic force (Without considering the magnetic saturation of the core)

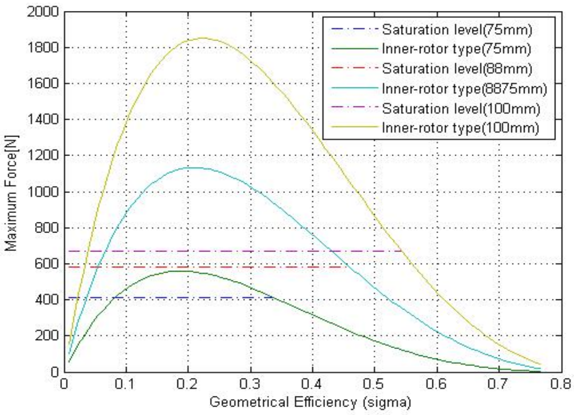

Fig. 6. Magnetic force for the inner-rotor type (Considering the saturation of the magnetic core)

Fig. 8 indicates the magnetic force of the two rotor types when the magnetic saturation is considered. The magnetic force moves in the direction that pole width W_p becomes wider when the outer radius becomes greater, and the

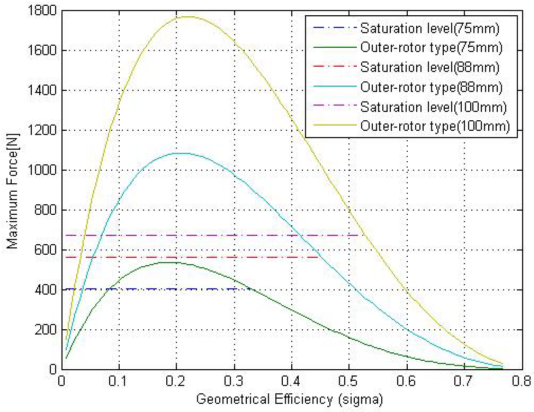

Fig. 7. Magnetic force for the outer-rotor type (Considering the saturation of the magnetic core)

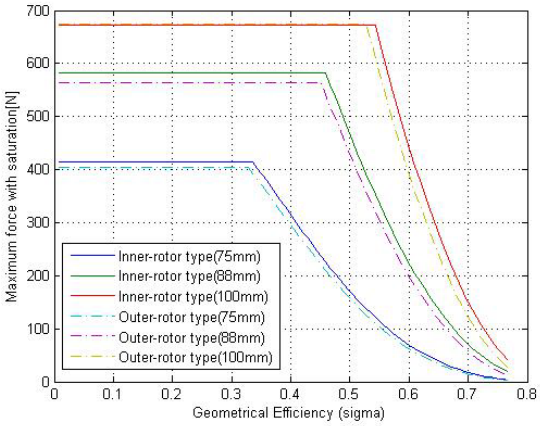

Fig. 8. Magnetic force considering the saturation

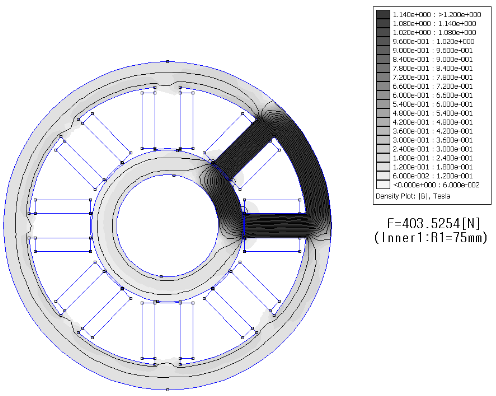

Fig. 9. FEM analysis (Inner OR 75mm)

magnetic force of the inner-rotor type is greater than that of the outer-rotor type. This result presents that the load capacity of the inner-rotor type magnetic bearing is superior to that of the outer-rotor type magnetic bearing.

Figs. 9-11 show that the magnetic flux calculated by finite element method and numerical analysis of the magnetic force for the inner-rotor type magnetic bearing. In the FEM analysis maximum flux density is 1.2 Tesla for the silicon iron (SiFe).

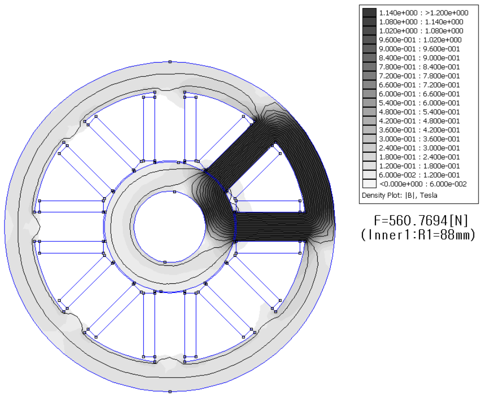

Fig. 10. FEM analysis (Inner OR 88mm)

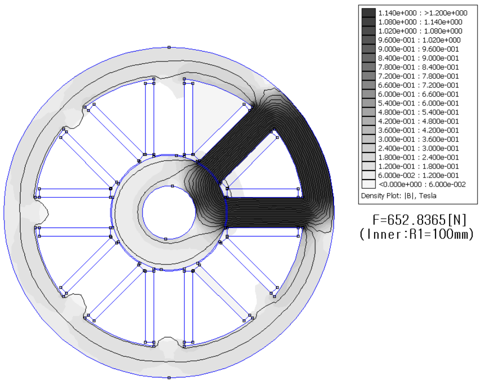

Fig. 11. FEM analysis (Inner OR 100mm)

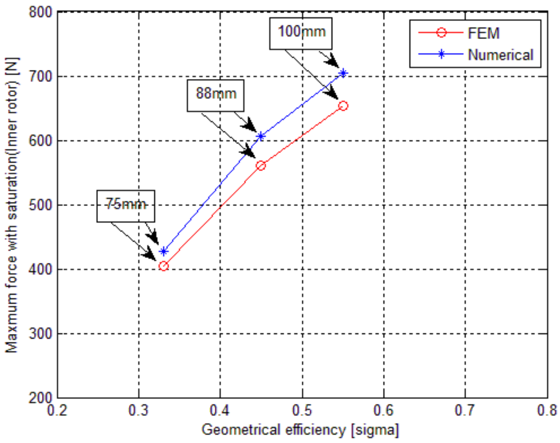

Fig. 12. Comparison between numerical and FEM analysis (Inner-rotor type)

The greater OR(outer radius) the greater maximum magnetic force as shown in those figures. Fig. 12 shows the maximum magnetic force of the magnetic bearing that has been designed through the design procedures proposed in this paper and the maximum magnetic force calculated by the FEM, and also indicates that the maximum magnetic force calculated by those two methods is almost same.

Figs. 13-15 show that the magnetic flux calculated by finite element method and numerical analysis of the

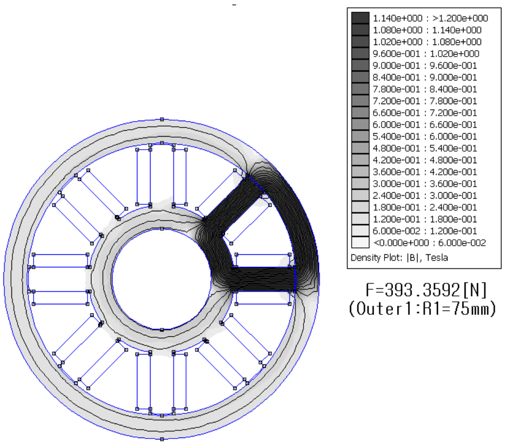

Fig. 13. FEM analysis (Outer OR 75mm)

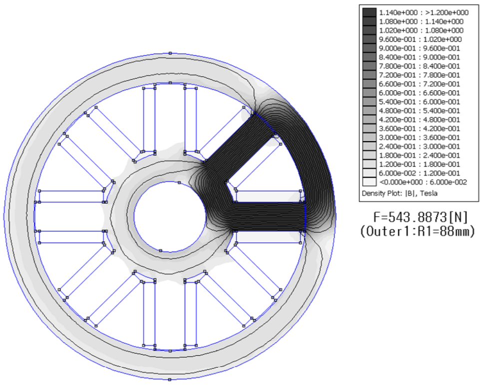

Fig. 14. FEM analysis (Outer OR 88mm)

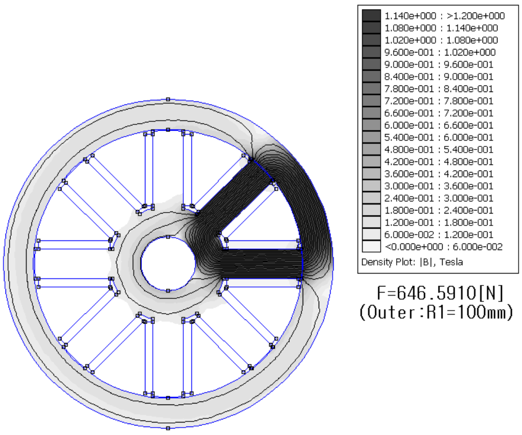

Fig. 15 FEM analysis (Outer OR 100mm)

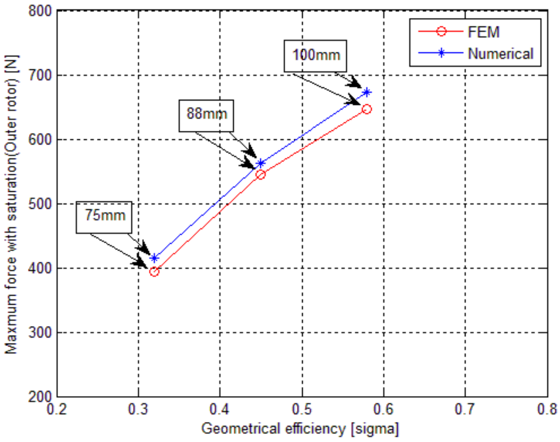

Fig. 16 Comparison between numerical and FEM analysis (Outer-rotor type)

magnetic force for the outer-rotor type magnetic bearing. The greater OR(outer radius) the greater maximum magnetic force as shown in the inner-rotor type. Fig. 16 also shows that the maximum magnetic force calculated by FEM and the maximum magnetic force calculated by numerical analysis proposed in this paper are almost same.

4. Conclusion

This paper presented a design procedure of both inner- and outer-rotor type magnetic bearings and verified usefulness of the proposed design procedure by comparing with the simulation results of numerical analysis and finite element method. From the results, it was proved that the load capacity depended on the geometrical coefficient (geometrical efficiency), and relation between magnetic force and according to the various outer radius. The results of the maximum attractive magnetic force calculated by numerical analysis also were almost same with that of the finite element method analysis, which means that it is possible for the proposed design procedures to be employed for the design of the magnetic bearing system and also to be applied for the industrial applications and flywheel energy storage system.

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