Parameter design and electromagnetic field analysis of electromagnetic biased axial magnetic bearing

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Abstract. A type of electromagnetic biased axial magnetic bearing is studied. Compared with traditional axial magnetic bearings, it has a smaller external diameter of the thrust plate, which is helpful to improve the critical speed of the rotor in theory. The structural parameters are obtained and finite element model (FEM) is established. The magnetic flux leakage coefficients and the magnetic resistances are calculated. The rationality of parameter design is verified. The results show that the parameter design and the electromagnetic field simulation are in accordance with rationality of the design. Therefore, the magnetic biased axial magnetic bearing is not only simple in structure, but also reasonable in design, which is of great significance to the design of magnetic bearing.

1. Introduction

The paper relates to an electromagnetic biased axial magnetic bearing, which is a novel bearing capable of stably suspending a rotor by utilizing an electromagnetic force, realizing no mechanical contact between the rotor and stator. The principle and structure of electromagnetic active control magnetic bearing are introduced[1]. The structure and working principle of bearing-free single degree of freedom active magnetic bearing are introduced[2]. The parameters are designed and the calculation method is given[3]. A calculation model of eddy current loss magnetic circuit based on effective magnetic resistance method and equivalent magnetic circuit method is presented[4]. The working principle of maglev wind turbine is introduced[5]. The structures of two kinds of redundant magnetic bearings are introduced[6]. A uniform polar permanent magnet biased radial magnetic bearing consisting of four C-shaped cores is proposed, the magnetic bearing has lower iron loss and lower cost[7]. A permanent magnet biased magnetic bearing with claw structure is proposed, which is suitable for the case of limited radial space. By controlling the levitation force produced by different claw poles, the control of three degrees of freedom of the rotor can be realized[8]. Two types of permanent magnet biased axial-radial magnetic bearings with similar structures have been proposed[9 -10]. In this paper, a kind of electromagnetic biased axial magnetic bearing is studied. Compared with the traditional axial magnetic bearing, it has a smaller external diameter of thrust plate. The magnetic field is analyzed by FEM. The magnetic leakage coefficient and magnetic resistance are calculated by magnetic density to verify the feasibility of the theoretical design.
2. Structure of axial magnetic bearing

Figure 1 reveals the structure. Figure 2 reveals the magnetic circuit diagram. Because the magnetic bearing structure is axisymmetric, the model can be transformed into two-dimensional model.

![Diagram of Structure](image1)

**Figure 1. Structure diagram**

When current is passed into coils, a magnetic field is generated in the iron core, and a closed loop is formed by the stator sleeve, the internal axial stator disc, the internal axial magnetic pole, the internal axial air gap, the external axial air gap and the external axial stator disk.

![Diagram of Magnetic Circuit](image2)

**Figure 2. Magnetic circuit diagram**

3. The parameter design of axial magnetic bearing

It is necessary to calculate the relationships between the parts to obtain the design parameters of the structure. $B_{max}$ is maximum magnetic flux density in axial air gap. $S_a$ is sum of the internal and external axial air gap areas. The total magnetic flux is as in equation (1).

$$S_a = \frac{2 \times \mu_0 \times F_{max}}{B_{max}}$$  

(1)

The winding ampere turns and the number of turns in the axial winding are as in equation (2) and (3) respectively. $I_0$ is biased current, $I_{max}$ is maximum control current.

$$N = \frac{(NI)_a}{I_0 + I_{max}}$$  

(2)

$$N = \frac{(NI)_a}{I_0 + I_{max}}$$  

(3)

The cross-sectional area of each turn and the root number of enamelled wire per turn are as in equation (4) and (5) respectively. $J_f$ is current density.

$$S_a = \frac{I_0 + I_{max}}{J_f}$$  

(4)

$$N_a = \frac{S_a}{0.25 \times \pi \times d_b^2}$$  

(5)

The sectional area of the axial winding (bare wire) is as in equation (6).

$$S_{mn} = 0.25 \times \pi \times d_b^2 \times N_a \times N$$  

(6)

Parameters related to the internal axial magnetic pole are internal diameter $D_{int}$, external diameter $D_{ext}$, their relationship is as in equation (7).

$$D_{ext} = \sqrt{\frac{2 \times S_a}{\pi} + D_{int}^2}$$  

(7)

The parameters of stator disk are as follows: internal diameter $D_{spi}$, external diameter $D_{spo}$, axial thickness $T_{sp}$. The value of thickness of the stator disk is as in equation (8). The relevant parameters
of thrust plate is the thickness of thrust plate $T_{t}$, and the value of it is as in equation (9).

$$T_{t} = \frac{P}{B_{\text{max}} \times \pi \times D_{\text{st}} \times \text{sio}}$$  \hspace{1cm} (8)

$$T_{t} = \frac{P}{B_{\text{max}} \times \pi \times D_{\text{st}} \times \text{sio}}$$  \hspace{1cm} (9)

Parameters related to stator sleeve are: internal diameter $D_{\text{si}}$, outside diameter $D_{\text{so}}$, $S_{f}$ is slot full rate. $L_{c}$ is the winding thickness. $D_{\text{aci}}$ is the axial winding internal diameter. The relationship of them is as in equation (10) and (11) respectively.

$$D_{\text{si}} = \frac{2 \times S_{f}}{S_{f} \times L_{c}} + D_{\text{aci}}$$  \hspace{1cm} (10)

$$D_{\text{so}} = \sqrt{D_{\text{so}}^{2} + \frac{4 \times P}{\pi \times B_{\text{max}}}}$$  \hspace{1cm} (11)

4. Electromagnetic field analysis

The two-dimensional model of the magnetic bearing is built in the simulation software.

4.1 Simulation and verification analysis of magnetic field trend in closed loop

Figure 3 and figure 4 reveal that the closed loop of the internal axial stator disk is formed, which verifies the correctness of the theoretical analysis.

Figure 5 reveals that the magnetic density of the internal axis air gap and external axis air gap, proving the rule that the flux density does not exceed the saturation flux density of 1.4 tesla. Figure 6-9 reveal the magnetic density of other parts. Figure 10 reveals that the magnetic fluxes and magnetoresistance and magnetic leakage coefficients of each part. The magnetic leakage coefficient at the internal axial air gap and the external axial air gap is larger, because some magnetic fields will diffuse around the air gap.

Figure 3. Magnetic force

Figure 4. Magnetic line vector

(a) internal axial air gap

(b) external axial air gap

Figure 5. Magnetic flux density of the upper and lower magnetic fields in the external axial air gap
**Figure 6.** Internal axial magnetic pole

**Figure 7.** Internal axial Stator disk

**Figure 8.** External axial stator disk

**Figure 9.** Stator sleeve

| Parameter                   | magnetic flux                                                                 | magnetoresistance | Magnetic flux leakage coefficient |
|-----------------------------|-------------------------------------------------------------------------------|-------------------|-----------------------------------|
| The inner axial gap         | \( \Phi_{\text{ap}} = 0.25 \cdot \pi \cdot B_{\text{ap}} \cdot (D_{\text{air}} - D_{\text{air}}^2) \) \( = 27.8 \times 10^{-4} \) (Wb) | \( R_{\text{mle}} = \frac{L_{\text{ap}}}{\mu \cdot S_{\text{ap}}} = 39.788 \) H\(^{-1}\) | 5.13 |
| The outer axial gap         | \( \Phi_{\text{ap}} = 0.25 \cdot \pi \cdot B_{\text{ap}} \cdot (D_{\text{air}} - D_{\text{air}}^2) \) \( = 20.05 \times 10^{-4} \) (Wb) | \( R_{\text{mle}} = \frac{L_{\text{ap}}}{\mu \cdot S_{\text{ap}}} = 44.209 \) H\(^{-1}\) | 7.13 |
| The inner pole              | \( \Phi_{\text{ap}} = 0.25 \cdot \pi \cdot B_{\text{ap}} \cdot (D_{\text{air}} - D_{\text{air}}^2) \) \( = 80.73 \times 10^{-4} \) (Wb) | \( R_{\text{mle}} = \frac{L_{\text{ap}}}{\mu \cdot S_{\text{ap}}} = 455 \) H\(^{-1}\) | 1.77 |
| The inner stator disk       | \( \Phi_{\text{ap}} = \pi \cdot B_{\text{ap}} \cdot D_{\text{st}} \cdot T_{\text{st}} \) \( = 107 \times 10^{-4} \) (Wb) | \( R_{\text{mle}} = \frac{\ln \frac{L_{\text{st}}}{\mu}}{2 \cdot \ln \frac{\mu + \mu_{\text{st}}}{\mu}} \) \( = 110.29 \) H\(^{-1}\) | 1.33 |
| The outer stator disk       | \( \Phi_{\text{ap}} = \pi \cdot B_{\text{ap}} \cdot D_{\text{st}} \cdot T_{\text{st}} \) \( = 98.65 \times 10^{-4} \) (Wb) | \( R_{\text{mle}} = \frac{\ln \frac{L_{\text{st}}}{\mu}}{2 \cdot \ln \frac{\mu + \mu_{\text{st}}}{\mu}} \) \( = 104.66 \) H\(^{-1}\) | 1.44 |
| The stator sleeve           | \( \Phi_{\text{st}} = 0.25 \cdot \pi \cdot B_{\text{st}} \cdot (D_{\text{st}} - D_{\text{st}}^2) \) \( = 142.5 \times 10^{-4} \) (Wb) | \( R_{\text{mle}} = \frac{L_{\text{st}}}{\mu \cdot S_{\text{st}}} = 328.36 \) H\(^{-1}\) | 1 |

**Figure 10.** Parameter calculation
4.3 Current stiffness simulation verification analysis
It can be seen that the axial suspension force on the rotor with electromagnetic biased axial magnetic bearings is basically linearly related to the control current, and the greater the control current in the coil, the greater the axial suspension force on the rotor from figure 11.

4.4 Displacement stiffness simulation verification analysis
Figure 12 reveals that the axial suspension force on the rotor is basically linearly related to displacement. When the displacement of the rotor exceeds 0.6 mm, the axial suspension force required exceeds the maximum force that can be generated, so the rotor can’t return to middle position. In practice, the auxiliary bearing will be placed at both sides of the thrust plate so that the rotor can be stabilized in the middle position when the displacement is too large.

5. Conclusion
The results show that maximum levitation force and flux density curve can be generated. The magnetic field leakage coefficient of the structure is calculated by the formula, and the design parameters are verified to meet the design requirements. This kind of magnetic biased axial magnetic bearing studied in this paper is proved to be reasonable by finite element simulation, which not only meets the design requirements, but also has a simple structure, which has important reference value for the design of electromagnetic biased axial magnetic bearing.

6. References
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