A Type of Electromagnetic Biased Axial Magnetic Bearing with Low Target OD

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Abstract. A type of electromagnetic biased axial magnetic bearing is proposed. Compared with traditional axial magnetic bearings, it has low target OD, which is helpful to improve the critical speed of the rotor in theory. By using the equivalent magnetic circuit method, a magnetic circuit analysis is carried out. The expressions of magnetic flux density of each part are obtained, and the structural parameters are obtained and the finite element model (FEM) is established. The magnetic flux leakage coefficient and magnetic resistance are calculated by using simulation data, and the rationality of the parameter design is verified. The results show that the parameter design and electromagnetic field simulation of this type of the electromagnetic bias axial magnetic bearing are in accordance with the rationality of the design. It can be used as a reference for 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. Compared with the common bearing, the electromagnetic biased axial magnetic bearing has the advantages of no mechanical friction, no need of lubrication, long service life, low loss and so on, therefore it has great research value in the aspect of high-speed motor and flywheel energy storage.

The principle and structure of electromagnetic active control magnetic bearing are introduced in reference [1]. The structure and working principle of bearing-free single degree of freedom active magnetic bearing are introduced in reference [2]. The parameters are designed and the calculation method is given in reference [3]. A new structure of electromagnetic magnetic circuit formed by the second air gap is proposed to reduce the eddy loss in reference [4]. The structures of two kinds of redundant magnetic bearings are introduced in reference [5]. A permanent magnet biased radial magnetic bearing with four independent poles is proposed, and its parameter optimization design is studied based on the method of sequential quadratic programming in reference [6]. A six-pole heteropolar permanent magnet biased radial magnetic bearing is proposed, and a mathematical model based on equivalent magnetic circuit and coordinate transformation method is established in reference [7]. A uniform permanent magnet bias radial magnetic bearing composed of four C-shaped cores is proposed in reference [8]. The magnetic bearing has lower iron loss and lower cost. The optimal design of a permanent magnet biased axial-radial magnetic bearing is studied in reference [9]. Considering the incompatibility of the optimization model, a multi-objective optimization method is
In this paper, a kind of magnetic biased axial magnetic bearing is studied. Compared with the traditional axial magnetic bearing, it has low target OD, in other words, it has a smaller external diameter of thrust plate. The magnetic field is analyzed by FEM. The magnetic leakage coefficient and magnetic reluctance are calculated by magnetic density of each part to verify the feasibility of the theoretical design.

2. Structure of axial magnetic bearing

2.1. Structure of the electromagnetic biased axial

The structure is shown in the figure 1. The magnetic circuit diagram is shown in the figure 2. Because the magnetic bearing structure is axisymmetric, the model can be transformed into two-dimensional model for analysis. 1-rotating shaft, 2-internal axial stator disk, 3-internal axial magnetic pole, 4-upper coil winding A, 5-stator sleeve, 6-external axial stator disk, 7-thrust plate.

When the current is passed into the coil, 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.

2.2. Working principle of electromagnetic biased axial magnetic bearing

The basic working principle is as follows: the magnetic flux at the air gap is the synthesis of the biased magnetic flux and the control magnetic flux. It is assumed that the lower air gap is increased while the upper air gap is reduced when the position of the axial magnetic bearing rotor is offset. The position sensor detects the displacement of the rotor and passes the signal to the controller, the controller makes corresponding adjustment according to the signal, and transmits the control signal to the power amplifier, and the power amplifier then converts the signal into a control current. The current flows through the coil winding of the electromagnet to generate a control magnetic field. In the lower air gap, the direction of the biased magnetic field is the same as that of the control magnetic field, the total air gap magnetic flux increases, and in the upper air gap, the direction of the biased magnetic field is opposite to that of the control magnetic field, the total magnetic flux decreases. Finally, the total magnetic flux in the lower air gap is greater than the upper air gap, so that the electromagnetic force generated in the lower air gap is greater than the upper air gap, and finally the rotor moves to the intermediate position.

3. The parameter design of axial magnetic bearing

3.1. Magnetic circuit model

In order to simplify the magnetic circuit diagram, considering the magnetic reluctance of the working air gap and neglecting the magnetic reluctance of the rotor and the eddy current loss, the equivalent magnetic circuit analysis is carried out on the upper electromagnet core. The equivalent magnetic circuit model of the magnetic bearing can be obtained as shown in the figure 3, and the equivalent magnetic circuit of the lower electromagnet core can be obtained by the same principle.

In the figure 3, $R_{g1}, R_{g2}$ are magnetic reluctance of internal axial air gap and external axial air gap respectively, $R_0$ is leakage magnetic reluctance of air gap, $\Phi_{g1}$ is its magnetic flux, $\Phi_{g2}$ is its leakage flux.
magnetic flux. $R_{g1}$ is magnetic reluctance of external axial stator disk, $R_{g2}$ is its leakage magnetic reluctance. $\Phi_{g2}$ is magnetic flux of external axial stator disk, $\Phi_{g3}$ is its leakage magnetic flux. $R_{g4}$ is magnetic reluctance of stator sleeve, $R_{g5}$ is its leakage magnetic reluctance. $\Phi_{g5}$ is magnetic flux of external axial stator disk, $\Phi_{g6}$ is its leakage magnetic flux. $R_{g7}$ is magnetic reluctance of internal axial stator disk , $R_{g8}$ is its leakage magnetic reluctance. $R_{g9}$ is magnetic reluctance of internal axial pole, $R_{g10}$ is its leakage magnetic reluctance. $\Phi_{g11}$ is magnetic flux of internal axial pole, $\Phi_{g12}$ is its leakage magnetic flux. $N_I$ is an electrically excited equivalent magnetic potential, $e\Phi$ is coil magnetic flux generated by coil windings.

3.2. Parameter design based on magnetic circuit method

In order to obtain the design parameters of the structure, it is necessary to use the formula to calculate the relationship between the parts. $B_{max}$ is the maximum magnetic flux density in the axial air gap. $S_a$ is the sum of the internal and external axial air gap areas. The total magnetic flux is:

$$S_a = \frac{2 \times \mu_0 \times F_{max}}{B_{max}^2}$$  \hspace{1cm} (1)

The winding ampere turns and the number of turns in the axial winding are:

$$N_L = \frac{2 \times f_0 \times B_{max} \times Z_0}{\mu_0}$$  \hspace{1cm} (2)

$$N = \frac{N_L}{I_{max}}$$  \hspace{1cm} (3)

The cross-sectional area of each turn and the root number of enamelled wire per turn are:

$$S_{at} = \frac{I_{max}}{J_i}$$  \hspace{1cm} (4)

$$Nat = \frac{S_{at}}{0.25 \times \pi \times db^2}$$  \hspace{1cm} (5)

In the form, $J_i$ is the control winding current density. Select the standard wire diameter is: $db = 1 \times 10^{-3}$. The thickness of the wire paint film is: $q_s = 0.035 \times 10^{-3}$. The winding thickness is: $L_w = 20 \times 10^{-3}$. The sectional area of the axial winding (bare wire) is:

$$S_{aw} = 0.25 \times \pi \times db^2 \times Nat \times N$$  \hspace{1cm} (6)

Related to the internal axial magnetic pole are internal diameter $D_{ai}$, Outside diameter $D_{ao}$:

$$D_{aw} = \sqrt{\frac{2 \times S_{a} \times \pi}{\pi} + D_{ai}^2}$$  \hspace{1cm} (7)

The parameters of stator disk are as follows: internal diameter $D_{spi}$, external diameter $D_{spo}$, axial thickness $T_{sp}$. The relevant parameters of thrust disc is: thickness of thrust disc $T_{tr}$.

$$T_{sp} = \frac{P}{B_{max} \times \pi \times D_{aw}}$$  \hspace{1cm} (8)

$$T_{tr} = \frac{P}{B_{max} \times \pi \times D_{aw}}$$  \hspace{1cm} (9)

Parameters related to stator sleeve are: internal diameter $D_{ssi}$, outside diameter $D_{sso}$, $S_f$ is slot full rate.

$$D_{sa} = \frac{2 \times S_s}{S_f \times L_{aw} + D_{aw}}$$ \hspace{1cm} (10)

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

The final parameter settings are shown in the following table 1.
Table 1. Design of structural parameters

| Parameter Name                                             | Parameter Values |
|------------------------------------------------------------|------------------|
| Rated maximum bearing capacity/ $N$                        | 5000             |
| Axial air gap length/ $mm$                                 | 1                |
| Axial magnetic pole area/ $cm^2$                           | 78               |
| Internal diameter of axial magnetic pole/ $mm$             | 112              |
| External diameter of axial magnetic pole/ $mm$             | 145              |
| Thrust disk thickness/ $mm$                                | 7                |
| Stator disk thickness/ $mm$                                | 15               |
| Axial winding turns                                        | 241              |
| Internal diameter of internal stator disk/ $mm$            | 145              |
| External diameter of internal stator disk/ $mm$            | 302              |
| Internal diameter of external stator disk/ $mm$            | 166              |
| External diameter of external stator disk/ $mm$            | 302              |
| Internal diameter of stator sleeve/ $mm$                   | 302              |
| External diameter of stator sleeve/ $mm$                   | 327              |

4. Electromagnetic field analysis

According to the parameters, the two-dimensional model of the magnetic biased axial magnetic bearing is symmetric about the upper and lower electromagnets, so the upper electromagnets selected is simulated and analyzed. The structure of the model is shown in the figure 1.

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

Figure 4 and figure 5 show that the magnetic flux path generated by coil windings passes through the stator sleeve, the external axial stator disk, the external axial magnetic pole, the external axial air gap, the rotor thrust plate, the internal axial air gap, and the internal axial magnetic pole. The closed loop of the internal axial stator disk is formed, which verifies the correctness of the theoretical analysis.
4.2. Simulation verification and analysis of magnetic flux density

The magnetic density in each part of the structure are shown in figure 6–figure 11, proving the rule that the magnetic flux density does not exceed the saturation magnetic flux density of 1.4 tesla.

The magnetic flux magnetic reluctance and magnetic leakage coefficients of each part are shown in the table 2. 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.

Table 2. Parameter calculation

| Parameter                  | Magnetic flux       | Magnetic reluctance | Magnetic flux leakage coefficient |
|----------------------------|---------------------|---------------------|----------------------------------|
| The internal axial air gap | $\Phi_{aig} = 0.25 \cdot \pi \cdot B_{aig} \cdot (D_{aig}^2 - D_{aie}^2)$ | $R_{mig} = \frac{L_{mig}}{\mu \cdot S_{mig}} = 165786 \text{ H}^{-1}$ | 3.3                              |
| The external axial air gap | $\Phi_{oig} = 0.25 \cdot \pi \cdot B_{oig} \cdot (D_{oig}^2 - D_{oie}^2)$ | $R_{mog} = \frac{L_{mog}}{\mu \cdot S_{mog}} = 265258 \text{ H}^{-1}$ | 4.08                             |
| The internal axial pole    | $\Phi_{aip} = 0.25 \cdot \pi \cdot B_{aip} \cdot (D_{aip}^2 - D_{aie}^2)$ | $R_{mip} = \frac{L_{mip}}{\mu \cdot S_{mip}} = 537 \text{ H}^{-1}$ | 1.99                             |
| The internal axial stator disk | $\Phi_{asip} = \pi \cdot B_{asip} \cdot D_{asip} \cdot T_{asip}$ | $R_{masp} = \frac{\ln \frac{r_2}{r_3}}{2 \cdot L_{asip} \cdot \pi \cdot \mu_0 \cdot \mu}$ | 1.12                             |
|                           | $= 156.5 \times 10^{-4} \text{ (Wb)}$ | $= 118 \text{ H}^{-1}$ |                                  |
| The external axial stator disk | $\Phi_{osp} = \pi \cdot B_{osp} \cdot D_{osp} \cdot T_{osp}$ | $R_{mosp} = \frac{\ln \frac{r_4}{r_3}}{2 \cdot L_{osp} \cdot \pi \cdot \mu_0}$ | 1.1                              |
|                           | $= 160.1 \times 10^{-4} \text{ (Wb)}$ | $= 112 \text{ H}^{-1}$ |                                  |
| The stator sleeve         | $\Phi_s = 0.25 \cdot \pi \cdot B_{as} \cdot (D_{ais}^2 - D_{aie}^2)$ | $R_{ms} = \frac{L_{ms}}{\mu \cdot S_{ms}} = 290 \text{ H}^{-1}$ | 1                                |
|                           | $= 175.4 \times 10^{-4} \text{ (Wb)}$ | |                                  |

5. Conclusion

In this paper, a type of electromagnetic biased axial magnetic bearing with low target OD is designed, its structure and working principle are analyzed, the magnetic circuit model is established, and the related parameters are designed based on the magnetic circuit method. Finally, the finite element
simulation and analysis are carried out. The simulation results show that the maximum suspension force can meet the design value required by the theory. According to the magnetic density curve, the magnetic flux leakage coefficient and the magnetic reluctance of each part of the structure are calculated by the formula, and the rationality of each design parameter is verified.

The finite element model studied in this paper proves the rationality of its design, and has important reference value for the design of electromagnetic bias axial magnetic bearing.

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