Design and analysis of permanent magnet biased radial magnetic bearing with external rotor for vacuum tube

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Abstract. A permanent magnet biased radial magnetic bearing with external rotor for vacuum tube was introduced, and the configuration and operating principle were analyzed. The parameter design method based on the total magnetic flux was established to deduce the calculation formulas of the parameters of the permanent magnet radial magnetic bearing. The magnetic flux leakage coefficient and the magnetic resistance coefficient were considered, and the calculations were constrained to the degree of magnetic flux density unsaturation of the internal magnetic field of the soft magnetic material. Finite element software was used to execute simulation analysis and modeling of the permanent magnet biased radial magnetic bearing. The results show that the design method is reasonable and efficient, and the design magnetic bearing is compact and easy to control, which is more suitable for the liner motion with low power consumption.

1. Introduction

As a new type of ultra-high speed transportation, vacuum tube uses magnetic suspension technology and vacuum sealed tube to realize the operation of non-friction, low noise and ultra-high speed[1,2]. In order to realize no mechanical friction of vacuum tube, magnetic bearing can be used to provide support for it. Magnetic bearing is a kind of high-performance bearing which uses electromagnetic force to suspend the rotor [3]. The permanent magnet biased magnetic bearing is a kind of magnet bearing, which combines the advantages of passive and active magnetic bearings. It uses the permanent magnet to generate static biased magnetic field, and the control coil to generate the control magnetic field to balance the load and interference. Therefore, it greatly reduces the power loss and the weight and volume of the bearing [4-7]. It has a wide application prospect in the field of vacuum tube transportation.

The magnetic field distribution is complex, because there are both permanent magnetic field and electromagnetic field in the permanent magnet biased radial magnetic bearing. There are many magnetic flux leakages and magneto resistances, and the forming bias magnetic field cannot be changed, so the parameters design of the permanent magnet biased radial magnetic bearing has become one of the key and difficult issues [8-11]. In order to simplify the design difficulty, the magnetic flux leakage and magneto resistance are ignored in the traditional design method of magnetic bearing, and the design accuracy is not high [12-15].

In this paper, a parameter design method based on the total flux of magnetic field is used to design the parameters of the outer rotor permanent magnet biased radial magnetic bearing for vacuum tube. In this
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method, the leakage coefficient and the magnetoresistance coefficient are considered, and the constraint condition of the flux density unsaturated in the soft magnetic material is satisfied. Therefore, the design efficiency and the correctness of the design results are improved.

2. The structure and working principle of the permanent magnet biased radial magnetic bearing with external rotor

2.1. Basic Structure

The basic structure of the permanent magnet biased radial magnetic bearing is shown in Fig. 1. The structure consists of rotor core, stator yoke, stator pole, ring permanent magnet and control coil. The rotor core, stator yoke and stator pole are all made of soft magnetic materials. The magnetic bearing has 8 stator poles, which form a radial air gap with the rotor core. Each pole is wound with a control coil, and the corresponding two control coils are connected in series. The ring permanent magnet is made of neodymium iron boron, which has the best magnetic properties, and is magnetized axially. The control coil is made of enameled wire.

![Figure 1. Structure of permanent magnet biased radial magnetic bearing.](image)

1: rotor core; 2: stator yoke; 3: radial air gap; 4: control coil; 5: stator pole; 6: ring permanent magnet

2.2. Working Principle

The magnetic field distribution of the permanent magnet biased radial magnetic bearing is shown in Fig. 2. The ring permanent magnet establishes a static bias magnetic field in the magnetic bearing, as shown in Fig. 2 (a). After the control coil is energized, a control magnetic field for balancing load and interference is established in the magnetic bearing, as shown in Fig. 2 (b).

Due to the symmetry of the magnetic bearing structure, when the rotor is in the center position under the static bias magnetic field generated by the ring permanent magnet, the flux density of the bias magnetic field in each air gap is equal, and the suspension force on the rotor is zero.

Taking the vertical direction as an example, when the rotor is disturbed by a positive direction along the Y axis in the center position, the rotor deviate from the center position and move towards the +Y direction, so that the air gap in the +Y direction is larger, and the generated suction is smaller. At the same time, the air gap in the -Y direction is smaller, and the generated suction is larger. At this time, the sensor detects the displacement of the rotor away from the center position and transmits the displacement signal to the controller; the controller transforms the displacement signal into a control signal and transmits it to the power amplifier; the power amplifier converts the control signal into a control current, which flows through the control coil to generate a control flux. At the air gap of +Y direction, the direction of the control magnetic field is the same as the bias magnetic field, so the magnetic field is enhanced, and the suction is increased. At the air gap of -Y direction, the direction of the control magnetic field is opposite to the bias magnetic field, so the magnetic field is weakened, and the suction is reduced. The rotor receives the downward suspension force, and returns to the center position.
If the rotor is disturbed in other directions, the working principle is similar. When the disturbance of the rotor does not exceed the bearing capacity of the magnetic bearing, the permanent magnet biased radial magnetic bearing can produce radial suspension force to realize the stable suspension of the rotor.

![Bias magnetic circuit](image1)  ![Control magnetic circuit](image2)

**Figure 2.** Distribution of magnetic field in magnetic bearing.

3. Parameters design of permanent magnet biased radial magnetic bearing with external rotor

3.1. Calculation of Total Magnetic Flux of Magnetic Field

If the linear range of the magnetization curve of the soft magnetic material is \([B_{\text{min}}, B_{\text{max}}]\), at the radial air gap, the magnetic flux density of the bias magnetic field, \(B_b\), and the magnetic flux density of the control magnetic field, \(B_c\), are:

\[
B_b = \frac{1}{2}(B_{\text{min}} + B_{\text{max}}) \tag{1}
\]

\[
B_c = \frac{1}{2}(B_{\text{max}} - B_{\text{min}}) \tag{2}
\]

According to the calculation formula of radial suspension force:

\[
F_r = \frac{2B_b B_c S_{\text{rgp}}}{\mu_0} \tag{3}
\]

The projection area of a single radial air gap is:

\[
S_{\text{rgp}} = \frac{\mu_0 F_r}{2B_b B_c} \tag{4}
\]

Where, \(\mu_0\) is air permeability.

According to the geometric relationship of the bearing, the projection area of a single radial air gap is:

\[
S_{\text{rgp}} = D r_i T_r \sin \left(\frac{1}{2} \alpha_r \right) \tag{5}
\]
The area of a single radial air gap is:

\[ S_{rg} = \frac{1}{2} D_{rti} \alpha_{rp} T_{rp} \]  

(6)

Where, \( \alpha_{rp} \) is radial pole radian; \( D_{rti} \) is the inner diameter of rotor; \( T_{rp} \) is the thickness of stator pole. From equations (5) and (6), it can be concluded that:

\[ S_{rg} = \frac{\alpha_{rp} S_{rgrp}}{2 \sin \left( \frac{1}{2} \alpha_{rp} \right)} \]  

(7)

According to equations (4) and (7), the area of a single radial air gap is:

\[ S_{rg} = \frac{\alpha_{rp} \mu_0 F_r}{4 B_b B_c \sin \left( \frac{1}{2} \alpha_{rp} \right)} \]  

(8)

The total flux of the bias field is:

\[ \phi_b = 4 \sigma_b B_b S_{rp} \]  

(9)

Where, \( \sigma_b \) is the air gap leakage coefficient of the bias magnetic field. The total flux of the control magnetic field is:

\[ \phi_c = \sigma_c B_c S_{rp} \]  

(10)

Where, \( \sigma_c \) is the air gap leakage coefficient of the control magnetic field.

3.2. Design of Soft Magnetic Material Parameters
Taking the stator yoke as an example, according to the geometric relationship of the magnetic bearing, the axial thickness of the stator yoke is:

\[ T_{sy} = \frac{2 S_{rg}}{D_{rt} \alpha_{rp}} \]  

(11)

The flux of the stator yoke bias field is:

\[ \phi_{b_{sy}} = \frac{\phi_b}{\sigma_{b_{sy}}} \]  

(12)

Where, \( \sigma_{b_{sy}} \) is the flux leakage coefficient of the stator yoke with bias magnetic field.
The flux density of the stator yoke bias field is:

\[
B_{by} = \frac{\phi_{by}}{\pi \left( \frac{D_{sy}}{2} \right)^2 - \left( \frac{D_{syl}}{2} \right)^2}
\]  

(13)

Where, \( D_{sy} \) is the outer diameter of the stator yoke, \( D_{syl} \) is the inner diameter of the stator yoke.

The flux of stator yoke control magnetic field is:

\[
\phi_{cxy} = \frac{\phi_c}{\sigma_{cxy}}
\]

(14)

Where, \( \sigma_{cxy} \) is the flux leakage coefficient of the stator yoke with bias magnetic field.

The flux density of the stator yoke control magnetic field is:

\[
B_{cxy} = \frac{\phi_{cxy}}{T_{sy} \left( \frac{D_{sy}}{2} - \frac{D_{syl}}{2} \right)}
\]

(15)

Then the flux density of the superposition field of the bias magnetic field and the radial control magnetic field of the stator yoke is:

\[
B_{sy} = \sqrt{B_{by}^2 + B_{cxy}^2} \leq B_{max}
\]

(16)

According to formula (16), the magnetic field in the stator yoke can be guaranteed to be unsaturated.

3.3. Design of Control Winding Parameters

According to the ampere turns of the control winding, the turns of the control winding is:

\[
N = f_c \frac{B_{c} g_r}{\mu_0 I_{max}}
\]

(17)

Where, \( f_c \) is magnetoresistance coefficient of control magnetic field; \( g_r \) is the air gap length; \( I_{max} \) is the maximum current.

The cross-sectional area of each control winding is:

\[
S_{c} = \frac{I_{max}}{J_s}
\]

(18)

Where, \( J_s \) is the current density.

The number of parallel windings per turn of control winding is:
Where, \( d_r \) is the diameter of enameled wire.

The cross-sectional area of the whole control winding is:

\[
S_{rc} = (d_r + 2q_m)^2 \, N_{rt} \, N
\]  

(20)

Where, \( q_m \) is the film thickness of enameled wire.

3.4. Design of Parameters of Ring Permanent Magnet

The demagnetization curve of the ring permanent magnet material is close to a straight line. In order to improve the utilization rate of the permanent magnet material, its working point is set near the maximum magnetic energy integration point.

The flux density at the working point of the ring permanent magnet is:

\[
B_{mg} = B_r - \frac{B_r}{H_c} \, H_{mg}
\]  

(21)

Where, \( B_r \) is the residual flux density of the ring permanent magnet, \( H_c \) is the coercive force of the ring permanent magnet.

The neutral area of the ring permanent magnet is:

\[
S_{mg} = \frac{\phi_b}{B_{mg}}
\]  

(22)

The inner diameter of permanent magnet material is equal to the inner diameter of stator yoke. According to the geometric relationship, the outer diameter of permanent magnet material is:

\[
D_{mgo} = \sqrt{D_{mg_i}^2 + \frac{4S_{mg}}{\pi}}
\]  

(23)

Where, \( D_{mg_i} \) is the inner diameter of permanent magnet material.

If the outer diameter of the permanent magnet material is larger than the outer diameter of the stator yoke, the outer diameter of the stator yoke shall be equal to the outer diameter of the permanent magnet material.

According to the equivalent magnetic circuit method, the axial thickness of the ring permanent magnet is:

\[
T_{mg} = \frac{2f_r B_r S_r}{\mu_0 H_{mg}}
\]  

(24)
Where, $f_b$ is the magnetic resistance coefficient of the bias magnetic field.

4. **Parameters optimization process based on total flux calculation**

As shown in Fig. 3(a), magnetic flux leakage and magnetoresistance are considered in the traditional design process of the permanent magnet biased radial magnetic bearing, so the design accuracy is not high. At the same time, the parameter design needs to be constantly modified, which is cumbersome and inefficient. The parameters design flow based on the total flux is shown in Fig. 3(b). The relevant parameters of the permanent magnet biased radial magnetic bearing are obtained by the magnetic resistance coefficient and magnetic leakage coefficient of the bias magnetic field and the control magnetic field, which improves the accuracy and design efficiency of the magnetic bearing parameter design.

![Diagram](image)

**Figure 3.** Parameters design flow chart of permanent magnet biased radial magnetic bearing of outer rotor.

As shown in Table 1, there are known parameters. In the preliminary design, the magnetic flux leakage coefficient and magnetoresistance coefficient are taken as 1. Through the finite element simulation results, the obtained magnetic flux leakage coefficient and magnetoresistance coefficient are substituted into the parameter design formula to carry out the parameter design again. And the new design results are simulated and analyzed again to obtain the new magnetic flux leakage coefficient and magnetoresistance coefficient. In this way, the cycle iteration is carried out until the magnetic flux leakage coefficient and
magnetoresistance coefficient tend to the fixed value, and at the same time, the magnetic flux all indexes of the bearing reach the design goal.

Through the above parameter design method, the magnetic resistance coefficient and leakage coefficient of bias magnetic field and control magnetic field tend to constant value, and their values are shown in Table 2.

| Known parameters                   | Value     |
|------------------------------------|-----------|
| The maximum radial force, $F_r$    | 1000N     |
| The radial air gap length, $g_r$   | 1mm       |
| The coercive force of permanent magnet material, $H_c$ | 798KA/m |
| The residual flux density of permanent magnet material, $B_r$ | 1.066T |
| The maximum flux density of soft magnetic material, $B_{max}$ | 1.4T |
| Maximum current, $I_{max}$         | 3A        |
| Current density, $J_s$             | 4A/mm²    |
| Radial pole arc, $\alpha_{rp}$    | $2\pi/9$rad |

| Magnetic resistance coefficient and leakage coefficient of bias magnetic field | Value | Magnetic resistance coefficient and leakage coefficient of control magnetic field | Value |
|-------------------------------------------------------------------------------|-------|-------------------------------------------------------------------------------|-------|
| $f_b$                                                                         | 1.1   | $f_c$                                                                         | 1.28  |
| $\sigma_b$                                                                   | 3.34  | $\sigma_c$                                                                   | 1.1   |
| $\sigma_{bxy}$                                                               | 1.9   | $\sigma_{cxy}$                                                               | 1     |

5. The magnetic field simulation results of permanent magnet biased radial magnetic bearing with external rotor
In order to verify the rationality of the design parameters of the bearing, two-dimensional and three-dimensional finite element simulation software is used.

5.1. Two Dimensional Finite Element Simulation Results
Because the bias magnetic field and the control magnetic field are not in the same plane, two models need to be built to simulate and analyze in 2D finite element simulation. The bias magnetic field is simulated by the axisymmetric model, and the control magnetic field is simulated by the plane model.

The simulation results of the bias magnetic field are shown in Fig. 4. According to the simulation results, it is shown that the flux density of the bias magnetic field in the radial air gap is about 0.7T.
The simulation results of the control magnetic field are shown in Fig. 5. According to the simulation results, it is shown that the flux density of the control magnetic field in the radial air gap is about 0.7T.
5.2. Three Dimensional Finite Element Simulation Results

As shown in Fig. 6, it is a three-dimensional finite element sectional drawing of the permanent magnet biased radial magnetic bearing.

Figure 5. The finite element simulation results of control magnetic field

Figure 6. Three-dimensional finite element mesh generation.
When the control winding current is zero, there is only the flux density of the bias magnetic field in the air gap, and its distribution is shown in Fig. 7. According to the simulation results, the flux density of the bias magnetic field at each air gap is basically the same, and they are all about 0.7T, reaching the design goal.

![Figure 7. Flux density of bias magnetic field in air gap.](image)

Taking the Y direction as an example, when the control winding in the Y direction receives the maximum current, the flux density distribution in the radial air gap is shown in Fig. 8. According to the simulation results, the air gap flux density in the + Y direction increases to about 1.4T, the air gap flux density in the - Y direction decreases to about 0T, while the air gap flux density in the X direction is basically unchanged. The simulation results show that it is consistent with the design goal, and the external rotor permanent magnet biased radial magnetic bearing has good decoupling.

![Figure 8. Flux density in air gap after maximum current of Y direction control winding.](image)

Using the magnetic circuit analysis, when the radial magnetic bearing rotor is shifted to the right by $x$, the bearing capacity of $F_x$ to the left needs to be generated and linearized.

The linear equation of the rotor near the balance position is:
Where, the first and second coefficients are displacement stiffness and current stiffness of radial bearing respectively.

The performance curve of radial magnetic bearing is shown in Fig. 9. The results of magnetic circuit analysis are basically close to the results of finite element simulation, which verifies the accuracy of the established magnetic circuit model and the rationality of the design results.

\[
F = \frac{\partial F_x}{\partial x} \bigg|_{x=0} x + \frac{\partial F_x}{\partial i} \bigg|_{i=0} i
\]  \hspace{1cm} (25)

Figure 9. The calculation results of permanent magnet biased radial magnetic bearing with external rotor.

6. Conclusion
In this paper, the permanent magnet biased radial magnetic bearing with external rotor for vacuum tube has the advantages of compact structure, simple control and low power consumption, and has a wide application prospect in the field of high-speed transportation.

The method based on the total flux of the magnetic field is used to design the parameters of the magnet bearing. The design accuracy and efficiency are improved by considering the leakage coefficient and the magnetoresistance coefficient and taking the flux density of the internal magnetic field of the soft
magnetic material as the constraint condition. The simulation results show that the design results are accurate and reasonable, and achieve the design goals.

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