Finite element analysis on the electromagnetic fields of active magnetic bearing

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Abstract. To increase the carrying capacity and reduce the weight and size of AMBs, it is necessary to use a ferromagnetic material with high magnetic flux density, which can make AMBs run in the nonlinear region. The simple linear model before is not gratifying, so some more precise analysis methods are demanded, the finite element method (shorted as FEM) is one of such methods. In this paper, the mathematic model and the simplified calculation of AMB rotor are introduced, and the finite elemental model and its boundary condition are produced. Then, the coupling phenomena of the magnetic fields and the effects of different parameters on the magnetic fields of AMB with a non-homocentric rotor are simulated using the FEM analysis software of ANSYS. The distributions of 2D magnetic lines of force and the flux density in rotor and stator are given. The conclusions are of instructed meaning for the design of AMBs.

1. INTRODUCTION

Active magnetic bearing (AMB) is a new kind of bearing. Unlike conventional bearings, which rely on mechanical forces originating from fluid films or physical contact to support bearing loads, AMB systems utilize controllable electromagnetic force caused by electromagnet to levitate and support a shaft in an air-gap between the bearing stators\cite{1-4}. The technology of AMB relates to many subjects such as Electromagnetism, Control Theory, Mechanics, Rotor Dynamics, etc. Compared to conventional mechanical bearings, AMB offers the following unique advantages: non-contact, no friction, high speed, low power loss, high accuracy, elimination of lubrication and so on. Due to these advantages, AMB is used widely in many fields such as transportation, high-speed machine tool, aerospace, nuke industry, etc\cite{5,6}.

The carrying capacity of the active magnetic bearing is the sum of the dynamic carrying capacity and the static one. The largest carrying capacity is determined by the largest magnetic flux density of the

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magnetic materials. To gain higher static carrying capacity, the dynamic force is limited. Therefore, in some conditions, a large control current can make the magnetic materials of a AMB into the nonlinear region[7]. The traditional analysis methods for the magnetic circuits seldom consider the effects of such facts as the nonlinearity of the materials, the vortex, the hysteresis, the edge effect and the magnetic flux leakage on the idiosyncrasy of AMBs. To increase the carrying capacity and reduce the weight and size of AMBs, it is necessary to use a ferromagnetic material with high magnetic flux density, which can make AMBs run in the nonlinear region. The simple linear model before is not gratifying, so some more precise analysis methods are demanded, the finite element method(shorted as FEM) is one of such methods.

Recently there were some research works that studied the magnetic field of AMB using FEM[8,9]. These works mainly studied the coupling phenomena of the magnetic fields and the effects of the bias current on the magnetic field.

In this work, the effects of different parameters(control current in electromagnet windings and offset of the rotor) on the magnetic fields of AMB with a non-homocentric rotor are studied, as well as the coupling phenomena of the magnetic fields.

2. MATHMATIC MODEL AND FORMULATIONS DERIVATION

The stator and the shaft sleeve of rotor are made of soft magnetic materials, and the rotor is made of materials of low permeability. Therefore, in the linear analysis, the effects of such facts as the magnetic flux leakage, the magnetic resistances of stator and rotor, the vortex and the hysteresis of the materials are ignored. The magnetic lines of force are nearly vertical upon its leaving from the magnets, and the wavelength of the alternating magnetic field is much larger than its geometric size, so the magnetic system is considered as a static field. To gain the linear analysis of the magnetic field, take the example of single DOF(degree of freedom) radial AMB excitated by differential mode, shown in figure 1(8 magnetic poles). The total electromagnetic force on y-direction caused by the pair of electromagnets up and down is:

\[
f_y = \frac{A_r}{\mu_0} (B_2^2 - B_1^2) = \frac{\mu_0 A_r N^2}{4} \left[ \frac{(i_b + i_c)^2}{(y_0 - y)^2} - \frac{(i_b - i_c)^2}{(y_0 + y)^2} \right] \cos \alpha \tag{1}
\]

where, \( \mu_0 \) is vacuum magnetic permeability, \( \alpha \) represents half of the angle between the two poles of a electromagnet(for 8 magnetic poles AMB, \( \alpha = 22.5^\circ \)), \( N \) represents coil turns, \( A_r \) is the cross section area of gap, \( y_0 \) is the nominal air gap, \( y \) is the varied value of gap, \( i_b \) is the bias current, \( i_c \) is the control current, \( B_1, B_2 \) are respectively the magnetic flux density of the gaps above and below the rotor.

![Figure 1. Configuration of single DOF radial AMB.](image)
Near the steady balance point, \( y \ll y_0 \), thus the linearized expression of (1) is presented as the following:

\[
f_y = k_y i + k_y y
\]

(2)

where, \( k_y \) is displacement stiffness coefficient, \( k_y = \frac{\mu_0 A_i N^2 i_b^2}{y_0^3} \cos \alpha \), and \( k_i \) is current stiffness coefficient, \( k_i = \frac{\mu_0 A_i N^2 i_b}{y_0^2} \cos \alpha \).

3. **FINITE ELEMENTAL ANALYSIS**

Because the control current \( i_c \) is much less than the bias current \( i_b \), so the magnetic field can be considered as static field. The Maxwell equations of the AMB system are:

\[
\begin{align*}
\nabla \times H &= -J_z \\
\nabla \cdot B &= 0 \\
B &= \mu H
\end{align*}
\]

(3)

Magnetic potential \( A \) is produced as:

\[
\nabla \cdot A = 0
\]

(4)

Through expressions (3) and (4), the partial differential equation of the magnetic potential in 2-D plane field can gained as following:

\[
\nabla^2 A = -\mu J_z
\]

(5)

In 2-D plane magnetic field, both current density vector \( J \) and the magnetic potential vector \( A \) only have one component \( J_z \) and \( A_z \) on \( Z \) direction. The AMB system is dealt as a problem of plan-symmetry magnet. The solving region is supposed as \( \Omega \) and the boundary is supposed as \( \Gamma \). Thus, the boundary value problem of AMB magnetic potential function is,

\[
\begin{align*}
\text{region} \ \Omega: \quad & \nabla^2 A = \frac{\partial A_z}{\partial x} + \frac{\partial A_z}{\partial y} = -\mu J_z \\
\text{the first boundary condition} \ \Gamma_1: \quad & A_z = 0 \\
\text{the second boundary condition} \ \Gamma_2: \quad & \frac{\partial A_z}{\partial n} = 0
\end{align*}
\]

(6)

where, \( x, y \) are the two different coordinate direction, \( n \) is the normal direction of the curved surface of the boundary.

Expression (6) is the mathematical model for solving the physical quantity of AMB. This boundary value problem can solve the varying rules of the magnetic potential \( A \) along with the coordinates \((x, y)\) under the given solving region and boundary conditions according to the foregone physical rules.

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4. **FINITE ELEMENTAL SIMULATIONS**

In order to find out the distributing rules of radial AMB electromagnetic fields, the FEM analysis software ANSYS is used. Using FEM in solving the partial differential equation, ANSYS can realize high-precision numerical calculation.

Instancing the general radial AMB with 8 magnetic poles equally distributing, the AMB electromagnetic forces under different conditions are analysed. The main parameters of this radial AMB are: diameter 45mm×100mm, width 20mm, area of magnetic pole 180mm², radial air gap 0.4mm, coil turn number of single pole 100 turns, bias current 1.5A. The rotor shaft material is 45
steal, the stator and rotor materials are cold rolling silicon steel slice 50W350 and the folding coefficient is 0.9.

The radial AMB is plan-symmetry figure, so its section is used to be analysed. The boundary conditions are defined as following: taking the excircle of the stator as the boundary and taking the first boundary condition, viz. there is no magnetic leakage outside the stator and the whole field region is limited in the rotor.

4.1. Analysis on the coupling phenomena of magnetic fields

In order to analyse the coupling circumstances between magnetic poles, the magnetic fields between stator and rotor of radial AMB are calculated using non-symmetry parameters. Vary the current among the four poles of radial AMB, and check the effects on the magnetic couple, the results are shown in figure 2.

Figure 2 shows the distribution of the magnetic force lines in different condition. In figure 2(a), the upper and the lower magnetic pole coils are supplied the same current and he polarities of neighbour poles are opposite. In figure 2(b), the left and right magnetic pole coils are supplied the same current and the polarities of neighbour poles are same. In figure 2(c), the four poles are all supplied the same current and the polarities of neighbour poles are opposite. In figure 2(d), the four poles are all supplied the same current and the polarities of neighbour poles are same. It can be seen that there are strange couplings between the pole pairs in figure 2(a) and figure 2(c), and that there are nearly no couplings between each two poles in figure 2(b) and figure 2(d).

Thus, it can be concluded that there will be magnetic couplings between the poles if no measures are adopted in the radial AMB. The magnetic couplings between the magnetic poles can be ignored by adopting symmetry configure and symmetry parameters and making the polarities of neighbour poles same.

4.2. Analysis of the AMB magnetic field under the rotor eccentricity

The radial AMB is an axis-symmetry configuration, so only the AMB parameters on one coordinate axis are needed to be calculated, and the ones on another coordinate axis can be known followed. Therefore, the effects of eccentricity on the magnetic field are analysed by instancing the y coordinate. Figure 3 shows the distributions of magnetic lines of force and the magnetic flux under different control current with the offset of y=+0.2mm.

It can be seen from figure 3, when the rotor is off-centre along y direction, without control current (viz. \(i_c=0\), shown in figure 3(a)), the magnetic field in the upper pole pair will be increased for the air gap becomes less and the magnetic field in the lower pole pair will be weakened for the air gap becomes
larger. If the control current is supplied in the mode of differential stimulating (shown in figure 3(b)), the distributions of magnetic fields of both the upper and the lower poles can be changed. Increasing the control current in certain scope can increase the magnetic field force.

![Figure 3](image)

**Figure 3.** Distributions of magnetic lines of force and magnetic flux \((y=0.2\text{mm})\)

4.3. Calculation of the magnetic forces under different rotor offsets and different control currents

Magnetic forces on rotor can be calculated in two ways, by virtual work and by Maxwell, shown in figure 4. To analyse the varying rule of magnetic forces with control current under different rotor offsets, the magnetic forces of the rotor are calculated with the parameters of \(y=-0.2\text{mm}, -0.1\text{mm}, 0\text{mm}, 0.1\text{mm}, 0.2\text{mm}\), and \(i_c = 0\text{A}, 0.25\text{A}, 0.5\text{A}, 0.75\text{A}, 1\text{A}\). The results are shown in Figure 5.

![Figure 4](image)

**Figure 4.** Magnetic forces on the rotor

From figure 5, it can be seen that when the offset is constant, the magnetic force varies with the control current nearly in a linear rule, which shows the linear assumption is feasible, and that under the same control current, the larger the offset is, the larger magnetic force is.
Conclusions

Without any measures, there will be generally coupling between the magnetic poles of radial AMB. So when designing AMBs, in order to reduce and ignore the magnetic coupling between the magnetic poles, symmetry configuration and symmetry parameters should be adopted and the neighbor poles’ polarity should be same.

For the AMB whose rotor is non-homocentric, while the air gap above and below the rotor becoming less and larger, the relevant magnetic fields will increase and decline respectively.

If the control current is supplied differentially, the distributing condition of the magnetic fields of different poles can be changed. Increasing the control current in certain scope can increase the magnetic force.

When the rotor offset is constant, the magnetic force varies with the control current nearly in a linear rule. Under the same control current, the larger the offset is, the larger the magnetic force is. Thus, the magnetic forces can be controlled through controlling the rotor offset and the control current, ultimately the stable levitation of AMB rotor can be realized.

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