Modeling and Analysis of Hybrid Permanent Magnet Type Bearingless Motor

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The traditional bearingless permanent magnet synchronous motor(BPMSM) has complex decoupling control problems. To overcome the drawbacks above, a novel hybrid permanent magnet type bearingless motor(HPMTBM) is proposed to this paper, which has integrated the merits of hybrid excitation permanent magnet motor and magnetic bearings. The main advantages of this HPMTBM are the simple control mechanism and the low power consumption. First, the principle and theoretical background of this motor is introduced. Then, the mathematical models of radial suspension force and torque are established using Maxwell stress tensor method, and air-gap magnetic fields, radial suspension forces and torque are calculated by three-dimensional transient finite element analysis. Finally, the prototype motor is designed and constructed. The radial suspension forces are tested. The simulation and experimental results show the feasibility of the proposed HPMTBM.

***Index Terms*—Magnetic bearing, bearingless motor, magnetic levitation, rotary machinery, finite element analysis**

I. Introduction

FOR HIGH rotating speed, high power and clean-environment applications, bearingless motor which combine a rotary motor and a magnetic bearing have been used to support rotors without physical contact, and give rotating torque to the rotor [1]. This replaces the contact components and reduces the overall size. However, this requires two kinds of rotating magnetic flux for producing rotation and suspension force, respectively, which makes construction of the motor and control system complicated [2]. In addition, to realize rotor stable suspension and rotation, several bearingless motors and magnetic bearings are required to form a five degree of freedom suspension system. Thus, the rotor becomes long and is apt to produce bending vibration [3]. To overcome those difficulties, a new HPMTBM is proposed which the dc magnetic flux is used to control radial suspension force, and the control system of radial suspension force and the rotating torque are independent. Hence, the structure and control system can be simplified. In addition, the permanent magnets produce the static bias flux, and control windings produce only the control flux. Therefore, power consumption is small.

In this study, a new structure of HPMTBM is proposed, as shown in Fig.1. First, the structure and suspension principle are introduced. Then, the air-gap flux is analyzed and the mathematical models of radial suspension force and torque are deduced. Finally, the magnetic circuits and the radial suspension force are calculated by finite element method. The prototype motor is constructed and radial suspension forces are tested to prove the feasibility of this new HPMTBM.

II. Structure and Suspension Principle

Fig.1 shows the basic structure, winding arrangement and magnetic path of HPMTBM. In axial section, the left and right sides are the bearingless motor. Between them an axially magnetized annular permanent magnet is installed which gives the static bias flux as shown by the solid arrow line. The right and left view indicate the construction of bearingless motor. The stator has two kinds of coil: one is for levitation control and the other is for rotation. There are two levitation coils of the x and y direction, both of which are 2-pole coils. These produce the control flux as shown by the dotted line and radial suspension force. The rotation can be controlled by means of the traditional permanent magnet motor.

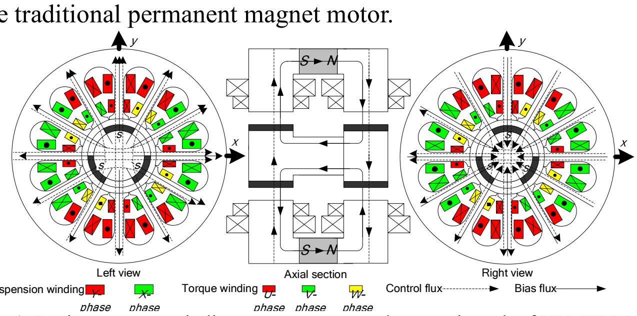


Fig. 1. Basic structure, windings arrangement and magnetic path of HPMTBM.

III. Mathematical Models

Fig.2 shows the motor coordinate system. The flux distribution produced by rotor permanent magnet B_p, the flux distribution produced by torque coil B_m, the radial suspension force control flux B_b are shown in Fig.3.

According to the traditional theory of electrical machine. The air-gap flux densities B_r, B_p, B_m and B_g can be approximately expressed as follows

$$
\begin{cases}
B_r = B_0 + B_1 \cos(M\theta - \omega t) \\
B_m = B_2 \cos(M\theta - \omega t - \psi) \\
B_b = B_3 \cos(\theta - \phi) \\
B_g = B_r + B_m + B_b
\end{cases}
\tag{1}
$$

where, B_0 is the average bias flux density; B_1 is the peak flux value produced by rotor permanent magnet; B_2 is the peak value of torque flux; B_3 is the peak value of levitation control flux; M is the pole pair number; θ, ω, ψ, ϕ are the stator angular coordinate, angular velocity, torque flux phase, radial suspension force control flux phase, respectively.
According to the Maxwell's electromagnetic force equation:

$$
dF = \frac{B_g^2}{2\mu_0} rld\theta \tag{2}
$$

where r, and l are the radius and length of rotor, respectively.

Therefore, the polar coordinate equation of radial suspension force can be derived as follows.

$$
F = \frac{B_0 B_3 lr\pi}{\mu_0} \angle\phi \tag{3}
$$

The radial suspension force can be controlled independently form θ, rotor permanent magnet flux B_1, torque flux B_2 and torque flux phase ψ.

On the other hand, the torque is expressed by the following equation:

$$
T = \frac{rl\pi g B_1 B_2}{\mu_0} \sin\psi \tag{4}
$$

The T can be controlled independently from the static bias flux B_0, radial suspension force control flux B_3 and radial suspension force control flux phase ϕ.

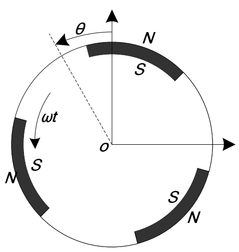


Fig. 2. Coordinate system.

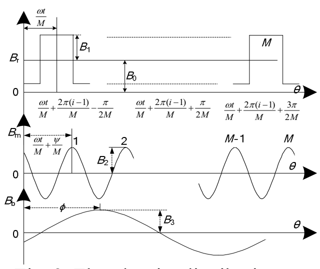


Fig. 3. Flux density distributions.

IV. Finite Element Analysis and Experimental Research

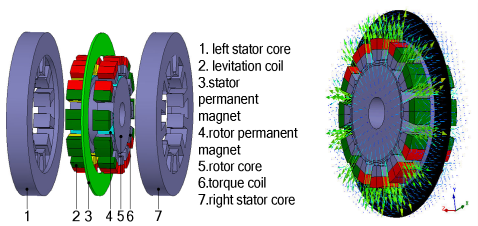
A. Finite element model

Design parameters of the prototype motor are summarized in Table I. To evaluate the effect of this HPMTBM, Finite element simulation was carried out. For simplicity, the flux density produced by the rotor permanent magnets and the flux density produced by the suspension coils were calculated separately.

Fig.4(a) shows the calculation model. Only the bias flux density produced by stator permanent magnet is shown in Fig.4(b). Thus, the correctness of the magnetic circuit design is verified.

TABLE I
Main Design Parameters Of The Simulation and Experimental Motor

Item	Type Size(points)
Stator outer diameter(mm)	120
Stator inner diameter(mm)	64
Rotor outer diameter(mm)	63
Rotor length(mm)	20
Stator core thickness(mm)	30
Rotor magnet length(mm)	20
Torque coil turns	40
Air gap(mm)	1
Levitation coil turns	40
Rotor magnet thickness(mm)	1
Stator magnet thickness(mm)	1
Coil diameter(mm)	0.9



(a) (b)

Fig. 4. Finite element analysis, (a) finite element model, (b) bias flux distribution produced by stator permanent magnet.

B. Radial suspension

To confirm the proposed HPMTBM, levitated rotating tests are performed. The radial suspension force is measured by applying external force to the rotor and recording the corresponding coil current. Fig.5 shows the experimental results. The radial force mathematical model is verified by finite element analysis and experimental results.

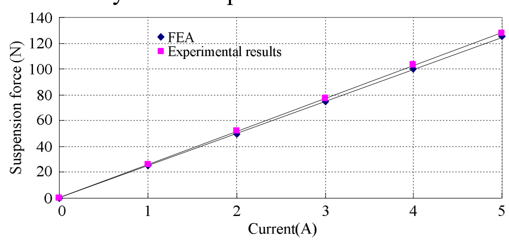


Fig. 5. Radial suspension force.

C. Conclusion

In this paper, a new HPMTBM is proposed. The principles are introduced. The mathematical models are deduced. The finite element analysis and static suspension experiment are carried out to verify the feasibility of the HPMTBM.

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