The Simulation of Novel Bearingless Consequent-pole Slice Motor

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Abstract

In the bearingless slice motor, two radial degrees magnetic levitation is realized by utilizing bearingless technology. Meanwhile three out of five degrees can be stabilized passively. In this paper, a novel bearingless slice motor is proposed. The levitation control is independent of the drive-winding magnetic field. This paper introduces the principle of radial force, as well as the advantages of the motor. Furthermore, the equations of radial levitation force are given. At last, the main levitation characteristics of the novel machine are analyzed by using 2D/3D finite element analysis in detail. The results verify the validity of the proposed motor.

1 Introduction

In most of bearingless motors, the information of the instantaneous orientation of the revolving magnetic field is required in the levitation controller.[1~5] The levitation system may not run stably if the field rotational position has a significant error. Therefore, there is cross coupling between the torque control and levitation control. To realize the decoupling control of them, the control algorithm of bearingless motors is very complex.

The coupling relationship among the degrees of freedom of the rotor in a bearingless slice motor is strong because of its special configuration. Levitation of high accuracy and good dynamic performance is hard to realize by using traditional controller. However, the work to apply some complicated non-linear control theory is tremendous if decoupling model is used. Therefore, the performances of the bearingless slice motor are limited.

A novel bearingless consequent-pole slice motor (BCPSM) with five spatial degrees of freedom magnetic levitation is proposed in this paper. In this new machine, two radial degrees magnetic levitation is realized by utilizing bearingless technology. Because of its special structure, the levitation control is independent of the angular of revolving magnetic field.[6~8] Meanwhile three out of five degrees can be stabilized passively[9].

This paper analyzes the principle of radial force production in the BCPSM briefly. The advantages of the BCPSM are discussed. The radial force equations are derived based on equivalent magnetic. Furthermore, the characteristics of the BCPSM levitation system are analyzed by using 2D/3D finite element analysis. At different rotor rotational angular positions, the distribution of the magnetic field, the levitation force in radial direction and the levitation force in axial direction are studied. The situation when the rotor has eccentric displacement is also taken into account.

2 Principle

Fig.1 shows structure of bearingless consequent-pole slice motor. The BCPSM consists of a rotor divided into two sections similar to traditional consequent-pole motor: one section has partial surface-mounted PMs, which are radially magnetized; the other has an iron pole. Its axial length is far smaller than the radial length.

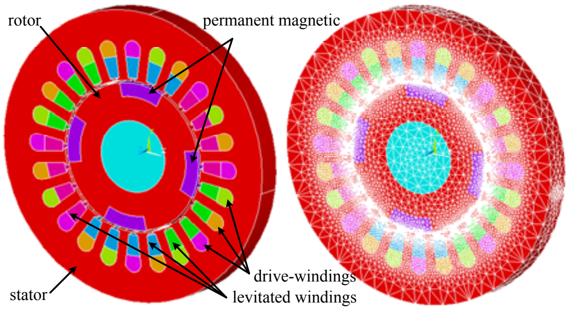
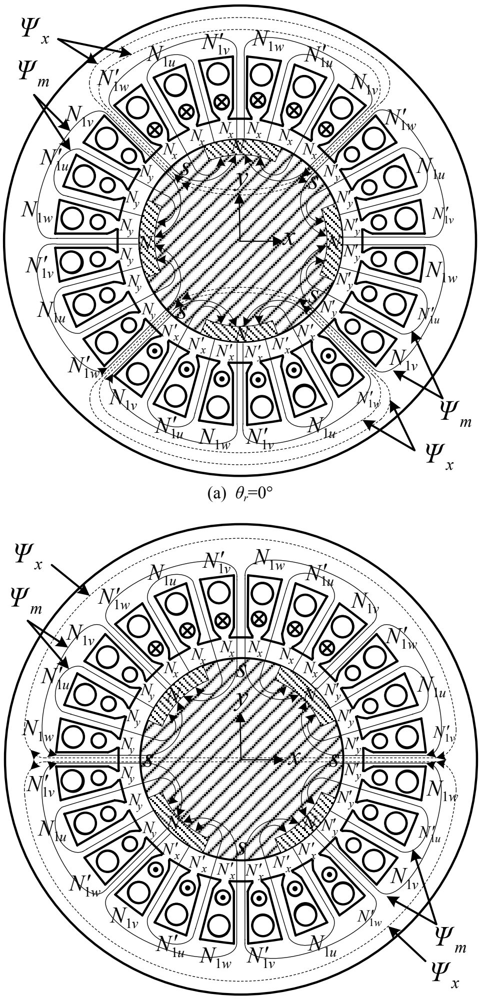


Fig.1 Structure of bearingless slice motor

Fig.2 (a) and (b) show the radial forces generated in x direction with the rotor angle at 0° and 45°, respectively. Ψ_m, the solid line, represents the flux linkage generated by permanent magnet. Ψ_x, the dashed line, is the flux linkage produced by the levitation windings N_x. The magnetic flux of the radial force windings always goes across the rotor iron instead of the permanent magnet regardless the rotor rotational position, for the magnetic reluctance of the rotor iron is smaller than that of the permanent magnets. Therefore, the levitation control is independent of the angular of revolving magnetic field. In this motor, bearingless technology can realize active levitation in two radial directions. On the other hand, passive levitation in axial direction and torsional direction can be realized automatically.



(a) θ_r=0°

(b) θ_r=45°

Fig.2 Principles of Radial Force Production (x)

3 Advantages

By contrast, with the classical bearingless slice motors, this novel machine has the following advantages[6~8]:

(1) Better capability of field-controlling. Levitation flux goes through rotor iron poles instead of the permanent magnets. Thus, reluctance in the levitation flux loop is low. It is obvious that low MMF is required in radial force generation. In other words, the salient-poles have the effects to enhance the radial levitation force generation.

(2) Decoupling between the levitation and torque control. As for traditional bearingless machines, field-orientation control strategy is commonly applied to the torque subsystem, because that accurate information of the rotating magnetic field of the drive windings is needed. This will cause that levitation performance is heavily effected by the torque performance. What's more, the control strategy of the torque windings is limited by the principle of the levitation force. In the BCPSM, the levitation control is independent of the rotating magnetic field generated by the drive windings. Therefore, the control strategy for BCPSM is easier compared to other types of bearingless machine. The reliability of the system is strengthened and the control system design is much less complicated.

(3) Simple equations of levitation control. There is no cross coupling between the levitation control and torque control. The mathematical model of the levitation system is simple, like traditional magnetic bearing. To improve the performance and flexibility of the levitation system, some advanced nonlinear control algorithms, such as H∞ and unbalance compensation, may be conveniently applied to the levitation subsystem controller.

To sum up, this new machine has a simpler control system and higher reliability than conventional bearingless motors. It combines all advantages of magnetic bearings and bearingless motors. What's more, it is very fit to be used in ultra-pure areas of modern industry, medicine chemical, life science, aerospace, and so on.

4 Equations of Levitation Force

A BCPSM prototype, which combines drive windings with four pairs of magnetic pole and levitation windings with one pair of magnetic pole, is analysed in this paper. Some assumptions should be declared before all the derivation: leakage flux is negligible; the fringe effect is negligible; MMF produced by the iron core is small; the rotor is concentric with the stator.

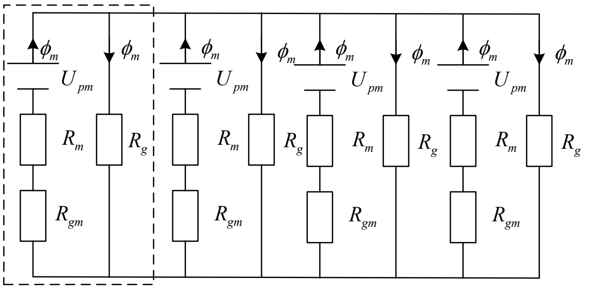


Fig.3 Equivalent Magnetic Circuit

Fig. 3 shows the magnetic equivalent circuit for the permanent magnet of the BCPSM. The magnetic flux per pole can be written as,

$$\phi_m = \frac{U_{pm}}{R_m + R_{gm} + R_g} \tag{1}$$

Where, $R_m = 4l_m/(\mu_0\mu_r r\pi)$, $R_{gm} = 4l_g/(\mu_0 r\pi)$, $R_g = 4l_g/(\mu_0 r\pi)$, $U_{pm} = H_c l_m$.

Where r is the radius of the air gap, μ_r is the relative permeability of the PM, l_g is the air-gap width, l_m is the radial length of the PM.

Magnetic flux density of PM is expressed as

$$B_p = \begin{cases} \dfrac{4\phi_m}{\pi r} & \text{(under PM pole)} \\ -\dfrac{4\phi_m}{\pi r} & \text{(under iron pole)} \end{cases} \tag{2}$$

The flux density is the product of the MMF and the permeability of the air gap. Magnetic flux density of the levitation windings is expressed as

$$B_l = GU_l \cos(\theta + \theta_r + \theta_l) \tag{3}$$

Where θ is the rotor angle in rotating reference and θ_l is the phase angle of the MMF generated by the levitation windings. The permeability in the air gap can be written as

$$G = \begin{cases} \dfrac{\mu_0\mu_r}{l_m + \mu_r l_g} & \text{(under PM pole)} \\ \dfrac{\mu_0}{l_g} & \text{(under iron pole)} \end{cases} \tag{4}$$

Similarly, the magnetic flux density produced by the drive windings in rotor reference can be expressed as,

$$B_T = GU_T \cos 4(\theta + \theta_r + \theta_T) \tag{5}$$

Where θ_T is the phase angle of the MMF of the drive windings.

The whole flux density is the superposition of those of the PM, levitation windings and drive windings.

$$B = B_p + B_l + B_T \tag{6}$$

Assuming that the flux density in tangential direction is negligible, the equations of the levitation force in stator reference can be written as,

$$\begin{cases} F_x = \displaystyle\int_0^{2\pi} \frac{B^2}{\mu_0} r l_x \cos(\theta + \theta_r) d\theta \\ F_y = \displaystyle\int_0^{2\pi} \frac{B^2}{\mu_0} r l_x \cos(\theta + \theta_r) d\theta \end{cases} \tag{7}$$

Where l_x is the axial length of the machine.

With I_d=0 control strategy, the radial force equations can be written as (8) by substituting equation (1) to (6) into (7),

$$\begin{cases} F_x \approx kU_l \cos\theta_l \\ F_y \approx -kU_l \sin\theta_l \end{cases} \tag{8}$$

Where $k = \dfrac{2\pi\mu_0 H_c l_m^2 r l_x}{l_g(l_g + l_m)(3l_g + 2l_m)}$

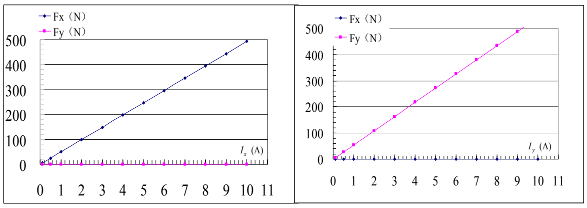
The above equations tell that the levitation force in the BCPSM is only determined by the MMF of the levitation windings, independent of drive windings and the rotor angle.

The deduction of the axial levitation force is not included in this paper because it is not needed in the control system.

5 Simulation and Analysis

Some major parameters are given: stator outside radius 122mm, stator inside radius 63.6mm, air gap length 0.9mm, rotor outside radius 61.8mm, rotor inside radius 30mm, axial length of the machine 10mm. The material for the lamination slices W09. Coercive force of the PM 8.34E5A/m.

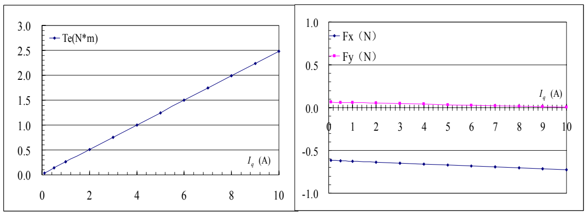
Fig.4 shows the radial force curve in terms of levitation winding currents. We can find that the radial force in x direction is increasing with increased current of the levitation windings X, independent of the current in the other levitation windings.



(a) I_y=0A (b) I_x=0A

Fig.4 Levitation Forces VS Levitation Winding Currents

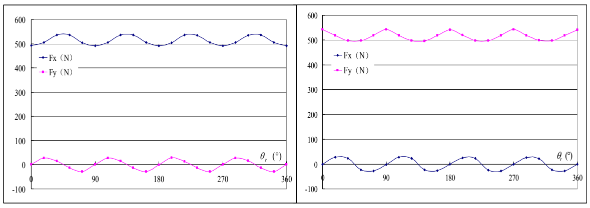
Fig.5 (a) demonstrates the relationship between the torque and the drive winding current. If I_d=0 vector control is applied, the torque is approximately proportional to the torque current I_q. Fig.5 (b) shows the relationship between the radial force and the drive-winding current, from which we can find that drive-winding current has little effect on the radial force.



(a) (b)

Fig.5 Effects of Torque Current

In Fig.6, the radial force, which produced by constant levitation-winding current, almost remains constant with different rotor angles. However, it is easy to figure out that 4th harmonic still exists. The harmonic force composes approximately 4.2% of the total quantity.

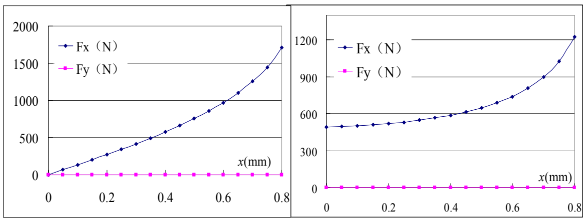


(a) I_x =10A, I_y =0A (b) I_x =0A, I_y =10A

Fig.6 Levitation Forces VS Rotor Angular Rotation

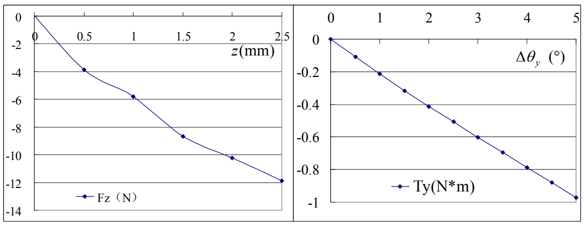
Fig.7 (a) indicates that the radial force produced by the PM is increasing with increased displacement of the rotor in radial direction. What's more, the radial force mentioned above is uncontrollable.

From Fig. 7(b), the radial force is increasing slightly with increased levitation current when the displacement of the rotor is small. When the displacement of the rotor is large, the radial force is increasing much faster than before. Thus, equation (8) is correct only if the displacement of the rotor in radial direction is small. The dynamic model of the machine with the rotor having a displacement in the radial direction will be discussed in later papers.



(a) I_x =0A, I_y =0A, with PM (b) I_x =10A, I_y =0A, without PM

Fig.7 Effects of the radial displacement



(a) z offset (b) rotate about y axias

Fig.8 Effects of Passive Levitated Force / ReactionTorque

The levitation force in axial direction (z axis) is approximately inverse proportional to the displacement of the rotor in axial direction from Fig.8 (a). The relationship of the levitation force in torsional direction and the torsional angle of the rotor is shown in Fig.8 (b), from which we can find that the levitation force is approximately inverse proportional to the rotor torsional angle. With effects of these passive levitation forces, the rotor will be forced to come back to the balance position.

6 Conclusion

In this paper, a novel bearingless consequent-pole slice motor is proposed. Its levitation control is independent of the drive-winding magnetic field. This paper introduces the principle of radial force briefly. Meanwhile, the advantages of the BCPSM are discussed. Furthermore, the equations of radial levitation force are given in this paper. At last, the main characteristics of the BCPSM are analyzed by using 2D/3D finite element analysis in detail.

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