Design and Analysis of Axial Hybrid Magnetic Bearing with Asymmetric Axial Air Gaps

Wang Kang[1], Wang Dong[2], Lin Heyun[1]*, Zhang Xianbiao[2], Feng Yi[1], Yang Hui[1]

[1] Engineering Research Center for Motion Control of Ministry of Education, Southeast University, Nanjing 210096, China

[2] Institute of Power Electronics, China Navy University of Engineering, Wuhan 430033, China

* hyling@seu.edu.cn

***Abstract*—A novel hybrid magnetic bearing (HMB) with asymmetric axial air gaps is proposed. The magnetic bias force between the upper and lower surfaces counteracts the rotor's gravity to keep the rotor at equilibrium position. The magnetic circuit model considering the flux leakage is established to calculate the electromagnetic parameters and optimize the main dimensions. The inductances of the control windings and the relationship between bias force and position displacement is calculated and analyzed by the finite element method (FEM). The linear expression of the net force governed by the position displacement and control current is presented. The FEM results verify the validity and correctness of the magnetic circuit model.**

***Index Terms*—Hybrid magnetic bearing (HMB), finite element method (FEM), permanent magnet (PM) bias force.**

I. INTRODUCTION

Magnetic bearing is widely applied in flywheels, high speed machines and so on. The active magnetic bearing (AMB) produces more losses, while the passive magnetic bearing (PMB) cannot be adjusted flexibly. Compared with AMB and PMB, hybrid magnetic bearing (HMB) receives more attentions as it can overcome their shortcomings [1-5].

A novel axial HMB suitable for vertical rotor system is proposed in this paper, in which permanent magnet (PM) bias force counteracts the rotor's gravity to keep the rotor at the equilibrium position. The axial symmetry structure mitigates the variation of the flux so that the eddy current and hysteresis losses can be reduced markedly. A magnetic circuit model considering the flux leakage is built to fast determine the main dimensions. The inductances of the windings and the relationship between bias force and rotor displacement are calculated and analyzed by the finite element method (FEM). The FEM results verify the validity and correctness of the magnetic circuit model.

II. STRUCTURE AND WORKING PRINCIPLE OF HMB

The stator of the proposed HMB comprises a stator core, a PM ring and two control windings. The rotor thrust disk is a ferromagnetic ring while the shaft is made of non-magnetic material. There are three air gaps between the stator and the rotor as shown in Fig. 1. The magnetization direction of the PM ring is radial. Winding 1 and winding 2 are the control windings which can correct the disturbed rotor position by imposing different currents.

In Fig. 1, the red lines represent the flux generated by the PM, and the blue ones indicate the flux produced by electrical excitation windings. The fact that the fluxes of the control windings do not pass through the PM ensures the stability of the PM characteristics. As the magnetic fluxes generated by the PM and the control windings pass through the rotor simultaneously, the rotor core is utilized efficiently.

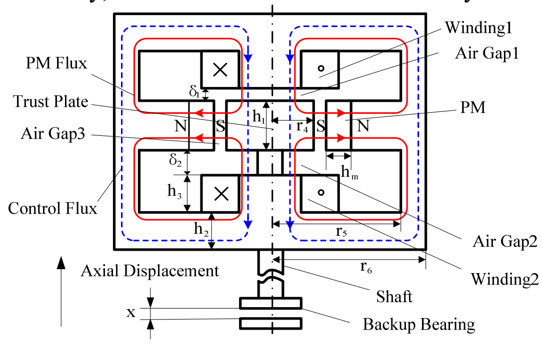


Fig. 1. Structure and flux paths of the HMB

III. MAGNETIC CIRCUIT MODEL AND MAIN PARAMETERS

The magnetic circuit model is built, in which the leakage flux is considered as reluctances $R_{\sigma 1}$ and $R_{\sigma 2}$. The main dimensions of the HMB can be fast determined as shown in Table I by solving the model with a nonlinear iteration algorithm.

TABLE I
MAIN PARAMETERS OF HMB

Item	Value	Item	Value
δ_1	1mm	r_4	14.8mm
δ_2	3mm	r_5	25.7mm
h_1	10.8mm	r_6	30mm
h_2	3.5mm	h_m	3.3mm
h_3	6mm	Turns of winding1/2	100turns

IV. FEM ANALYSIS OF HMB

A. Magnetic Field Distribution

The FEM is employed to analyze the magnetic field of the studied HMB and calculate the bias forces subsequently. The magnetic field produced by the PM when the rotor is at the equilibrium position is shown in Fig. 2. The flux leakage can be observed clearly so that the flux leakage should be considered in the magnetic circuit model.

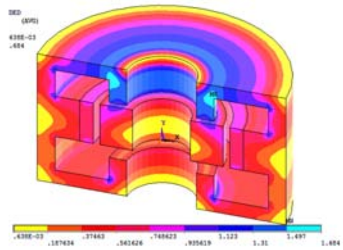
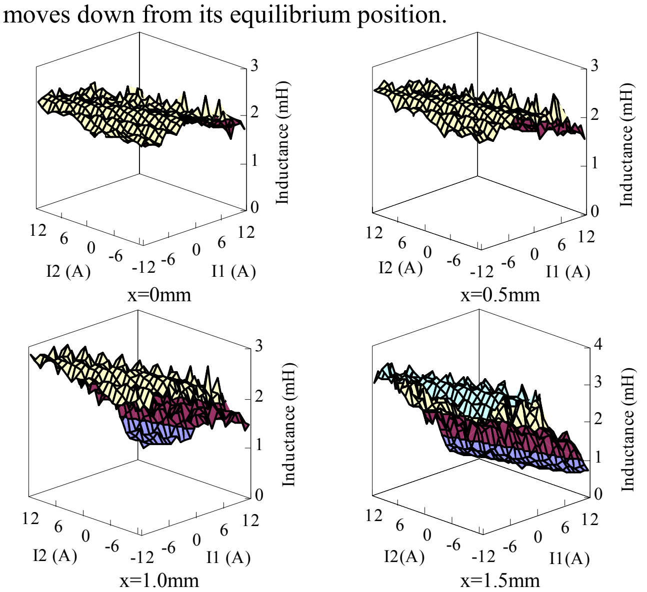


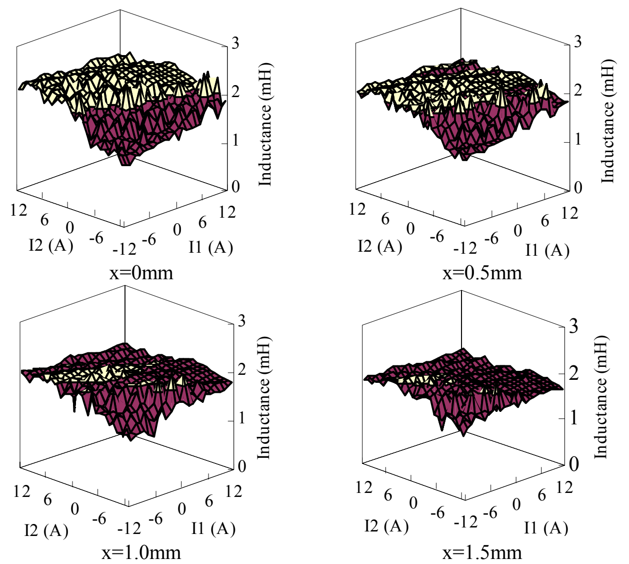
Fig. 2. 3D flux distribution of the HMB

B. *Inductance Parameters of the HMB*

The inductances of winding 1 and winding 2 when the rotor is at different axial displacements, as a function of winding currents, are calculated and shown in Fig. 3. When the rotor moves upward along the axial direction from its equilibrium position, the inductance of winding 1 changes more evidently than that of winding 2. It is not difficult to understand that the contrary is indeed true when the rotor moves down from its equilibrium position.



(a) Inductance of winding 2 at different rotor displacements



(b) Inductance of winding 2 at different rotor displacements

Fig. 3. Inductances of windings versus rotor displacement and currents

C. *Force Characteristic*

The net force, which is approximately proportional to the control currents at some rotor position, can be expressed as

$$f_x = k_{1x} i_1 + k_{2x} i_2 + f_{0x} \quad (1)$$

where, i_1 and i_2 are the currents in winding 1 and winding 2 respectively, f_{0x} is the PM bias force of the rotor without control currents, and k_{1x} and k_{2x} are the current stiffness coefficients. Fig. 4 shows the current stiffness coefficients at different rotor positions. Fig. 5 shows the PM bias force and its position stiffness coefficient at different rotor positions solved by the FEM and the magnetic circuit method (MCM).

The fact that the position stiffness is negative means that the HMB will be unstable without the control currents. The PM bias force is designed to just overcome the gravity of the rotor at the equilibrium position.

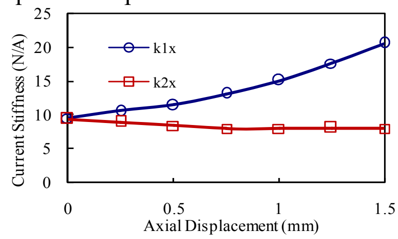


Fig. 4. Current stiffness of different displacement

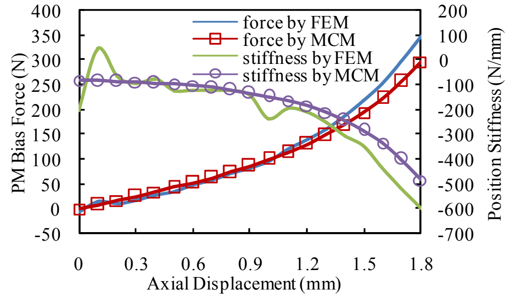


Fig. 5. Position stiffness/PM bias force of different displacement

V. Conclusion

A novel axial HMB with asymmetric axial air gaps is proposed. The fluxes produced by the PM and the control current pass through the same air gap, which makes the HMB compact and reliable. The magnetic circuit model is built to determine the main dimensions of the HMB. The magnetic fields of the HMB under different rotor positions and different control currents are analyzed by the FEM to yield the bias force. The analysis results illustrates that the proposed HMB is reasonable in structure and the magnetic circuit model is capable for its electromagnetic design.

The detailed analysis and test will be given in the full paper.

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