Analysis and Design of a Novel Heteropolar Radial Hybrid Magnetic Bearing

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In this paper, a novel heteropolar radial hybrid magnetic bearing (HRHMB) is proposed for flywheel energy storage system (FESS). Firstly, its configuration and working principle are introduced. Then, its mathematical equations are derived based on magnetic circuit model, including displacement stiffness, current stiffness and load capacity. And then, the three-dimension finite element analysis (3-D FEA) model is built under the original structure to further analyze its suspension performance and power losses. Finally, a simple optimal design for the novel HRHMB is discussed to improve its performance, such as lesser control current and losses, greater load capacity.

***Index Terms*—Heteropolar radial hybrid magnetic bearing (HRHMB), flywheel energy storage system(FESS), suspension performance, optimal design.**

I. INTRODUCTION

HETEROPOLAR radial hybrid magnetic bearing (HRHMB) has many virtues, such as small size, high efficiency and low running cost. These advantages make the HRHMB widely used in industrial applications in association with vacuum, high speed and flywheel technology, etc. [1].

At present, the structure of HRHMB is mainly used in eight poles structure, which is proposed by Okada, *et al*. But the displacement stiffness of this structure is large due to four uncontrollable poles with permanent magnet [2]-[3]. In addition, its rotor iron loss will be non-negligible at high-speed, especially in the vacuum environment where rotor can only transfers heat through radiation.

To overcome this drawback, this paper proposes a novel HRHMB to realize both high suspension performance and low loss.

II. STRUCTURE AND WORKING PRINCIPLE

Structure of the magnetic bearing is illustrated in Fig. 1. The bias flux path and control-flux path for y-axis are also shown. The bias-flux starts from permanent magnet, and closes via stator-rotor laminations, air gap. Besides, second air gap is introduced in the novel HRHMB to prevent short circuit of permanent magnet.

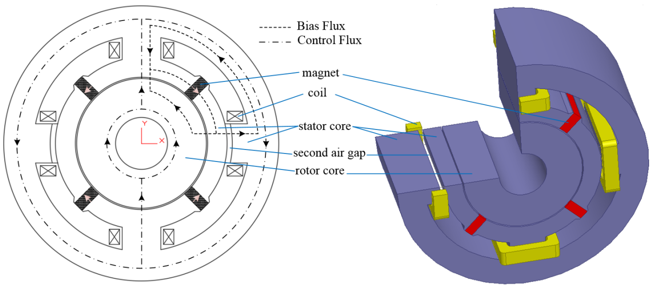


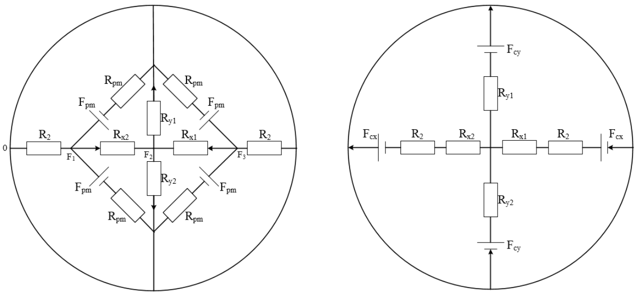
Fig. 1. Structure for new HRHMB.

Based on Fig. 1, the working principle of the new HRHMB is illustrated, taking x-axis as an example. If the rotor is ideally located at the central position, the total magnetic forces in horizontal directions to be zero. Supposing that the rotor is disturbed to move in +X direction, the resultant force generated by the bias flux causes the rotor to translate further in the direction. To restrain this imbalance, the control flux is added to the bias flux in -X direction and subtracted from the bias fluxes in +X direction. Afterward, a restoring force is produced to move the rotor toward the central position [3].

III. MATHEMATICAL MODEL

A. Equivalent Magnetic Circuit

In this section, both the bias flux circuit and the control flux path circuit for this bearing are shown in Fig. 2. To simplify the calculation of the magnetic flux path, only the leakage fluxes through second air gap are considered in the model, the others are considered by leakage coefficients.



(a) (b)

Fig. 2. Equivalent magnetic circuits. (a). Bias flux paths. (b). Control flux paths.

B. Fundamental Equations

Based on the magnetic circuit model, the performance equations for the novel HRHMB are derived. The displacement stiffness and the current stiffness expressions in two differential axis could be expressed as (1) and (2). The maximum force produced by the novel HRHMB is given by (3).

$$\begin{cases} k_{d_x} = \left.\dfrac{\partial F_x}{\partial x}\right|_{\substack{x=y=0\\ i_x=i_y=0}} = -\dfrac{32\left(R_2+R_{pm}\right)F_{pm}^2R_2^2}{\mu_0^2A^2[R_2R_{pm}+4R_0\left(R_2+R_{pm}\right)]^3} \\ k_{d_y} = \left.\dfrac{\partial F_y}{\partial y}\right|_{\substack{x=y=0\\ i_x=i_y=0}} = -\dfrac{32R_0F_{pm}^2R_2^2}{\mu_0^2A^2[2R_0R_2R_{pm}+R_0^2\left(8R_2+4R_{pm}\right)]^2} \end{cases} \qquad (1)$$

Where R_0, R_2 *and* R_{pm} are reluctance of main air gap, second air gap and permanent magnet, respectively. F_{pm}

denotes the magneto-motive-force of permanent magnet. μ_0 is the vacuum permeability. *A* is the area of magnetic pole.

$$\begin{cases} k_{i_x} = \left.\dfrac{\partial F_x}{\partial i_x}\right|_{\substack{x=y=0 \\ i_x=i_y=0}} = \dfrac{2\phi_{p0} N_c}{g\left(1+\dfrac{R_2}{R_0}\right)} \\ k_{i_y} = \left.\dfrac{\partial F_y}{\partial i_y}\right|_{\substack{x=y=0 \\ i_x=i_y=0}} = \dfrac{2\phi_{p0} N_c}{g} \end{cases} \tag{2}$$

$$F_{\max} = \frac{2\phi_{p0}^2}{\mu_0 A} \tag{3}$$

Where Φ_{p0} and g represent the flux and length of main air gap. N_c is the turns of winding coil. The detailed formula derivation will be given in the full paper.

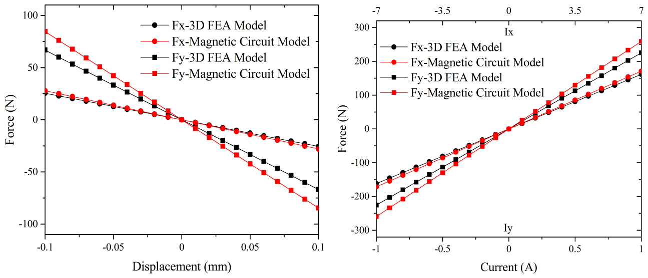
TABLE I
PARAMETER FOR NOVEL HRHMB

Parameter	Value
Outer diameter of the stator, D_{so}/mm	106
Outer diameter of the rotor, D_{ro}/mm	50
Length of magnetic bearing, L/mm	45
Length of main air gap, g/mm	0.5
Length of second air gap, g_2/mm	2
Thickness of permanent magnet, T_{pm}/mm	4
Area of permanent magnetic, A_{pm}/mm^2	36
Turn of control coil, N/turn	100
Maximum control current, i_x/i_y/A	16/1.8
Bias flux density, B_0/T	0.4
Maximum load force, F/N	370

IV. PERFORMANCE ANALYSIS AND OPTIMAL DESIGN

A. *Suspension Performance*

To further analyze the suspension performance, the 3-D FEA model for the novel HRHMB is built. Its main parameters are shown in Table I.



(a) (b)

Fig. 3. Stiffness for new HRHMB. (a). Force-displacement curves. (b). Force-current curves.

As is shown in Fig.3, the force-displacement curves and the force-current curves under 3-D FEA model are near consistent with that under magnetic circuit model. Besides, displacement stiffness and current stiffness of x-axis are smaller due to added second air gap than those of y-axis. Actually, the turns of control coil of x-axis can be increased properly in order to raise the current stiffness.

B. *Loss Analysis*

The power losses in magnetic bearing mainly include copper losses, rotor iron losses, air drag losses and losses in the amplifiers [4]. And rotor iron losses is vital in high-speed, particular in vacuum applications where the generated heat is difficult to be dissipated [4]-[5]. Since the number of poles for novel HRHMB is reduced to half of that for traditional 8-pole HRHMB, rotor iron losses of this novel structure are reduced obviously.

C. *Optimal Design*

The dimensions of second air gap and permanent magnet is mainly considered to the optimal design of the magnetic bearing [6]. And the main procedures are shown in Fig.4.

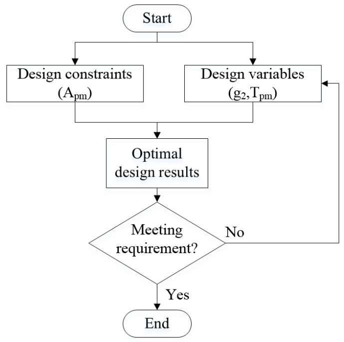


Fig. 4. Main procedures of optimal design.

TABLE II
OPTIMIZATION RESULT

		Before Optimization	After Optimization
Design variables	g_2	2mm	1.8mm
	T_{pm}	4mm	3.8mm
	A_{pm}	36mm^2	36mm^2
Optimal result	Rotor iron losses	12.05W	12.36W
	Maximum control current of x-axis	16A	15A
	Maximum load force	370N	385N

Optimization result is shown in Table II. After applying the optimal design, the rotor iron losses are nearly the same as before, but the needed maximum control current of x-axis is decreased obviously. Besides, the magnetic bearing will has greater load capacity.

V. CONCLUSION

In this paper, a novel HRHMB with small displacement stiffness and low power losses has been put forward. It indicates the novel HRHMB is more suitable to be used in high-speed applications as flywheel energy storage device.

VI. REFERENCES

[1] X. Yanliang, D. Yueqin, W. Xiuhe, and K. Yu, “Analysis of hybrid magnetic bearing with a permanent magnet in the rotor by FEM,” *IEEE Trans. Magn.*, vol. 42, no. 4, pp. 1363–1366, Apr. 2006.

[2] Y. Okada, H. Koyanayi, and K. Kakihara, “New concept of miracle magnetic bearings,” in *Proc. 9th Int. Symp. Magnetic Bearings*, Lexington, KY, Aug. 2004, pp. 89–95.

[3] H. Eryong and L. Kun, “A novel structure for low-loss radial hybrid magnetic bearing,” *IEEE Trans. Magn.*, vol. 47, no. 12, pp. 4725–4733, Dec. 2011.

[4] G. Schweitzer and E. Maslen, *Magnetic Bearings-Theory, Design, and Application to Rotating Machinery*. Berlin, Germany: Springer Verlag, 2009.

[5] H. Kim and C. Lee, “Analysis of eddy-current loss for design of small active magnetic bearings with solid core and rotor,” *IEEE Trans. Magn.*, vol. 40, no. 5, pp. 3293–3301, Sep. 2004.

[6] J. Fang, C. Wang, and T. Wen, “Design and optimization of a radial hybrid magnetic bearing with separate poles for magnetically suspended inertially stabilized platform,” *IEEE Trans. Magn.*, vol. 50, no. 5, pp. 1–11, May 2014.