Research on Permanent Magnet Biased Hybrid Magnetic Bearing

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Abstract: In this paper, a novel structure of permanent magnet biased hybrid magnetic bearing with inductance displacement sensor is proposed. The operating principle of the permanent magnet biased hybrid magnetic bearing is introduced. The design method of structure parameters presented in the paper is given, which is useful for the hybrid magnetic bearing design. An example is given with the design method presented. The analysis of finite element method shows that the structure of the permanent magnet biased hybrid magnetic bearing proposed is feasible and the calculation method for hybrid magnetic circuit used in this paper is correct.

1 Introduction

Magnetic bearings are designed to support rotating machinery elements without contacting with the rotor. The advantages result from no contact between the rotor and the bearing are free of wearing and maintenance, no lubrication required. So it is widely used in aviation, high speed turbine machine, vacuum technique and machine tool field [4].

According to principle of producing force, magnetic bearings are divided into passive magnetic bearing, active magnetic bearing and hybrid magnetic bearing. In hybrid magnetic bearing, biased magnetic field produced by current in active magnetic bearing is replaced by permanent magnet. So power loss is decreased, the size of magnetic bearing is reduced and supporting capacity is increased.

2 Structure of the hybrid magnetic bearing

The structure of the hybrid magnetic bearing proposed in this paper, shown in Fig.1, is composed of rotor, stator, control coil, permanent magnet and inductance displacement sensor.

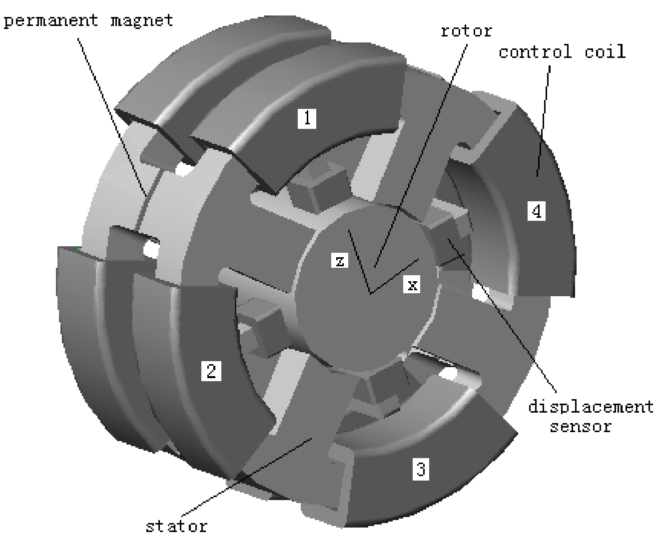

Fig.1 Structure of the hybrid magnetic bearing proposed

The control coil 1 in series with coil 3 produce X directional force to control the rotor moving right or left and the coil 2 in series with coil 4 produce Z directional force to enable the rotor move up or down. The rotor is made of the ferromagnetic material assembled on the rotating shaft. The rare earth permanent magnet adopts the neodymium-iron-boron material which features larger residual flux density, coercivity, and maximum energy product. The differential inductance displacement sensors are used in this kind of the hybrid magnetic bearing to measure the displacement of the rotor in X and Z direction.

3 Operating principle of the hybrid magnetic bearing

The principle that an electromagnet (stator) will attract a ferromagnetic material (rotor) in its magnetic field is applied to the hybrid magnetic bearing. In fact, the attract force comes from both the permanent magnet and the electromagnet in the hybrid magnetic bearing proposed to make the rotor levitate. See Fig.1.

The magnetic circuit of the permanent magnet is shown in Fig.2. ω_{PM} is the biased magnetic flux generated by the permanent magnet. And the magnetic circuit of the electromagnet is shown in Fig.3. ω_1 to ω_4 is the control magnetic flux produced by the current in control windings. The magnetic flux through each air gap is compound of both the biased magnetic flux and the control magnetic flux.

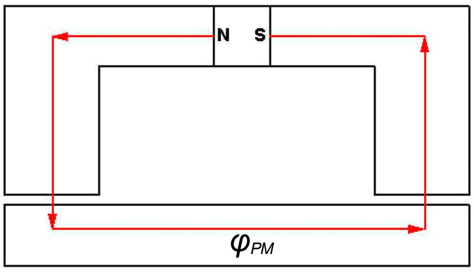

Fig.2 Magnetic circuit of the permanent magnet

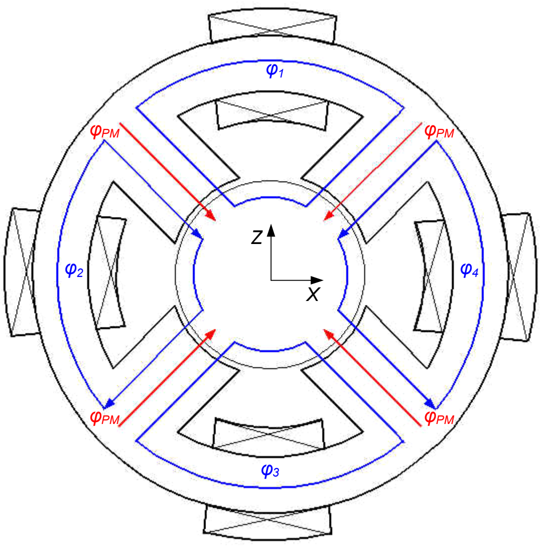

Fig.3 Magnetic circuit of the electromagnet

Owing to the symmetrical structure, the magnetic flux through any air gap, which is generated by the permanent magnet, are equal if the rotor is in center position. So the magnetic attracting force to rotor is same in any direction if $\omega_1=\omega_2=\omega_3=\omega_4=0$. Supposed the rotor is given a downward disturbance force, it will leave center position moving down. As long as the position error is detected by sensors, the current which is controlled by a controller will generate magnetic flux ω_2 and ω_4 which cause the flux in the upper air gaps to increase. The total flux of the upper air gaps become ω_{PM} + ω_2 and ω_{PM} + ω_4. And the total flux in the lower air gaps change into ω_{PM} - ω_2 and ω_{PM} - ω_4. The rotor will move up due to the upward magnetic force is greater than the downward magnetic force so that the position error is corrected. The opposite case will happen if the rotor is given an upward disturbance force. Same situation will happen to the leftward disturbance force and rightward disturbance force.

4 Design method of the hybrid magnetic bearing

In the case of reluctance of iron core and fringing flux are ignored, the magnetic flux density in upper air gaps and lower air gaps are described by equation 1 and 2 when the rotor move downward a distance z.

$$B_{S1} = \frac{F_m \mu_0}{2(g_0 - \sqrt{2}z)} + \frac{Ni\mu_0}{2g_0} \tag{1}$$

$$B_{S2} = \frac{F_m \mu_0}{2(g_0 + \sqrt{2}z)} - \frac{Ni\mu_0}{2g_0} \tag{2}$$

Where F_m = the internal magnetomotive force of the permanent magnet, g_0 = the air gap length, z=the displacement of the rotor, Ni = the ampere-turn product.

The magnetic force acting on the rotor is described by equation 3

$$F = 2\sqrt{2}\left(F_1 - F_2\right) = 2\sqrt{2}\left(\frac{B_{S1}^2 S}{\mu_0} - \frac{B_{S2}^2 S}{\mu_0}\right) \tag{3}$$

When B_{S1}=B_S B_{S2}=0 and the rotor is in the center position (z=0), the magnetic force acting on the rotor is maximum. In this case, the magnetic flux density in upper air gap and the magnetic flux density lower air gap are described by equation 4 and 5.

$$B_S = \frac{F_m \mu_0}{2g_0} + \frac{Ni\mu_0}{2g_0} \tag{4}$$

$$0 = \frac{F_m \mu_0}{2g_0} - \frac{Ni\mu_0}{2g_0} \tag{5}$$

The saturation magnetic flux density B_S of the soft magnetic material may be chosen as B_{max} usually. From equation 4, 5 and 3, B_S and F_{max} that is maximum magnetic force produced by hybrid magnetic bearing is described as follows

$$B_S = \frac{F_m \mu_0}{g_0} \tag{6}$$

$$F_{\max} = \frac{\sqrt{2}B_S^2 S}{\mu_0} = \frac{\sqrt{2}F_m^2 \mu_0 S}{g_0{}^2} \tag{7}$$

When no additional force acting on the rotor and the rotor is in center position, the magnetic flux density in each air gap is equal to biased magnetic flux density B_0 which is provided by permanent magnet.

B_0 is given by

$$B_0 = \frac{F_m \mu_0}{2g_0} \tag{8}$$

According to the maximum magnetic force, the magnetic pole sectional area of the stator and the ampere-turn product can be gotten.

$$S = \frac{F_{\max} \mu_0}{\sqrt{2} B_S^2} \tag{9}$$

$$Ni = \frac{2B_0 g_0}{\mu_0} \tag{10}$$

The magnetomotive force F_m provided by permanent magnet is related to the chosen permanent magnet curve. In order to minimize the size and weight of the permanent magnet, the material with a large value of residual flux density and coercivity is used normally. When the neodymium-iron-boron material is chosen, the demagnetization curve will close to linear

$$\varphi_m = \frac{\varphi_r}{F_c}(F_c - F_m) \tag{11}$$

Where ω_r is the residua flux, ω_m is the flux in magnetic circuit, F_c is the coercivity.

From the following equation

$$\varphi_m = 2B_0 S = B_S S \tag{12}$$

If the saturation magnetic flux density of soft magnetic material B_S and the desired maximum magnetic attracting force of magnetic bearing are given, the coercivity F_c and the residua flux ω_r can be calculated.

If F_c and ω_r are known, the dimension of the permanent magnet can be chosen.

5 A design example

Design required: the maximum magnetic force of magnetic bearing F_{max}= 100N; the air gap length g_0 = 0.5mm; saturation flux density B_s=0.8T; the permanent magnet adopting the neodymium-iron-boron material; the control coil using the enamel wire with equivalent diameter of 0.63mm.

The theory design result: the stator inner diameter is 41mm; stator length is 30mm, stator external diameter is 70mm; the pole area is 195 mm^2; the permanent magnet thickness is 3.9mm; inner diameter of the permanent magnet is 60mm; the maximum the ampere-turn product of the control coil is 160A.

6 Analysis by finite element method

A 2D model of the hybrid magnetic bearing is set up. After defining the load and the constraint condition, the distribution of the magnetic field of the magnetic bearing is given. Because of the 2D model used, the magnetic field produced by the permanent magnet cannot be showed. But the distribution of the magnetic field produced by current is approximately described in the Fig.4 and Fig.5.

The analysis result for the magnetic field with single DOF current of 4A is given on Fig-4 and Fig-5. Some magnetic leakage can be seen on Fig-4. The magnetic flux density in the corners is greater. But in the practice, this problem can be settled by rounding the corners.

Finite element calculation result: F_{max}=115N. The analysis results by means of finite element method shows that the structure of the permanent magnet biased hybrid magnetic bearing proposed in this paper is feasible and the calculation method for hybrid magnetic circuit used in this paper is correct.

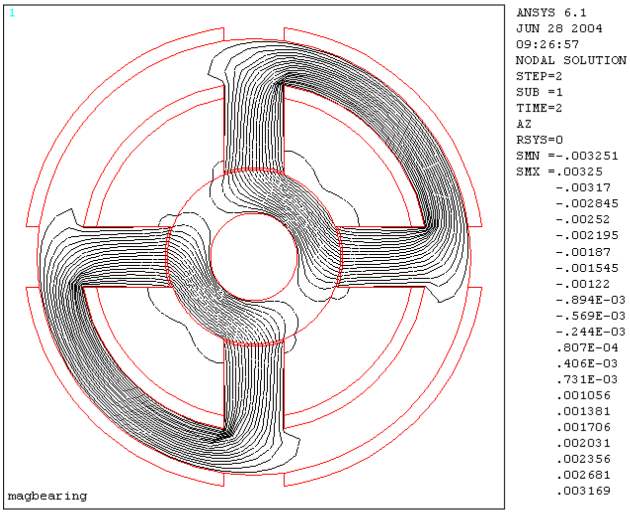

Fig.4 2D flux lines of single DOF

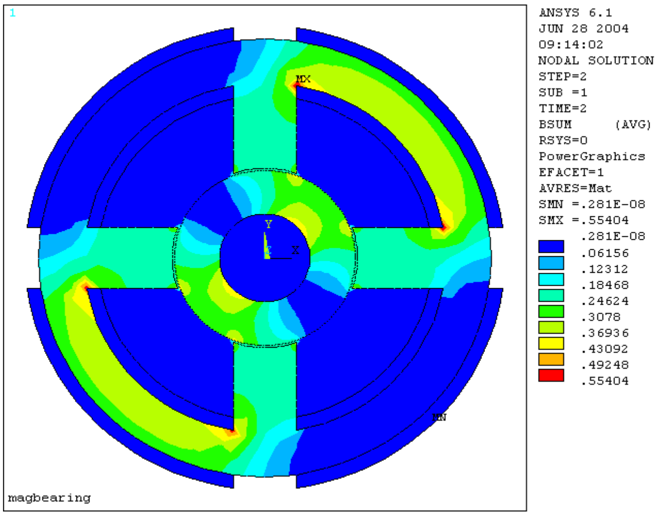

Fig.5 Magnetic flux density of single DOF

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