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A Control Method for Cancelling Oscillation in Electric Drive System using AFPM Motor Integrated Magnetic Bearings

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ABSTRACT: In the electric drive system using axial flux permanent magnet synchronous motor, when magnetic bearings are used instead of mechanical bearings at both ends of the shaft, can allow the motor to work at a higher speed above rated speed. Therefore, in addition to rotation of the motor shaft, there will be displacement in the x, y, z directions. Then, the phenomenon of interference between two perpendicular coordinates mounted on the magnetic bearings will appear. In this paper, a dynamic decoupling control method to overcome this phenomenon is implemented. The effectiveness of the method is proven through the simulation results of the system.

KEYWORDS: active magnetic bearing, axial flux permanent magnet, COG.

I. INTRODUCTION

Magnetic bearings have been developed in recent decades to replace mechanical bearings. The working principle of the active magnetic bearing is to use an electromagnetic force to generate levitation without any mechanical contact[1-5]. Compared with traditional mechanical bearings with many disadvantages [6-9], magnetic bearings exhibit many advantages such as: frictionless, lubricant-free operation, unbalanced compensating ability. Therefore, this object is a promising solution for high speed applications such as high speed motors [10-13]. Different from the motor working on the principle of using magnetic levitation, whose output control quantity is z-direction displacement [14-17], the motor integrated with the active magnetic bearing is considered in the study. This has two stators on either side and a disc-shaped dual permanent magnet rotor in the middle[18-23]. With this special structure, the motor is both capable of generating axial forces to keep the rotor in the nominal position.



Magnetic bearings during operation due to interference (mainly torque load) will have the rotational axis displacement parallel to the stator center axis (z) in the xz and yz planes, creating distances x_p and y_p relative to the z axis.

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Radial displacement of the rotor:



Fig. 2: Forces and torque act on the rotor

The translational and tilted forces are described basing on radial forces of AMB:

$$F_{xp} = F_{x1} + F_{x2}$$

$$F_{yp} = F_{y1} + F_{y2}$$

$$F_{xr} = F_{x1} - F_{x2}$$

$$F_{yr} = F_{y1} - F_{y2}$$
(2)

Dynamic equations for the translational motion:

$$\begin{split} & m\ddot{x}_{p} = F_{xp} + 2k_{x}x_{p} \\ & m\ddot{y}_{p} = F_{yp} + 2k_{x}y_{p} - mg_{a} \end{split} \tag{3}$$

Differential equations for the tilted motion:

$$\ddot{y} = \frac{\omega_{rm}J_{k}}{J_{i}}\dot{x}_{r} + \frac{2k_{x}l_{r}^{2}}{J_{i}}y_{r} + \frac{l_{r}^{2}}{J_{i}}F_{yr}$$

$$\ddot{x} = -\frac{\omega_{rm}J_{k}}{J_{i}}\dot{y}_{r} + \frac{2k_{x}l_{r}^{2}}{J_{i}}x_{r} + \frac{l_{r}^{2}}{J_{i}}F_{xr}$$
(4)

By combining the expressions (1),(2),(3),(4) a structure diagram is constructed as shown in Fig.3. In this structure, J_i and J_k are inertia torques relative to x axis and z axis. The z axis is not affected by the interference of two perpendicular coordinate systems due to the physical structure of the motor.

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Fig. 3: Interaction between the axis x,y

II. CONTROL DESIGN

The state space model of the 4 degrees of freedom (DOF) AMB as follows is derived from the system of differential equations (3) and (4), representing the translational and tilting motions of two 4 DOFs AMB that can be expressed in the form of a matrix differential equation as follows:

$$M\ddot{q} = G\dot{q} + Dq + B_f \underline{F} \qquad (5)$$

Where, M, G, D, B_f : are the coefficient matrices of the matrix differential equation.

$$M = \begin{bmatrix} J_i & 0 & 0 & 0 \\ 0 & m & 0 & 0 \\ 0 & 0 & J_i & 0 \\ 0 & 0 & 0 & m \end{bmatrix}; G = \begin{bmatrix} 0 & 0 & J_k \omega_{rm} & 0 \\ 0 & 0 & 0 & 0 \\ -J_k \omega_{rm} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix};$$
$$q = \begin{bmatrix} y_r \\ x_p \\ x_r \\ y_p \end{bmatrix}; B_f = \begin{bmatrix} l_r^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & l_r^2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} F = \begin{bmatrix} F_{yr} \\ F_{xp} \\ F_{xp} \\ F_{yp} \end{bmatrix}; D = \begin{bmatrix} 2K_s l_{rl}^2 & 0 & 0 & 0 \\ 0 & 2K_s & 0 & 0 \\ 0 & 0 & 2K_s l_{rl}^2 & 0 \\ 0 & 0 & 0 & 2K_s \end{bmatrix};$$

 $F_{yr}; F_{xp}; F_{xr}; F_{yp}$ calculated according to formula (2).

$$\mathbf{F}_{\mathbf{x}}(x,i) = K_i i_x + K_s x = m\dot{x}$$

In combination with (2) and (3), the electromagnetic force vector relationship is represented for 2 AMB

$$\underline{F} = -K_s q_b + K_i \underline{i}$$

Where,

$$K_{s} = \begin{bmatrix} 0 & 0 & K_{sA} & -K_{sB} \\ K_{sA} & -K_{sB} & 0 & 0 \\ K_{sA} & K_{sB} & 0 & 0 \\ 0 & 0 & K_{sA} & K_{sB} \end{bmatrix}; q_{b} = \begin{bmatrix} x_{bA} \\ x_{bB} \\ y_{bA} \\ y_{bB} \end{bmatrix}; K_{i} = \begin{bmatrix} 0 & 0 & K_{iA} & -K_{iB} \\ K_{iA} & K_{iB} & 0 & 0 \\ K_{iA} & -K_{iB} & 0 & 0 \\ 0 & 0 & K_{iA} & K_{iB} \end{bmatrix}; i = \begin{bmatrix} i_{xA} \\ i_{xB} \\ i_{yA} \\ i_{yB} \end{bmatrix}$$

I

 q_b : is the displacement vector.

 \underline{i} : is the control current vector for the solenoids of two AMBs.

From (5), (6) the matrix differential equation of motion for the rotor lifted by the AMBs is obtained:

(6)

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$$\begin{aligned} M\ddot{q} &= G\dot{q} + Dq + B_f \left(-K_s \underline{q}_b + K_i i \right) \\ y &= Cq \end{aligned} \tag{7}$$

By using the linear displacement matrix T_s , it is possible to convert the bearing reference system to the COG reference frame. According to [2] this transformation involving geometrical quantities l_{rt} is shown as follows.

$$q_{b} = \begin{bmatrix} x_{bA} \\ x_{bB} \\ y_{bA} \\ y_{bB} \end{bmatrix} = \begin{bmatrix} l_{rr} & 1 & 0 & 0 \\ l_{rr} & 1 & 0 & 0 \\ 0 & 0 & l_{rr} & 1 \\ 0 & 0 & l_{rr} & 1 \end{bmatrix} \times \begin{bmatrix} y_{r} \\ x_{p} \\ x_{p} \\ y_{p} \end{bmatrix}$$

$$\underline{q}_{b} = T_{s} \times \underline{q}$$
(8)

So, by substituting (8) into (7), we get:

$$M\ddot{q} = G\dot{q} + (D - B_f K_s T_s)q + B_f K_i i$$
⁽⁹⁾

Let's set:

$$X = \begin{bmatrix} \underline{q} & \underline{\dot{q}} \end{bmatrix}^T; U = \underline{i}; Y = \begin{bmatrix} x_{bA} & y_{bB} & y_{bA} & x_{bB} \end{bmatrix}$$
(10)

The state-space model of the entire 4 DOF AMB system would be:

$$\begin{cases} \dot{X} = AX + BU \\ Y = CX + DU \end{cases}$$
(11)

Where:

$$A = \begin{bmatrix} 0_{4\times4} & I_{4\times4} \\ M^{-1}(D - B_f K_s T_s) & M^{-1}G \end{bmatrix}; B = \begin{bmatrix} 0_{4\times4} \\ M^{-1}B_f K_i \end{bmatrix}; C = \begin{bmatrix} I_{4\times4} & 0_{4\times4} \end{bmatrix}; D = \begin{bmatrix} 0_{4\times4} \end{bmatrix}$$

The system has matrix of transfer functions:

$$G(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) & G_{13}(s) & G_{14}(s) \\ G_{21}(s) & G_{22}(s) & G_{23}(s) & G_{24}(s) \\ G_{31}(s) & G_{32}(s) & G_{33}(s) & G_{34}(s) \\ G_{41}(s) & G_{42}(s) & G_{43}(s) & G_{44}(s) \end{bmatrix}$$
(12)

$$G_{ik}(s) = \frac{1}{\det(sI - A)} \underline{c}_i^T (sI - A)_{adj} \underline{b}_k$$
(13)

III. SYSTEM SIMULATION

The parameters of a particular AMB 4 DOF system is given in Table 1.

Table 1. Parameters of a particular 4 DOF AMB

Weight of rotor (kg)	m =12,4
Distance from center of mass to rotor of AMB (m)	$l_{rt} = l_a = l_b = l_c = l_d = 0,21$
Moment of inertia on the axis k (kg.m ²)	$J_k = 6,88.10^{-3}$
Moment of inertia on the axis i and j (kg.m ²)	$J_i = J_j = 2,22.10^{-1}$
Rotor speed (rpm)	10000
Coefficient of electromagnetic force - current (N/A)	K _i =158
Coefficient of electromagnetic force - displacement (N/m)	$K_s = 1,58.10^6$
Gravity acceleration (kg.m/s ²)	g = 9.81

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Fig 5: System response

With input data $x_1 = 1.5$ mm; $y_1 = 1$ mm; $x_2 = -0.5$ mm; $y_2 = -0.6$ mm. The simulation results in Figure 5 show that the deviation of the axes reaches zero quickly after a period of 0.1s

IV. CONCLUSION

Axial flux permanent magnet synchronous motor when using magnetic bearings instead of mechanical bearings at both ends of the shaft will have an integrated axial magnetic bearing right on the motor to prevent axial movement. However, due to the use of two magnetic bearings at both ends of the shaft, the phenomenon of deviation from the balance position of the rotor shaft when there is load disturbance is a problem that occurs in practice. The control method implemented in this paper is based on the use of pre-processing controllers R and state feedback control M. MIMO system have been separated into independent SISO systems in the new state space. This makes the control design simple and highly applicable in controlling this object.

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