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Analysis and Control of a Three-Pole Permanent Magnet Type Bearingless Motor

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Abstract

The active magnetic bearing (AMB) possesses several advantages such as no friction, high rotational speed, less energy loss, and long life span etc. In rotation application, however, it must be connected to a motor, which may degrade its performance. Bearingless motor is the combination of the active magnetic bearing and motor. It saves software and hardware facilities, resulting in lower costs. This paper mainly designed a three-pole permanent-magnet type bearingless motor, and analyzed the rotational magnetic field, magnetic force of the bearing, and resulting torque of the motor. Finally, we established system dynamic mathematical model. The controller design and numerical simulations are implemented, and reach the last target.

Keywords: Active magnetic bearing, Bearingless motor

INTRODUCTION

Bearing is an important element for high-speed spindle machine tools or storage devices. Conventional bearings suffer the problems of wear and short lifetime due to the contact between bearing and rotor. There exist several types of non-contact bearings such as hydrodynamic, air, and magnetic bearings. The non-contact bearings can reduce or eliminate the problems of friction, vibration, and acoustic noise. Among them, the active magnetic bearing (AMB) is the most promising one due to the advantages of high load capacity, large stiffness, and no lubrication. However, it is expensive. To reduce AMB's cost, a 3-pole AMB has been proposed [4, 5]. It has been shown that the 3-pole AMB possesses the advantages of less power amplifiers and lower heat dissipation, leading to lower cost [5]. To further reduce the cost, a 3-pole bearingless motor is considered in this study.

A bearingless motor is a device that combines the function of motor and active magnetic bearing (AMB). It can save software and hardware facilities, resulting in lower cost. In this study, a 3-pole permanent-magnet (PM) type bearingless motor is proposed and analyzed. It is modified from the conventional 3-pole AMB. To become a bearingless motor, the 3-ople AMB must be able to produce rotational torque for motor function, in addition to the levitation forces for bearing function. Due to the special 3-pole structure, the 3-pole AMB can be easily integrated with the 3-phase currents to generate the motor function.

Since 1990, bearingless motors have been extensively studied. Most bearingless motors are simply the direct integration of motor and AMB. In other words, the translation and rotational forces are generated by two independent sets of coils and/or permanent magnets. The levitation forces of most bearingless motors are reluctance forces, but the rotational torque can be Lorentz or reluctance type. According to the way the torque is generated, bearingless motors can be classified into 3 types: reluctance type, induction type, and PM type.

The reluctance type bearingless motor uses non-uniform magnetic reluctances between rotor and stator to generate the required torque [9, 12, 14, 21, 22]. As a result, its rotor must be designed with salient poles.

The motoring torque is usually produced by the non-uniform magnetic reluctance. The magnetic flux must pass through the path with the least reluctance, so the salient pole on rotor will be engaged and rotation torque is generated. For reluctance type self-bearing motor, it adds additional windings on stator to provide radial suspension force. Both the motoring torque and levitation force are produced by reluctance force, and they can be reinforced simultaneously. There are many advantages for this type. First, it has the characteristic of fail-safe and can easily brake in case of emergency. Second, it is low-cost because of no coils or permanent magnet on the rotor and it is easy to be manufactured. Third, both translational and rotational torques can be enhanced simultaneously since they are both reluctance force. Fourth, temperature effect is insignificant compared to the PM type. The main disadvantage is that the coupling between the rotational flux and levitation flux is very serious and it is difficult for analysis. Also, the effect of cogging force cannot be neglected. However, strong cogging effect and serious coupling between the rotational and levitation flux make it extremely difficult for analysis.

The induction type bearingless motor uses the coil windings on the rotor to generate the torque. It is based on Faraday's induction law and Lorentz principle for the rotational torque [6-8, 10, 11, 17, 18, 20]. Additional coil windings are included in the stator to provide radial suspension force by reluctance force. Induction type bearingless motor has the advantages of low-cost, no permanent magnet, easy design, and larger radial suspension force. However, energy losses are considerably large because of slip. Also, the rotational flux and levitation flux are strongly coupled and hence complicated vector control is necessary.

The PM type bearingless motor uses the permanent magnet on the rotor to generate the torque through Lorentz principle. Similar to PM motor, the torque is generated by Lorentz force. In addition, there always exist several additional windings on the stator to provide reluctance forces for rotor levitation. The main advantage is that the torque and levitation force can be controlled independently. According to the location of the permanent magnet in the rotor, the PM type bearingless motor can be classified into several types, including surface permanent magnet type [2, 15], inset permanent magnet type [13], interior permanent magnet type [16], consequent-pole type [1], and toothless type [3, 19]. In general, if the thickness of permanent magnet is larger, the larger torque can be produced. However, the radial suspension force will become smaller. The design of toothless type can eliminate this effect because this type of bearingless motor uses Lorentz force to provide both motor torque and levitation force. These types of bearingless motors are different in the coupling effect between the rotational flux and levitation flux, making modeling and controller design difficult. The main advantage of the PM type is that the flux coupling effect is less significant, leading to easier analysis and control. We shall adopt the PM type in this work.

SYSTEM DESCRIPTION

Fig.1 is the proposed 3-pole bearingless motor. A pair of permanent magnets is mounted on the surface of the rotor. There are two sets of coil windings on the 3 poles of the stator. The first set, called bearing currents, is the same as that in the conventional 3-pole AMB, i.e., one independent coil on pole #1 and the other independent coil on poles #2 and #3 in the differential way. This set is to provide mainly the levitation force. The other set, called motor currents, is the usual 3-phase winding for the rotational torque.

DYNAMIC MODELLING

In order to get the dynamic model of the bearingless motor, we need to obtain the models of levitation forces and rotational torque. To this aim, the magnetic flux on each pole is first obtained by magnetic circuit analysis to yield

$$\begin{bmatrix}\phi_1\\ \phi_2\\ \phi_3\end{bmatrix} = \frac{N_1}{R_n}\begin{bmatrix}R_2+R_3 & -R_3 & -R_2\\ -R_3 & R_1+R_3 & -R_1\\ -R_2 & -R_1 & R_1+R_2\end{bmatrix}\begin{bmatrix}i_{b1}\\ i_{b2}\\ -i_{b2}\end{bmatrix} + \frac{N_2}{R_n}\begin{bmatrix}R_2+R_3 & -R_3 & -R_2\\ -R_3 & R_1+R_3 & -R_1\\ -R_2 & -R_1 & R_1+R_2\end{bmatrix}\begin{bmatrix}I_{m1}+I_{p1}\\ I_{m2}+I_{p2}\\ I_{m3}+I_{p3}\end{bmatrix} \tag{1}$$

where $R_n = R_1R_2 + R_2R_3 + R_3R_1$, $\phi_1 \sim \phi_3$ are magnetic fluxes, i_{b1} and i_{b2} are the bearing currents, $I_{m1} \sim I_{m3}$ are motor currents, $R_1 \sim R_3$ are magnetic resistance, N_1 is the number of bearing coils, and N_2 is the number of motor coils. Here, the concept of equivalent coil currents for the permanent magnets is used, i.e.,

$$\begin{cases} I_{p1} = i_p \sin(\theta) \\ I_{p2} = i_p \sin(\theta + \dfrac{2\pi}{3}) \\ I_{p3} = i_p \sin(\theta - \dfrac{2\pi}{3}) \end{cases} \tag{2}$$

where θ is the rotor angle. Then, the reluctance levitation forces can be obtained by the principle of virtual work, which are given by

$$F_x = (F_3 - F_2)\cos 30° = \frac{\sqrt{3}}{4\mu A}(\phi_3^2 - \phi_2^2) = mc_b \Psi_1 \Psi_2$$
$$F_y = (F_2 + F_3)\sin 30° = \frac{1}{4\mu A}[(\phi_3^2 + \phi_2^2) - 2\phi_1^2] = \frac{mc_b}{2}(\Psi_2^2 - \Psi_1^2) \qquad (3)$$

where

$$\Psi_1 = \frac{3}{4\mu A N_1}(\phi_3 + \phi_2) \qquad \Psi_2 = \frac{\sqrt{3}}{4\mu A N_1}(\phi_3 - \phi_2)$$

$$c_b = \frac{4\mu A N_1^2}{3m}$$

On the other hand, the rotational torque can be obtained by the Lorentz principle, i.e., the interaction of the PM magnetic field on the rotor and the coil currents on the stator poles. It is given by

$$T_t = (3rlB_p N_2 \sin\beta) i_m + (2rlB_p N_1 \sin\beta\cos\theta) i_{b1} - (2\sqrt{3}rlB_p N_1 \sin\beta\sin\theta) i_{b2}$$

where i_m is the amplitude of the 3-phase motor current. The first term in the torque equation is the contribution of the motor currents. The last two terms represent the coupling of the bearing currents to the motor torque. With the forces and torque in hand, the dynamic model of the system can be obtained as

$$\begin{aligned} \ddot{x}_r &= \frac{F_x}{m} = c_b \Psi_1 \Psi_2 \\ \ddot{y}_r &= \frac{F_y}{m} - g = \frac{c_b}{2}(\Psi_2^2 - \Psi_1^2) - g \\ \ddot{\theta} &= T_t - \frac{B}{J}\dot{\theta} \end{aligned} \qquad (4)$$

where x_r and y_r are the rotor displacements. Let the state variables be $x_1 = x_r$, $x_2 = \dot{x}_r$, $x_3 = y_r$, $x_4 = \dot{y}_r$, $x_5 = \theta$, and $x_6 = \dot{\theta}$. Then equation (4) can be expressed in the state space form as

$$\dot{x} = \begin{bmatrix} x_2 \\ c_b \Psi_1 \Psi_2 \\ x_4 \\ \frac{c_b}{2}(\Psi_2^2 - \Psi_1^2) - g \\ x_6 \\ -x_6 + T_t \end{bmatrix} \qquad (5)$$

CONTROLLER DESIGN

It is assumed that the operation of the bearingless motor is to levitate the rotor to the bearing center first, and then the 3-phase current is provided to activate the motor. In other words, at the levitation stage, $i_m = 0$. As a result, the levitation controller is almost the same as the conventional 3-pole AMB. The only difference is that one needs to compensate the coupling effects of the PM. Here, the integral sliding mode control [5] is employed. The overall control law is

$$\begin{bmatrix} i_{b1} \\ i_{b2} \end{bmatrix} = \frac{1}{\sqrt{c_b}} \begin{bmatrix} -2l_0 - y_r & x_r \\ \frac{x_r}{\sqrt{3}} & \frac{-2l_0 + y_r}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} p(\tilde{i}) \\ q(\tilde{i}) \end{bmatrix} - \frac{N_r i_p}{L} \begin{bmatrix} -2l_0 - y_r & x_r \\ \frac{x_r}{\sqrt{3}} & \frac{-2l_0 + y_r}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \end{bmatrix}$$

where

$$\begin{bmatrix} P_1 \\ P_2 \end{bmatrix} = \begin{bmatrix} (-2l_0 + y_r)\cos(\theta - \frac{\pi}{2}) + (l_0 - \frac{\sqrt{3}}{2}x_r - \frac{1}{2}y_r)\cos(\theta + \frac{\pi}{6}) + (l_0 + \frac{\sqrt{3}}{2}x_r - \frac{1}{2}y_r)\cos(\theta - \frac{7\pi}{6}) \\ \frac{\sqrt{3}}{3}(-\sqrt{3}x_r)\cos(\theta - \frac{\pi}{2}) + \frac{\sqrt{3}}{3}(-3l_0 + \frac{\sqrt{3}}{2}x_r - \frac{3}{2}y_r)\cos(\theta + \frac{\pi}{6}) + \frac{\sqrt{3}}{3}(3l_0 + \frac{\sqrt{3}}{2}x_r + \frac{3}{2}y_r)\cos(\theta - \frac{7\pi}{6}) \end{bmatrix}$$

$$\begin{bmatrix} p(\tilde{i}) \\ q(\tilde{i}) \end{bmatrix} = \begin{bmatrix} \sqrt{-(\tilde{i}_2 + g) + \sqrt{(\tilde{i}_2 + g)^2 + \tilde{i}_1^2}}\ \mathrm{sgn}(\tilde{i}_1) \\ \sqrt{(\tilde{i}_2 + g) + \sqrt{(\tilde{i}_2 + g)^2 + \tilde{i}_1^2}} \end{bmatrix}$$

$$\tilde{i} = -b_1\xi - b_2\eta - \frac{\rho + \alpha}{1 - k} sat(\frac{\xi + b_1\eta + b_2 z}{\varepsilon})$$
$$\dot{z} = \eta$$

and $L = 4l_0^2 - (x_r^2 + y_r^2)$, $N_r = N_2 / N_1$, $\eta = [\eta_1 \quad \eta_2]^T = [x_1 \quad x_3]^T$, $\xi = [\xi_1 \quad \xi_2]^T = [x_2 \quad x_4]^T$, and $b_1, b_2, \rho, \varepsilon, \alpha, k$ are control parameters.

At the rotation stage, it is assumed that the rotor is maintained at the bearing center. A simple PD controller is designed for the motor speed control. Simulation results are presented in Figs. 2 and 3, where Fig. 2 shows the rotor trajectory for the levitation control and Fig. 3 is the result of motor control with speed command of 10 rad/s. In the simulations, the system parameters are given in Table 1 and the control parameters are: $b_1 = 20$, $b_2 = 20$, $\rho = 5$, $\alpha = 3$, $k = 0.5$, $\varepsilon = 0.1$. The results indicate that the proposed 3-pole bearingless motor is feasible. However, the performance of motor control is less satisfied. Thus, the issue of motor control requires further investigation in the future.

CONCLUSIONS

A 3-pole PM type bearingless motor has been proposed. The dynamic model was obtained through the analysis of levitation forces and rotational torque. Controller for stable levitation and rotor speed control was designed accordingly. The simulation results indicated that the conventional 3-pole AMB can be easily integrated with the 3-phase currents to become a bearingless motor.

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Table 1. System parameters

$l_0 = 0.95\times10^{-3}\ m$	$\mu = 4\pi\times10^{-7}\ H/m$
$A = 4\times10^{-4}\ m^2$	$B_p = 0.5\,Tesla$
$J = 3.94\times10^{-4}\ kg\cdot m^2$	$\mathrm{B} = 0.002\ N\cdot m/rad/s$
$m = 0.6435\ kg$	$g = 9.81\,m/s^2$
$N_1 = 300$	$N_2 = 300$
$r = 0.035\,m$	$l = 0.02\,m$
$\beta = 32°$	$R_m = 2\,\Omega$

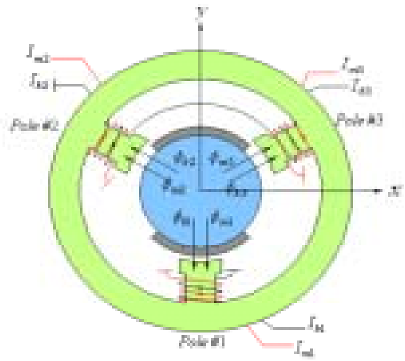

Fig. 1 The 3-pole bearingless motor

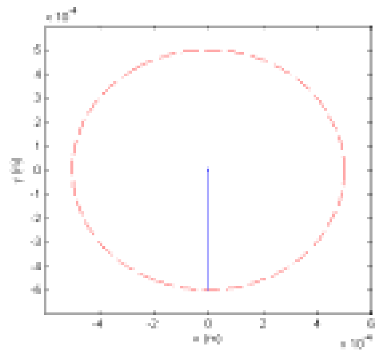

Fig. 2 The rotor trajectory

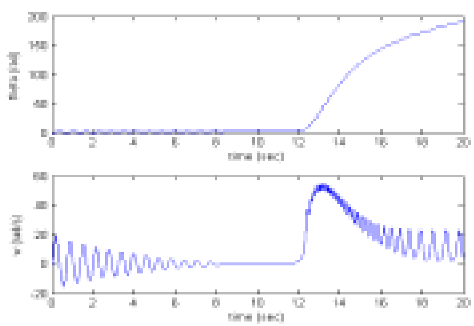

Fig. 3 The angular position and speed of the rotor