Tạp chí Khoa học và Công nghệ 121 (2017) 015-020

Modeling and Characteristics of an Axial-Gap Self-Bearing Motor

Xây dựng mô hình toán học và xác định các đặc tính của động cơ tự nâng từ trường dọc trục

Nguyen Huy Phuong

Hanoi University of Science and Technology, No. 1, Dai Co Viet Str., Hai Ba Trung, Ha Noi, Viet Nam

Received: April 03, 2017; accepted: September 5, 2017

Abstract

Axial-gap self bearing motor (AGBM) is a functional combination of axial magnetic bearing and axial flux motor. It means the AGBM can generate rotation and translation with only three-phase windings. The paper will introduce about the characteristics of an AGBM. First the mathematical model of the AGBM is developed in rotor field-oriented coordinate. Then the axial force and the motoring torque are analyzed theoretically to confirm its abilities. In order to evaluate the rightness of the proposed theory, a single stator AGBM has been made and tested. The experimental results confirm that the levitation force is propotional to direct axis current (i_{sd}) and the rotary torque is propotional to quadrature axis current (i_{sq}).

Keywords: Axial-Gap Motor, Axial Flux Motor, Self-Bearing Motor, Axial Magnetic Bearing

Tóm tắt

Động cơ tự nâng từ trường dọc trục (AGBM - Axial-Gap Self Bearing Motor) là một dạng động cơ điện có chức năng của cả ổ từ dọc trục và động cơ từ trường dọc trục. Như vậy AGBM có khả năng đồng thời tạo ra cả chuyển động quay và chuyển động dọc trục với chỉ các cuộn dây ba pha. Bài báo này sẽ giới thiệu và các đặc tính cơ bản của AGBM. Đầu tiên mô hình toán học của AGBM được xây dựng trong hệ tọa độ tựa theo từ thông rotor, sau đó lực nâng dọc trục và mô men quay được phân tích chi tiết để chỉ ra các đặc điểm cơ bản của động cơ. Để kiểm chứng cho phân tích ở trên, AGBM loại một stator được chế tạo và thử nghiệm. Kết quả thử nghiệm chỉ ra được lực nâng dọc trục là tỷ lệ với thành phần dòng điện dọc trục (i_{sd}) còn mô men quay là tỷ lệ với thành phần dòng điện ngang trục (i_{sq}).

Từ khóa: Động cơ tự nâng từ trường dọc trục, động cơ từ trường dọc trục, ổ từ dọc trục

1. Introduction

In some applications of electric motors, bearing maintenance is still a significant problem. For example, the bearings can present a major problem in motor drive applications in outer space, and also in harsh environments with radiation and poisonous substances. In addition, lubrication oil cannot be used in high vacuum, ultra high and low temperature atmospheres and food and pharmacy processes. Hence motor drives with magnetic suspension, i.e. magnetic bearing motor, can enlarge the possible application areas of motor drives. The conventional magnetic-bearing motors usually consist of a motor, two radial magnetic bearing (RMB) and an axial magnetic bearing (AMB). The RMBs create radial levitation forces for rotor, while an AMB produces a thrust force to keep the rotor in the correct axial position relative to the stator. Obviously, they are large, heavy, and complex in control and structure, which cause problems in applications that have limit space. Thus, a simpler and smaller construction and a less complex control system are desirable [1]-[3].

An axial magnetic bearing is composed of a rotary disc fixed on a rotary shaft and electromagnets arranged on both sides of the disc at a proper minute distance [4]-[5]. This structure is similar to that of an axial-flux AC motor [6]-[7]. Therefore, an axial-gap combined bearing motor has been introduced [8]-[12], in which the stator has only three-phase windings; however the motor can simultaneously provide non-contact levitation and rotation. This motor is then called an axial-gap self-bearing motor (AGBM) to imply that the motor has itself the function of bearing support without any additional winding. Obviously, it is the simplest in structure and control since hardware components can be reduced. The AGBM can be realized as an induction motor (IM) [9],[10], or a permanent magnet (PM) motor [8],[11]-[12]. The PM motor is given special attention, because of its high power factor, high efficiency, and simplicity in production. This paper presents the method of building the mathematical model and characteristics of the AGBM.

First, the axial force and the motoring torque are analyzed theoretically and the characteristics of the

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* Corresponding author: Tel.: 024.3869.6211
Email: phuong.nguyenhuy@hust.edu.vn

axial gap self bearing motor are derived. In this paper, a single stator AGBM with PM excitation is analyzed by using the extended technique of the conventional three phase motor analysis methods. Then control methods of the axial force and the motoring torque for the AGBM are derived.

2. Mathematical Model of AGBM

The structure of a single stator AGBM is shown in Fig. 1. This structure consists of a disc rotor and a stator. The radial motions x, y, θ_x and θ_y of the rotor are constrained by the radial magnetic bearing, F_b is the external applied force. Only rotational motion and translation along the z axis are considered. The rotor is flat disc with permanent magnets inserted on the disc to create a salient-pole rotor. The stator has three-phase windings that generate rotating magnetic fluxes in the air gap. These produce motoring torque T on the rotor and generate attractive force F between the rotor and stator.

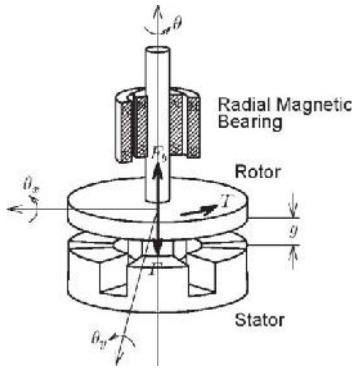

Fig. 1 Structure of a single stator AGBM

Similar to the conventional PM motor, the mathematical model of the AGBM is presented in a rotor field-oriented reference frame or so-called *d, q* coordinates, as indicated in Fig. 2. The *d* axis is aligned with the center lines of the permanent magnets and the *q* axis between the magnets. The axes *u, v,* and *w* indicate the direction of the flux produced by the corresponding phase windings. The phase difference between the *u* axis and the *d* axis is the electrical angular position *θ* of the rotor or the rotor flux vector.

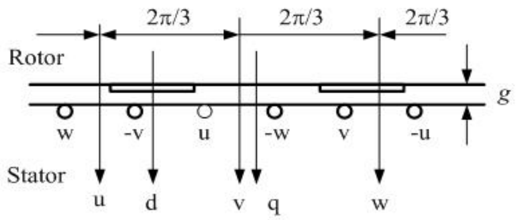

Fig. 2 Definition of coordinates

For the three-phase motor, the stator phase voltage equation in vector form is [13]

$$\boldsymbol{u}_s = \boldsymbol{i}_s \boldsymbol{R}_s + \frac{d\boldsymbol{\lambda}_s}{dt} \tag{1}$$

By using the power invariant transformation method, the component of the stator voltage and the flux of single axial-gap self-bearing motor in the d, q coordinates can be expressed in the following equations:

$$\begin{cases} u_{sd} = R_s i_{sd} + L_{sd}\dfrac{di_{sd}}{dt} - \omega_e L_{sq} i_{sq} \\ u_{sq} = R_s i_{sq} + L_{sq}\dfrac{di_{sd}}{dt} + \omega_e L_{sd} i_{sd} + \omega_e \lambda_m \\ \lambda_{sd} = L_{sd} i_{sd} + \lambda_m \\ \lambda_{sq} = L_{sq} i_{sq} \end{cases} \tag{2}$$

with L_{sd}, L_{sq} are the d- and q-axis phase inductance of the stator windings and ℓ_m is the flux linkage in the stator windings caused by the rotor magnetic field. They are calculated as follows [13]

$$\begin{cases} L_{sd} = \dfrac{3L'_{sd0}}{2g} + L_{sl} \\ L_{sq} = \dfrac{3L'_{sq0}}{2g} + L_{sl} \end{cases} \tag{3}$$

where L_{sl} is the leakage inductance, and the flux linkage $\ell_m = L_m i_f$. Considering the magnetic flux of the rotor to be an equivalent winding with a DC current i_f and an inductance L_f. The rotor flux can be expressed only in d axis as follows:

$$\ell_f = \ell_{fd} = i_f L_f + L_m i_{sd} \tag{4}$$

where the synchronous inductance L_f and the mutual inductance L_m are calculated as

$$\begin{cases} L_f = \dfrac{3}{2}\dfrac{L'_{sd0}}{g} + L_{sl} \\ L_m = \dfrac{3}{2}\dfrac{L'_{sd0}}{g} \end{cases} \tag{5}$$

From (2) & (4), the magnetic co-energy in the air gap is calculated as follows:

$$\begin{aligned} W &= \frac{1}{2}\left(\lambda_f i_f + \lambda_{sd} i_{sd} + \lambda_{sq} i_{sq}\right) \\ &= \frac{1}{2}\left\{L_{sq}\left(i_f^2 + i_{sd}^2\right) + L_{sq} i_{sq}^2 + 2L_m i_{sd} i_f\right\} \end{aligned} \tag{6}$$

In combination with (3) and (5), the magnetic co-energy is expressed as:

$$W = \frac{1}{2}\left\{\left(\frac{3}{2}\frac{L'_{sd0}}{g} + L_{sl}\right)\left(i_f + i_{sd}\right)^2 + \left(\frac{3}{2}\frac{L'_{sd0}}{g} + L_{sl}\right)i_{sq}^2\right\} \tag{7}$$

Therefore, the attractive force of the stator is

$$F = -\frac{\partial W}{\partial g} = \frac{3L'_{sd0}}{4g^2}(i_f + i_{sd})^2 + \frac{3L'_{sq0}}{4g^2}i_{sq}^2 \tag{8}$$

And the motoring torque is calculated by:

$$\begin{aligned} T &= P(-\lambda_{sd}i_{sq} + \lambda_{sq}i_{sd}) \\ &= \frac{3PL'_{sd0}}{2g}i_f i_{sq} + \frac{3P(L'_{sd0} - L'_{sq0})}{2g}i_{sd}i_{sq} \end{aligned} \tag{9}$$

with P is the number of pole pairs. By substituting $g = g_0 + z$, the total axial force F and torque T are given by:

$$F = \frac{3L'_{sd0}}{4(g_0 + z)^2}(i_{sd} + i_f)^2 + \frac{3L'_{sq0}}{4(g_0 + z)^2}i_{sq}^2 \tag{10}$$

$$T = \frac{3PL'_{sd0}}{2(g_0 + z)}i_f i_{sq} + \frac{3P(L'_{sd0} - L'_{sq0})}{2(g_0 + z)}i_{sd}i_{sq} \tag{11}$$

where g_0 is the axial gap at the equilibrium point and z is the displacement. From (2), (4), (10) and (11), the mathematical model of the single stator axial-gap self-bearing motor is completely constructed.

By linearization at operating point $\left(i_{sd0}, i_{sq0}, g_0\right)$, (10) becomes:

$$F = F_0 + F_1 - 2F_0\frac{z}{g_0} \tag{12}$$

with $$F_0 = \frac{3L'_{sd0}}{4g_0^2}(i_f + i_{sd0})^2 + \frac{3L'_{sq0}}{4g_0^2}i_{sq0}^2 \tag{13}$$

$$F_1 = \frac{3L'_{sd0}}{4g_0^2}2(i_f + i_{d0})i_{sd} \tag{14}$$

and (11) becomes:

$$\begin{aligned} T &= \frac{3PL'_{sd0}}{2g_0}i_f i_{sq} - \frac{3PL'_{sd0}}{2g_0}i_f i_{sq}\frac{z}{g_0} \\ &+ \frac{3P(L'_{sd0} - L'_{sq0})}{2g_0}i_{sq}i_{sd}(1 - \frac{z}{g_0}) \end{aligned} \tag{15}$$

Normally, the displacement z is significantly smaller than air gap g_0, and assuming that the different between L'_{sd0} and L'_{sq0} is small so they can be eliminated. Now (12) and (15) become:

$$F = F_0 + \frac{3L'_{sd0}}{4g_0^2}2(i_f + i_{sd0}).i_{sd} = F_0 + K_m i_{sd} \tag{16}$$

$$T = \frac{3PL'_{sd0}i_f}{2g_0}i_{sq} = K_T i_{sq} \tag{17}$$

where $K_m = \frac{3L'_{sd0}}{4g_0^2}2(i_f + i_{sd0})$ is force factor

and $K_T = \frac{3PL'_{sd0}i_f}{2g_0}$ is torque factor

By linearization around operating point, the relationships between F and i_d, and between T and i_q are linear. This linear relationship only exists when the current is small and the distance between stator and rotor has a little change round g_0. As a result, the AGBM can be controlled by a linear control scheme as shown in Fig. 3.

The axial displacement of the rotor from the equilibrium point along the z-axis, can be detected by the gap sensor. The detected axial position is compared with the axial position command z_{ref} and the difference is placed at the axial position controller R_z. The position command z_{ref} is always set to zero to ensure that there is a fixed air gap between rotor and stator. The output of the controller R_z is used to calculate the d-axis reference current i_{dref} of R_{id} controller.

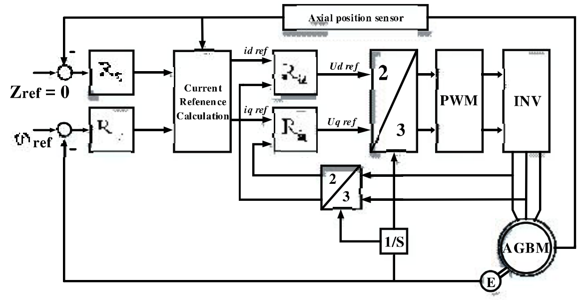

Fig. 3 Control Structure of AGBM

The rotor speed detected from the encoder is compared with the reference speed and the divergence is input to the speed controller R_ω. The output of the speed controller is used to calculate the q-axis reference current i_{qref}.

Using the inverse transformation from the d, q reference frame to the three-phase stator reference frame, the output of the current controllers R_{id} and R_{iq}, representing the voltage references, are subsequently directed to the motor using the PWM technique. All the controllers are PI controller except for the axial position controller is PID.

3. Implementation and results

In order to exploit the characteristics of the PM type AGBM, a single stator AGBM has been developed which is shown in Fig. 4. The rotor disc has a diameter of 50 mm and two neodymium iron magnets with the thickness of 0,8mm for each side are placed on its surfaces to create non-salient. For experimental simplicity, the rotor is supported by two radial ball bearings in order to restrict the radial motion of the rotor.

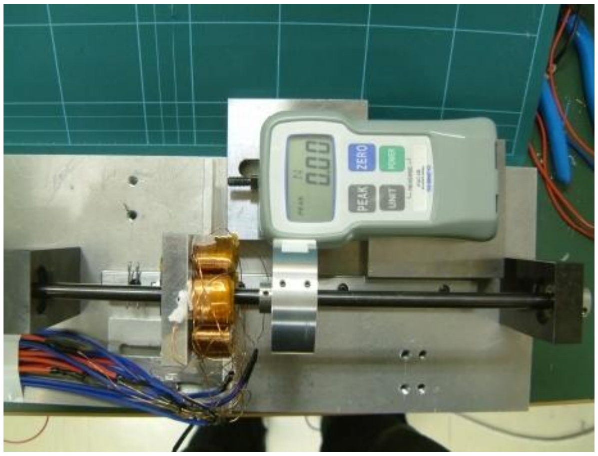

Fig. 4 Single stator AGBM

The stator has a diameter of core 50 mm and six concentrated wound poles, each with 200 coil turns. The stators can slide on linear guide to ensure the exchangeable air gap between rotor and two stator. A DC generator (Sanyo T402) is installed to give the load torque. In order to measure the rotor angle and the axial position, a rotary encoder (Copal RE30D) and an eddy-current-type displacement sensor (Sentec HA-101S) are installed, respectively.

The control hardware of the AGBM drive is based on a dSPACE DS1104 board dedicated to the control of electrical drives (Fig. 5). The DS1104 then calculates reference currents using the rotation control and axial position control algorithms and sends its commands to the three-phase inverter boards. The AGBM is supplied by two three-phase PWM inverters with a switching frequency of 20 kHz.

First, parameter estimation is carried out. The phase resistor is 2,6Ω. The static phase inductances are measured by measuring the frequency response of the voltage versus the current of the stator coil when the rotor is rotating from 0 to 360^0 and the air gap is 1,5mm. The result is shown in Fig. 5. Obviously, $L_{sq} = 9,76\times10^{-3}\ H$ and $L_{sd} = 8,25\times10^{-3}\ H$

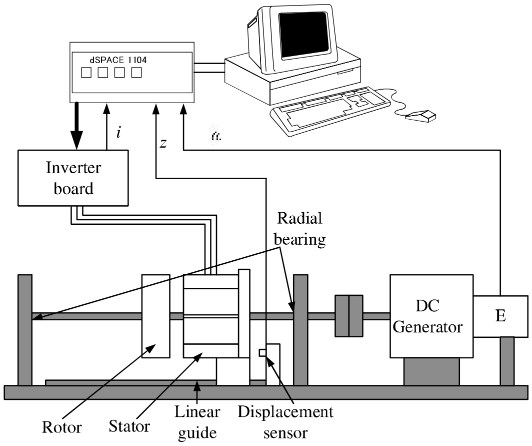

Fig. 5 Structure of experimental setup

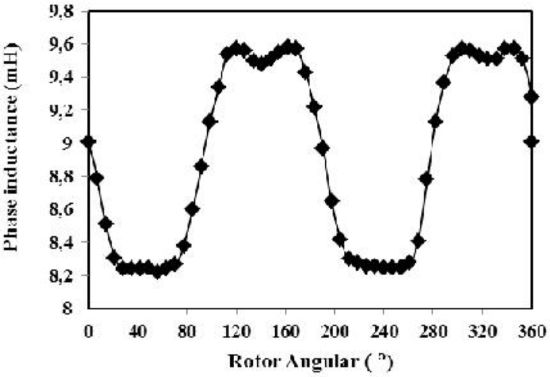

Fig. 6 Phase inductance vs rotor angular

To find the relation between phase inductance and air gap between the rotor and the stator. The static phase inductances are measured by measuring the frequency response of the voltage versus the current of the stator coil when the air gap is increasing from 1mm to 20mm. The result is shown in Fig. 6. This gives

$L'_{sd0} = 8,2\times10^{-6}\ Hm$ $L'_{sq0} = 9,6\times10^{-6}\ Hm$ and

$L_{sl} = 6\times10^{-3}\ H$.

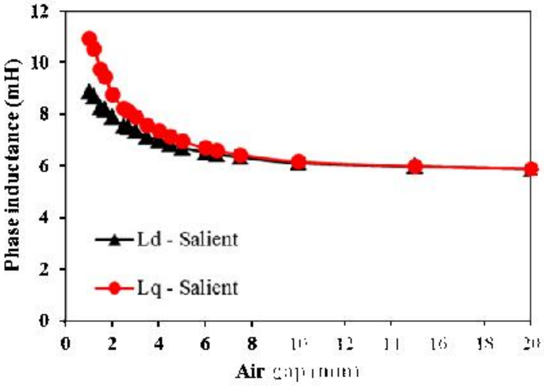

Fig. 7 Phase inductance vs air gap

The amplitude of the flux induced by the permanent magnets of the rotor in the stator phases can be estimated by measuring the no-load voltage of the AGBM in generator mode, shown in Fig. 7; it is easy to calculate the rotor flux $\lambda_m = 0,015Wb$.

The relation between the motor torque and the quadrature axis current i_q is harve sted by changing load torque when the air gap is fixed at 1,5mm. The theoretical torque calculated from (17). The result is shown in Fig. 8. Obviously, the motor torque is proportional with the quadrature axis current i_q.

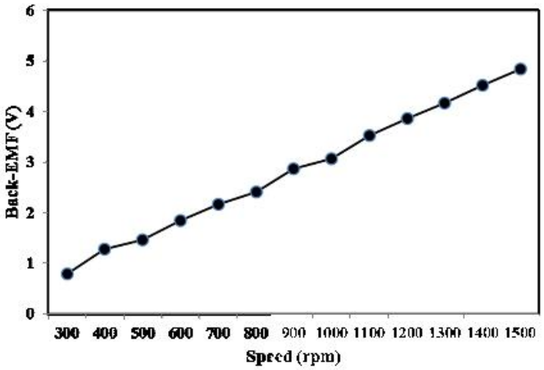

Fig. 8 Induced phase voltage (Back-EMF) of the AGBM

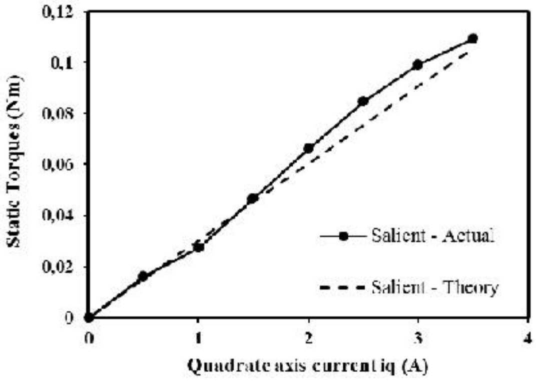

Fig. 9 Torque vs quadrate axis current

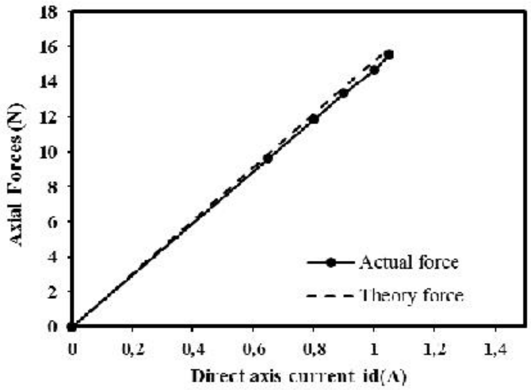

Fig. 10 Axial force vs direct axis current

To find the relation between the axial force and the direct axis current, the force meter is used to create thrust force, while the motor is at a standstill. The current i_d is calculated from measured phase currents for different values of the axial force through DS1104. The result is illustrated in Fig. 9. Obviously, the axial for is proportional with the direct axis current i_d.

4. Conclusion

Through the analysis of the mathematical model of the AGBM in rotor field-oriented coordinate and the experimental results, the paper shows that the AGBM can perform both functions of motor and axial bearing without any additional windings. In which, the motoring torque of the AGBM can be controlled by the q-axis current (i_q), while the axial force can be controlled by the d-axis current (i_d).

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