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Estimation of Magnetic Center Location in Radial Active Magnetic Bearings Through a Pull Test

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Abstract

The misalignment between the mechanical center and the magnetic center in a radial active magnetic bearing can cause serious problems and must be measured before commissioning the machine for field deployment. Once a suspension controller is operating, the misalignment can be estimated from the coil current imbalance. In this paper, we present a method of estimating the misalignment without the need for suspension. Through a simple test where the rotor is pulled to several different directions, the magnetic center can be estimated. For this purpose, a force model that relates the coil current and the force that the rotor experiences is derived. Utilizing this force model, a minimization proble is set up, where the discrepancies between the contact angle measurements and the force angles computed from the force model are minimized. The results of this minimization produce the estimation of the magnetic center. The validity of the method is checked through simulations and experiments.

Key words : Misalignment, Automatic testing, Commissioning

1. Introduction

From a product point of view, it is important to maintain the quality of the product. To ensure that a machine equipped with magnetic bearings perform as designed, the machine must go through a host of check-up tests such as misalignments in cablings and sensor ranges as a part of commissioning procedure (Smirnov, 2012).

One of the checks that must be done for an AMB system is the misalignment between the mechanical center (the center of backup bearing) and the magnetic center (the center of radial magnetic bearing). Manufacturing tolerances inevitably bring about the misalignment. If severe, the misalignment causes the actuator gain and the negative stiffness differ from the designed values, which may limit the performance obtainable from a controller. If the bias linearization is used, the linearity of the force model would be affected by the misalignment.

Once the rotor is levitated, the misalignment can be estimated from the current imbalance. In some cases, however, it is necessary to identify the misalignment and take a corrective measure before a suspension controller is implemented. Also, the current imbalance method require fairly accurate estimation of the actuator gain which is affected by the misalignment.

In this paper, we present a method of estimating the location of the magnetic center with respect to the mechanical center through a pull test. This test can be performed with suspension. Through of a series of pulling the rotor in different directions and measuring the locations of the contact points between the rotor and the backup bearing, the magnetic center can be identified.

Since a force model that relates the coil currents and the magnetic pulling force that the rotor experiences is utilized in the estimation process, the model is first presented. Using this model, a minimization problem is set up, the solution of which is the estimation of the the magnetic center location.

2. Force Model

Shown in Fig. 1 is a typical 8–pole radial active magnetic bearing. Two adjacent poles are wired in series and driven by a single coil current. Table 1 lists the pole numbers and how the poles are arranged for actuation. The force acting on the rotor is a vector sum of all eight attractive force and can be written as

$$\mathbf{F} = \sum_{i=1}^{8} F_i(\cos\theta_i\,\hat{\mathbf{x}} + \sin\theta_i\,\hat{\mathbf{y}}) \tag{1}$$

where $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ are the unit vectors in x and y axes respectively. In eq. (1), the pole angles are defined as

$$\theta_i = \frac{\pi}{8}(2i-1) \tag{2}$$

The active force of each pole is a function of the coil current and the air gap between the pole tip and the journal as well as geometrical parameters. Using a reluctance network, a force model can be obtained in the form of (Meeker, 1995)

$$F_x = \frac{1}{2}\mathbf{i}^T\mathbf{M}_x\mathbf{i} \tag{3}$$

$$F_y = \frac{1}{2}\mathbf{i}^T\mathbf{M}_y\mathbf{i} \tag{4}$$

where the current vector is $\mathbf{i} = [i_A\ i_B\ i_C\ i_D]^T$. The matrices $\mathbf{M}_x$ and $\mathbf{M}_y$ are functions of coil windings and reluctances of flux paths.

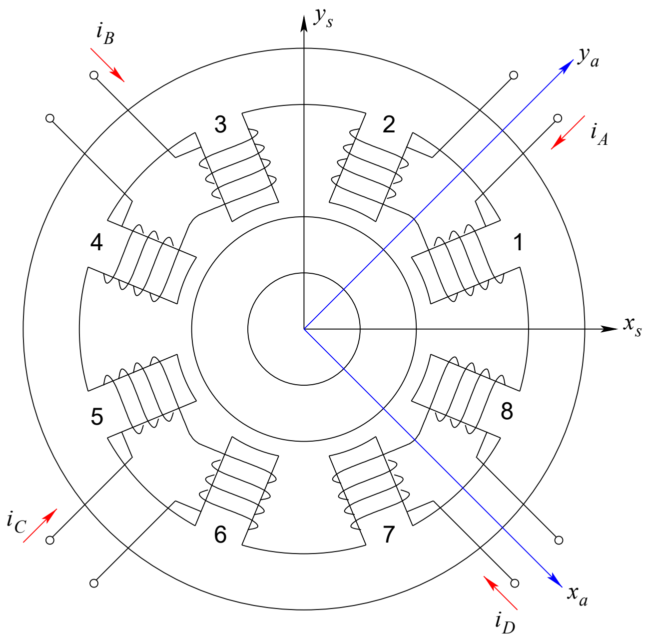

Fig. 1 Schematic of a typical 8–pole radial active magnetic bearing where two adjacent poles are wired in series

Table 1 Actuating directions and corresponding poles and coils

Actuating direction	Axis	Pole numbers	Coil Current
45°	$+y_a$	1, 2	i_A
135°	$-x_a$	3, 4	i_B
226°	$-y_a$	5, 6	i_C
−45°	$+x_a$	7, 7	i_C

Table 2 Combinations of coil currents in a pull test

Pull direction	i_A	i_B	i_C	i_D
0°	I_{max}	0	0	I_{max}
45°	I_{max}	0	0	0
90°	I_{max}	I_{max}	0	0
135°	0	I_{max}	0	0
180°	0	I_{max}	I_{max}	0
225°	0	0	I_{max}	0
−90°	0	0	I_{max}	I_{max}
−45°	0	0	0	I_{max}

3. Pull Test

Through a combination of coil currents, the rotor can be pulled to an arbitrary direction. Since the rotor motion is restricted by a backup bearing, the rotor would eventually come in contact with the backup bearing if it is pulled with large enough currents. When it is in contact with the backup bearing, it is reasonable to assume that the contact force is on the line extending from the mechanical center (i.e the center of the backup bearing) to the contact point. Otherwise, there would be a tangential force that results in rotation. This contact point is the position where the force balance is achieved.

When the rotor is pulled to eight directions listed in Table 2, eight contact points can be identified. If the backup bearing is perfectly aligned with the magnetic bearing (i.e. no misalignment between the mechanical center and the magnetic center), those contact would be determined similarly to the case depicted in Fig. 2(a). Due to gravity loading, the contact points 1 and 5 are determined somewhat lower than the pulling directions.

In case there is a misalignment between the mechanical center and the magnetic center, the contact points would change since the smallest air gaps become different for different pulling directions. This situation is shown in Fig. 2(b), where the backup bearing center is displaced to the lower right location. Obviously, the rotor is pulled with the greatest force to the direction 6 since it has the smallest air gap.

Using eqs. (3) and (4), the pulling forces can be computed. Since some part of the actuator would be saturated, it is important to consider the core reluctances with reduced permeability. The results of a simulated case is shown in Fig. 3. The data of the bearing is summarized in Table 3. It is assumed that the half of the rotor mass is applied to the bearing. The misalignment is (0.05, −0.02) mm with respect to the mechanical center. Not only the pulling forces are different, but also are the contact angles from the case without misalignment.

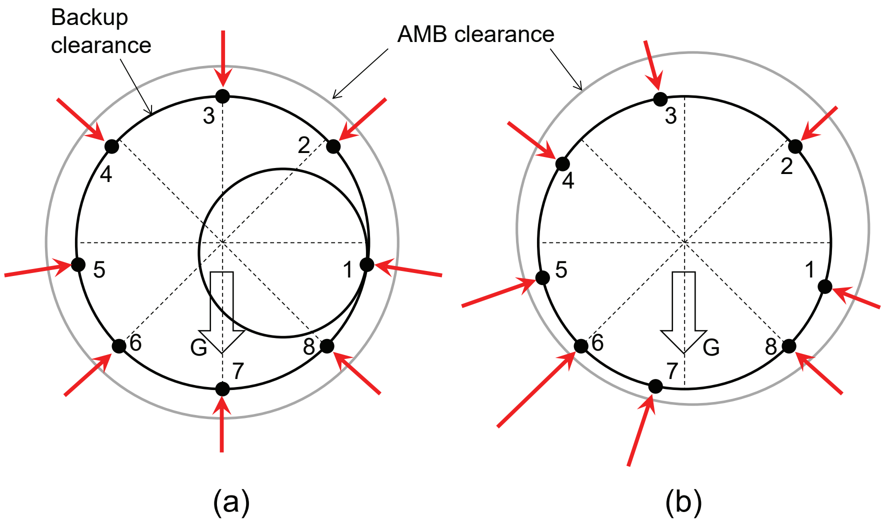

Fig. 2 Contact points in a pull test. (a) case without misalignment (b) case with misalignment

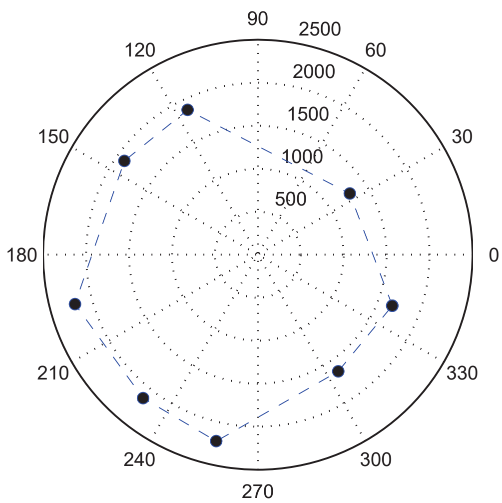

Fig. 3 Simulated pull test results when there is a misalignment

Table 3 Parameters of the radial active magnetic bearing

Parameter	Value
Number of coil turns per pole	32
Pole width	16.6 mm
Axial length	64 mm
Nominal air gap	0.5 mm
Backup clearance (radial)	0.2 mm
Rotor mass	75 kg

4. Estimation of Magnetic Center Location

Once the bearing is installed and the sensor signals are properly conditioned, it is straightforward to conduct a aforementioned pull test. The only assumption that must be satisfied is that the rotor motion is only restricted by the backup bearing. Thus, the case where the misalignment is larger than the difference between the nominal air gap and the backup clearance is not considered. Results of the pull tests for two radial bearings are shown in Fig. 4 Pulled displacements in x direction in the left bearing are slightly larger than 0.2 mm which is the backup clearance. This may be due to the larger sensitivity of the eddy current probe in the x direction than in the y direction.

Since the force angles would match the contact angle when the rotor is in contact with the backup bearing, and since the unknown misalignment can determine the force angles, it is possible to set up a minimization problem with a cost function of

$$J = \min_{(x_e, y_e)} \sum_{i=1}^{8} \left[\tan^{-1}\left(\frac{y_{c,i}}{x_{c,i}}\right) - \tan^{-1}\left(\frac{F_{y,i}}{F_{x,i}}\right) \right]^2 \tag{5}$$

where (x_e, y_e) is the location of the magnetic center with respect to the mechanical center. In (5), i-th measured contact angle is $\tan^{-1}\left(\frac{y_{c,i}}{x_{c,i}}\right)$ while the i-th force angles are computed from $\tan^{-1}\left(\frac{F_{y,i}}{F_{x,i}}\right)$. For the two bearings shown in Fig. 4, the minimization results in the estimations of the misalignment of $(-2, -56)$ μm for the bearing on the left and $(-6, -61)$ μm for the bearing on the right.

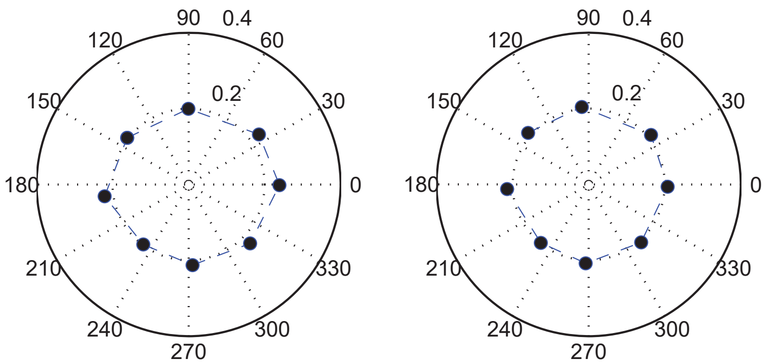

Fig. 4 Pull test results obtained from two radial bearings

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