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Position estimation accuracy improvement based on accurate modeling of self-sensing active magnetic bearings

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ABSTRACT

The Self-sensing Active Magnetic Bearings (SSAMBs) which feature for the simplification of independent displacement sensors, contribute to both cost reduction and convenience in control and assembly. The key point of this technique is to accurately estimate rotor position signals directly from coil voltages or currents, thus the actuator itself also serves as a virtual displacement sensor. Although several feasible approaches have been proposed to realize the self-sensing process, there still lie limitations in estimation accuracy, robustness and dynamic performance of the system. In fact, due to the nonlinear property of the self-sensing process, few accurate models are available for quantitative analysis of the estimation accuracy, and this restricts further development of this technique. Focusing on the modulation type SSAMBs, an accurate analytical model of the self-sensing in frequency domain is firstly established in this paper. Eddy current effects and filter properties are also considered for better accuracy. Based on this model, we evaluate possible estimation error sources during the self-sensing process, and investigate if the estimation accuracy can be improved fundamentally by selecting main system parameters properly. In this way, the estimation accuracy gets further improved under existing compensation methods, and better system robustness and dynamic performance can be achieved. Finally, the analytical model and associated conclusions are validated through static experiment, 4-Degree of Freedom (DOF) self-sensing rotor levitation experiment and 0–5000 rpm rotating operation experiment on a 4-DOF rigid rotor-radial SSAMBs platform.

1. Introduction

The Active Magnetic Bearings (AMBs) are well known for its fascinating friction-free and lubrication free property. Numerous prototypes and industrial products of AMBs have emerged in areas such as compressors, turbomolecular pumps, flywheel energy storage systems, etc. To decrease the system cost and avoid the sensor-actuator non-collocation problem in conventionally sensed AMB, the Self-sensing Active Magnetic Bearings (SSAMBs), in which individual displacement sensors are removed, have been widely studied in the past few years [1–4].

Generally, there are mainly three kinds of methods to realize the SSAMB: state observer, machine learning algorithm and parameter estimation. Linear Time Invariant (LTI) state observers are utilized to estimate the rotor displacement [5]. Affected by its high sensitivity to system parameters variation, this kind of SSAMB has limited robustness and dynamic performance [6,7]. The machine learning algorithms, such as neutral network [8] and support vector machine [9], are also applied to obtain rotor displacement, but they are generally complicated to implement. The basic principle of the parameter estimation method is that rotor displacement always leads to the variation of corresponding AMB's coil inductance, thus the rotor position estimation can be realized by measuring the coil inductance equivalently [10]. Supported by the linear periodic theory, this category of SSAMBs is believed to own better system robustness [11,12], thus is the research focus in recent years.

Generally, high frequency small dither signals are needed to detect the change of coil inductance. For AMBs using linear power amplifiers, small high frequency signals are often injected into the coil as the detection signals [13,14]. But since switching power amplifiers are often applied in most AMBs, the inherent high frequency switching ripple in the power amplifier's output can be directly utilized to estimate the rotor position.

For the commonly called "modulation type" SSAMBs [15], the amplitude change of the fundamental component of switching ripples reflects the rotor displacement, so that a demodulator circuit or algorithm is necessary for signal extraction and processing. The

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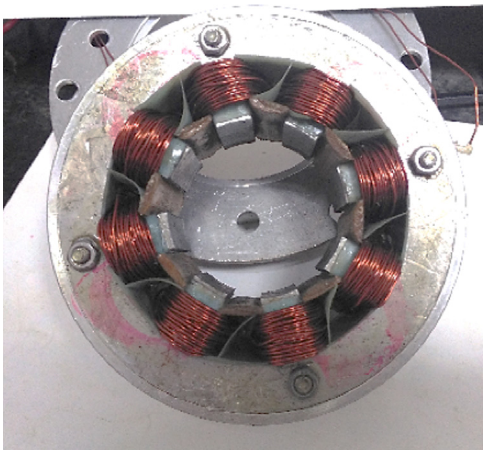

Fig. 1. Eight-pole heteropolar radial AMB (stator).

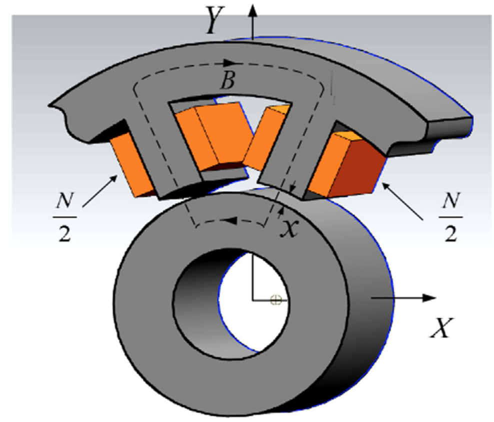

Fig. 2. Single pole model.

main drawback of modulation type SSAMBs is that the estimated rotor position is significantly coupled with the dynamic coil current, which may cause severe duty cycle variation and magnetic saturation problem [16,17]. Although several feasible compensation methods [18] are proposed, the accuracy of compensation is still limited, especially in high frequency domain.

The Direct Current Measurement (DCM) type SSAMBs [19,20], in which the current slope of the switching ripple is directly measured to calculate the coil inductance, are also proposed to avoid the duty cycle variation problem in the modulation type SSAMBs. However, the nonlinear eddy current effects become a big challenge for precisely measuring the current slope [21]. In addition, experimental results show that the DCM method is practically still sensitive to duty cycle variations [22].

In this paper, we still focus on the modulation type SSAMB and investigate if its dynamic performance can be further improved fundamentally. This purpose is firstly carried out by analytically modeling the self-sensing of SSAMB in the frequency domain. Based on this model, we evaluate possible estimation error sources during the self-sensing process, and analyze how main system parameters can be properly selected to reduce the estimation error, thus better system robustness and dynamic performance are achieved. Finally, the analytical model and associated conclusions are validated through static experiments, 4-DOF self-sensing dynamic rotor levitation experiments and 0–5000 rpm rotating operation experiments on a 4-DOF rigid rotor-radial SSAMBs platform.

2. The basic principles of the modulation-type self-sensing approach

2.1. Coil inductance model of AMB

If we assume that there lies no flux cross-coupling between adjacent poles of the AMB, then an eight-pole heteropolar radial AMB, as shown in Fig. 1, can be separated as four single pole pair models as shown in Fig. 2.

Based on the magnetic circuit theory, the equivalent coil inductance of the single pole pair model can be expressed as,

$$L = \frac{\mu_0 N^2 A_g}{2x + l_c/\mu_r} \tag{1}$$

in which μ_0 is the magnetic permeability of free space, N is the number of turns of pole pair coil, A_g is the cross-sectional area of the flux path at the air gap, x is the air gap length, l_c is the length of the flux path in the iron core section, μ_r is the relative magnetic permeability of the iron core, and l_c/μ_r stands for the equivalent air gap of iron core. Because the coil inductance L directly relates to the air gap, it is possible to estimate the rotor movement through measuring the variation of coil inductance.

As L also relates to μ_r, it is necessary to take both the magnetic saturation and the eddy current effects into account to ensure the estimation accuracy. The eddy current effects appears because of the time-varying magnetic flux in iron core, and makes μ_r frequency dependent [23], especially when the AMB is driven by switching power amplifiers. Both these two non-idealities decrease μ_r and cause estimation errors. However, if the highly saturation of iron core is avoided, the iron core is laminated and the switching frequency of power amplifier is properly chosen, the decrease of μ_r will be limited. In this case, it would be reasonable to assume $l_c/\mu_r \ll 2x$ for the laminated radial AMB in which l_c is relatively smaller than the axial one. Then an inversely proportional relationship between L and x can be obtained as,

$$L = \frac{\mu_0 N^2 A_g}{2x} \tag{2}$$

When the switching power amplifiers are used to drive the AMB, the high frequency switching ripple can be utilized as the detection signal of coil inductance variance. In this paper, we use the two-state current type Pulse Width Modulation (PWM) switching power amplifier for its stable and detectable switching ripple.

2.2. The property of switching harmonics of switching power amplifier

If the turn-on and turn-off time of power switching component are ignored, then the output voltage $V(t)$ of the two-state switching power amplifier can be modeled as PWM square waveform with time-varying duty cycle,

$$V(t) = \begin{cases} V_s & kT_s < t \le kT_s + \alpha T_s \\ -V_s & (k+\alpha)T_s < t \le (k+1)T_s \end{cases} \tag{3}$$

in which V_s is the bus voltage, T_s is the switching period and α is the PWM duty cycle in the kth switching period.

Within the kth switching period, $V(t)$ can be further expanded into the Fourier series form as,

$$V(t) = (2\alpha - 1)V_s + \sum_{n=1}^{\infty} \frac{4V_s}{n\pi} |\sin(n\pi\alpha)| \cos(n\omega_s t + \varphi_n) \tag{4}$$

in which $\omega_s = 2\pi/T_s$ is the switching angular frequency, $\varphi_n = -n\pi\alpha$ is the phase angle of the nth order harmonic. In Eq. (4), the $(2\alpha-1)V_s$ term relates to the power amplifier's desired output tracking its reference input, while the sum term corresponds to high frequency switching harmonics.