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A synchronous sampling-based direct current estimation method for self-sensing active magnetic bearings[*#]

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1 Introduction

The position estimator is a key module of self-sensing active magnetic bearings (AMBs). It can improve system dynamic performance and reduce the axial dimension. Generally, the estimation methods can be divided into two categories: state observer estimation and parameter estimation (Tan et al., 2019; Chen et al., 2020). A self-sensing estimator based on a state observer was first proposed by Vischer (1988). In this, the rotor position was calculated by a linear mathematical model with coil current (Glück et al., 2011). A state feedback controller was presented, and the linear amplifier and inductance transformer were adopted in a self-sensing system (Li et al., 2004). However, the system dynamics and robustness cannot be investigated.

For low stability and high sensitivity, most researchers prefer to perform the parameter estimation methods (Maslen et al., 2006; Park et al., 2008; Ji et al., 2012). First, a high frequency small dither signal is injected into the coil. Then, the rotor position is extracted from inductance characteristics. The methods are limited by the bandwidth of power amplifier (PA) and signal noise ratio (SNR), and with the disadvantage of additional circuits. Currently, AMBs commonly use pulse width modulation (PWM) to reduce hardware and manufacturing cost. By updating the disturbance amplitude and phase, a disturbance suppression method for self-sensing AMB rotor systems was proposed to reduce the self-sensing errors between the real and estimated rotor displacement (Yu and Zhu, 2018). The PWM ripple components are demodulated to estimate the rotor position because the working current and voltage were related to the inductance of the bearing coil (Schammass et al., 2005; Ranft et al., 2011; van Schoor et al., 2013). Amplitude demodulation methods inherently involve the low pass filter (LPF), band pass filter (BPF), and absolute value circuit to isolate the fundamental components of coil current or voltage (Yu and Zhu, 2016). Although system stability was improved, it is difficult to operate well in high-speed industrial application because of the phase shift in the sensing path. To simplify the estimation model, the direct current measurement method based on switching ripples was presented (Niemann et al., 2013; Zhang et al., 2017).

The technical aspects of the above self-sensing schemes are: the finite impulse response (FIR) filters or electronic filters are adopted in the self-sensing path. Since the external phase shift is introduced by these filters and complex estimation algorithms, the system stability margin will be limited. The symmetrical design of the demodulation circuit is the key section. This will take charge of the fundamental current and voltage extraction process concurrently. Consequently, the PWM switch amplifier-based self-sensing schemes have problems of sensing path, sensing accuracy, and working stability.

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In addition, because the switching frequency is generally high, it is difficult to update the rotor position at every switching cycle. Therefore, one suggestion is to reduce switching frequency or to update the position at every several cycles (Chen et al., 2020). It is a challenge for the AMBs to adapt to high-speed rotary machines.

To address the above problems, this paper proposes a synchronous sampling-based direct current estimation (SS-DCE) method. This can not only improve the dynamical performance of self-sensing AMBs, but also can provide technical support for the non-collocation design of magnetic levitation systems.

The theories of AMB reluctance model and SS-DCE method are provided in Data S1, including all governing equations, algorithm principle, derivation procedures, and explanations of variables.

2 Results and discussion

To check the technical advantages of the proposed method, a comparative numerical analysis with the analogue filtering amplitude demodulation method (AFAdM) and the digital filtering amplitude demodulation method (DFAdM) is performed.

The current and voltage signals are digitized via a 100 kHz A/D converter when they are filtered by the analog BPFs. Then, the ideal absolute value functions are implemented to detect the envelope of the current and voltage, and the position information is shifted to low frequencies. LPFs can select only the low frequency baseband signal as the control signal. The BPF constitutes a high-order FIR filter with a pass-band of 400 Hz and center frequency of 2 kHz. The 300th order FIR LPF has a cut-off frequency of 60 Hz, a pass-band of 30 Hz, and a stop-band of 400 Hz. The rotor position can be calculated by the quotient of the max values of the current and voltage, and be compensated by a nonlinearity of a magnetic module.

2.1 Position estimation for static performance

The numerical instances for static performances (position, inductance, linearity, and error) are established, in which the switching frequency and synchronous sampling frequency are 2 kHz, the control frequency is 50 Hz, the sampling frequency of DFAdM is 100 kHz, the bias current is 3 A, the nominal inductance is 13.2 mH, and the system power is 50 V.

The comparative results for position and inductance are shown in Figs. 1 and 2, respectively. The position estimation of SS-DCE can approach the referring position with the nominal inductance. Under open-loop conditions with referring sensor, the desired position is linearly varied from 50 μm to 250 μm. The linearity and error of the position estimation are shown in Figs. 3 and 4, respectively. Meanwhile,

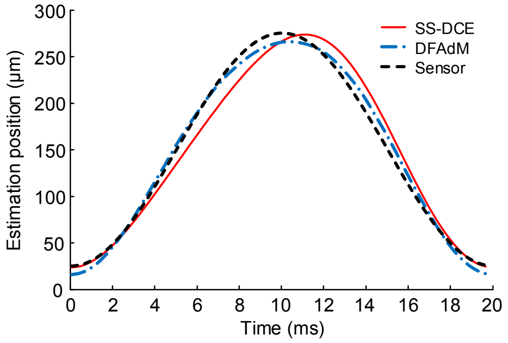

Fig. 1 Position estimation of SS-DCE and DFAdM

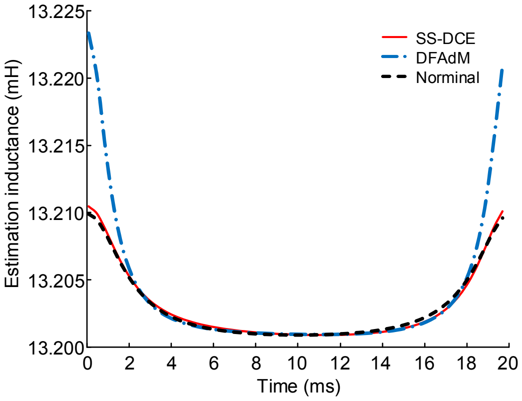

Fig. 2 Inductance estimation of SS-DCE and DFAdM

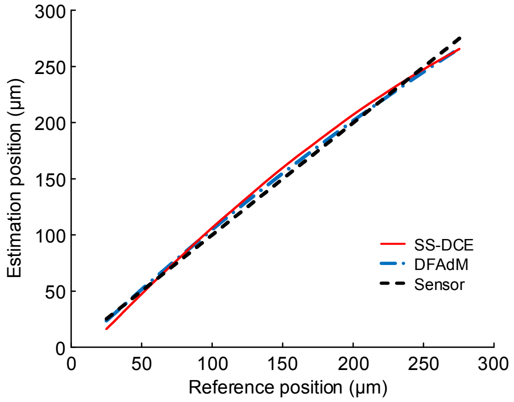

Fig. 3 Position linearity of SS-DCE and DFAdM

the estimation error is a function of two variables: frequency and position. In Fig. 5, the average value of SS-DCE precision ranging from 0.1Hz to 200 Hz reaches about 2%, and improves more one time compared with DFAdM.

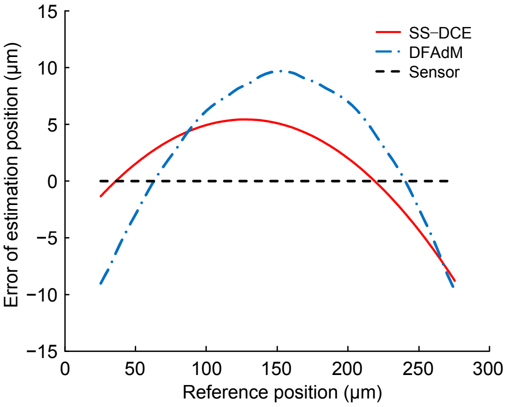

Fig. 4 Position error of SS-DCE and DFAdM

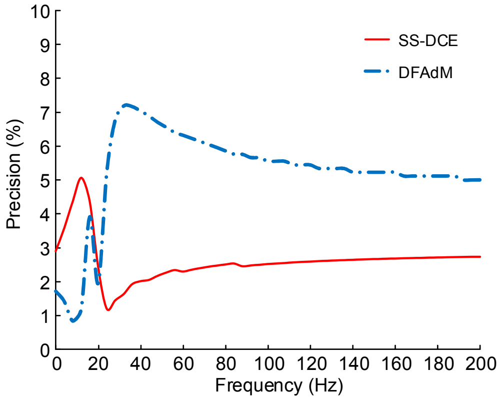

Fig. 5 Estimation precision of SS-DCE and DFAdM

2.2 Position estimation for dynamic performance

The gain and phase response of the self-sensing system is denoted as

$$G(\omega)=20\lg\frac{X_{\text{est}}(\omega)}{X_{\text{sen}}(\omega)}, \tag{21}$$

where $X_{\text{est}}(\omega)$ is the self-sensing output, and $X_{\text{sen}}(\omega)$ is the reference signal. The comparative results for dynamic performance are shown in Fig. 6.

Under the ideal condition, the frequency response is 0 dB, and the phase difference should be zero. The phase shift can be reduced compared with the methods of AFAdM and DFAdM. The phase lag of SS-DCE is around 220 at the eigen frequency of 19.3 Hz, but it has 820 phase margin when the rotor operates at 200 Hz.

Compared with AFAdM and DFAdM, the frequency response of SS-DCE is likely to be the same and the phase is closer to zero in the frequency range of 1–50 Hz. The SS-DCE has the best frequency response. This demonstrates that the AMB has better rising-speed characteristics.

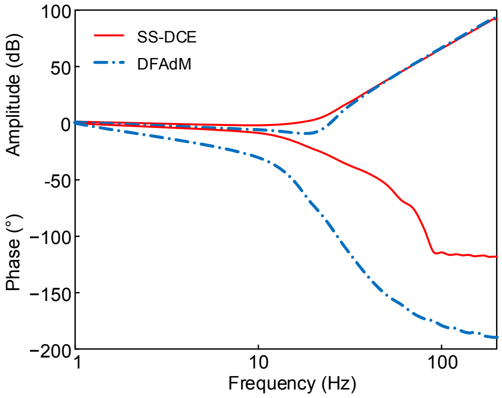

Fig. 6 Comparisons of system gain and phase response

2.3 Experimental results

To verify the effectiveness of the proposed method, a platform for experimental AMB is developed based on the SS-DCE and dual closed-loop control. The experimental platform consists of controller, micro-positioning platform, current sensor, switching Pas, and referring position sensor. The PAs are configured in two-state modes (±50 V) to ensure high frequency ripples, and increase the working stability of self-sensing AMB. The built-in control circuits can provide optimum gate drive and protection for the power devices.

For an air gap of the rotor from 50 to 250 μm, the output comparative experiments with the HZ-891 sensor are conducted, and the linearity results are shown in Fig. 7. The maximum precision of SS-DCE is about 3.64% when the test frequency is 50 Hz. The precision test results (Fig. 8) can prove that SS-DCE has a better estimation precision than DFAdM within 25–200 Hz, which accords with the numerical results.

To check the dynamic performance of the proposed method further, pulse response experiments are performed, in which a force disturbance is lightly applied through a knock on the truss by a rubber hammer. From Fig. 9, we can see that the system retains good stability under force disturbance, and has rapid convergence and acceptable overshoot. When the magnetic levitation rotor runs within the range −250–250 μm, the maximum absolute error of the SS-DCE is less than 20 μm.

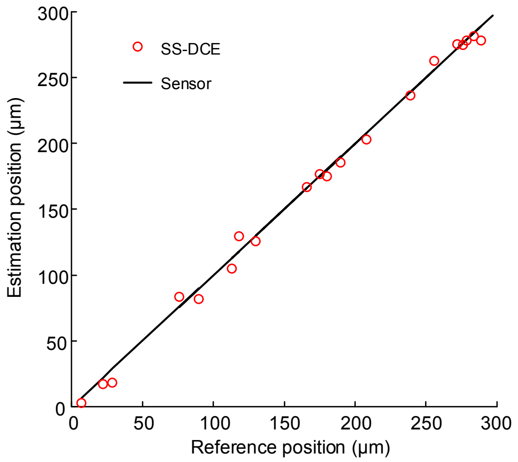

Fig. 7 Linearity test results of SS-DCE

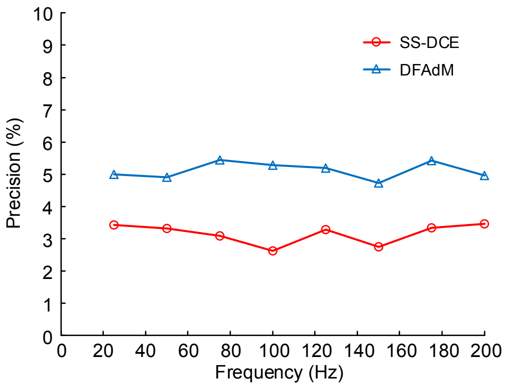

Fig. 8 Precision test results of SS-DCE and DFAdM

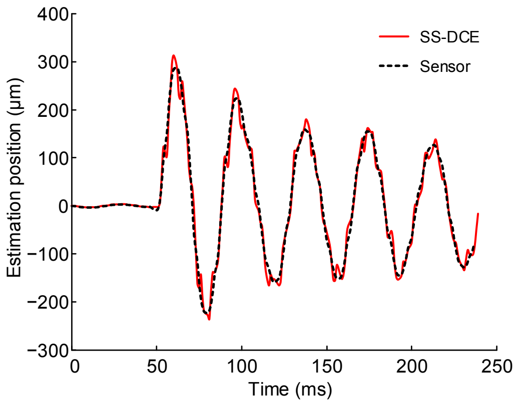

Fig. 9 Pulse response results of SS-DCE

3 Conclusions

Rotor position estimation is a key factor in the working performance of self-sensing AMBs. To resolve the problems of PWM switch amplifier-based self-sensing methods, an SS-DCE method is proposed, and the main conclusions can be drawn as follows.

1. The self-sensing path is determined by filter number, algorithm complexity, and phase lag. The rotor displacement is a nonlinear function about the voltage/current. This can be linearized by the switch amplifier ripples to reduce the self-sensing path.

2. The estimation error is a function of frequency and position. The SS-DCE method can obtain better static performance (position, inductance, linearity, and error).

3. A self-sensing AMB experimental platform is established, and the results prove that the SS-DCE method can restrain the phase shift, with better rising-speed response, rapid convergence, and acceptable overshoot.

Contributors

Xiong-xin HU designed the research. Fang XU processed the corresponding data. Xiong-xin HU wrote the first draft of the manuscript. Da-peng TAN helped to organize the manuscript, and revised the final version.

Conflict of interest

Xiong-xin HU, Fang XU, and Da-peng TAN declare that they have no conflict of interest.

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List of electronic supplementary materials

Data S1 Theory

中文概要

题　目：基于同步离散电流估计的磁轴承自传感方法

目　的：磁轴承自传感是一个关联磁悬浮转子动态特性的机电磁多物理场耦合问题。研究自传感磁轴承（AMBs）机电磁耦合机理与磁阻模型，对于其工作性能提升具有重要意义。当前基于脉宽调制（PWM）开关功放的磁轴承自传感方法，可缩小轴承几何尺寸，提高电气效率和转子动态性能，但存在传感精度不高、路径过长、稳定性较低等问题。针对上述问题，本文旨在提出一种基于PWM 开关频率同步采样的离散电流估计（SS-DCE）方法，以缩短自传感路径，改善传感精度，以及提高磁轴承动态性能与工作稳定性。

方　法：1. 通过分析两个相邻离散电流的数学关系，建立转子位移解析表达式；2. 基于 SS-DCE 方法，结合位置式双闭环控制技术，并借助物理传感器实现对 AMBs 自传感过程的关键参数测试和评估验证。

结　论：1. 磁轴承转子位移是一个关于电压/电流的非线性函数，而利用 PWM 开关功放纹波特性可使其线性化，进而缩短自传感物理路径，提高工作稳定性；2. 自传感路径的长度由滤波器数量和算法复杂度决定，与相位滞后紧密相关；3. 与模拟/数字滤波幅度解调法相比，基于 SS-DCE 的自传感方法的静态精度更高，稳定裕度更大，且具有较好的升速过程频率特性。

关键词：自传感磁轴承（AMBs）；回路磁阻；同步采样（SS）；离散电流估计（DCE）；双闭环控制