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Enhanced position estimation in self-sensing magnetic bearings using separate sensing and control functions

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Abstract

This paper presents a novel approach to enhance position estimation in self-sensing magnetic bearings (MBs) by employing separate windings for sensing and control functions. Traditional self-sensing MB systems utilize a single winding for both actuation and sensing, which leads to increased noise and estimation inaccuracies due to signal interference and mutual inductance effects. To address these challenges, a one-degree-of-freedom MB system was developed featuring dedicated bias windings for sensing and control windings for levitation actuation. Bipolar pulse-width modulation (PWM) was applied to the bias windings to amplify current slope measurements, while unipolar PWM and PI current control were used for the control windings to minimize current ripple. Experimental validation was performed using a DSP TMS320F28379D and commercial AEC PU-09 gap sensor as a reference. Results demonstrate that the proposed system achieves a 6.8-fold increase in average current slope and a 37% reduction in current slope noise compared to conventional single-winding designs. The gap estimation noise for the separate winding configuration is only 1.66 times higher than the commercial gap sensor, with levitation performance comparable to sensor-based feedback systems. The system bandwidth reaches 20 Hz, compared to the 15 Hz bandwidth of sensor-based feedback systems. These improvements confirm that separating sensing and control functions significantly enhances self-sensing accuracy in MBs, paving the way for cost-effective and reliable MB applications without external sensors.

Keywords : Self-sensing magnetic bearing, Position estimation, Separate winding, Noise reduction, Current slope

1. Introduction

Self-sensing is a signal-processing technique that estimates the position of a levitated object in a magnetic bearing (MB) using current signals (Schweitzer and Maslen, 2009). By eliminating the need for dedicated position sensors, self-sensing significantly reduces the cost and complexity of MB systems.

Conventional self-sensing MBs with a single winding - where the same winding is used for both actuation and sensing - suffer from noise and interference. Research has focused on improving estimation accuracy by addressing challenges such as noise, nonlinearity, and sensitivity to operating conditions through advanced signal processing, winding configurations, and control strategies (Kucera, 1997). Although a self-sensing MB with separate bias and control coils was proposed based on the principle of a differential transformer-type displacement sensor (Matsuda and Tani, 1997), the control winding was still used for both actuation and sensing.

This study presents enhanced position estimation in self-sensing MBs using separate sensing and control functions. In the proposed configuration, the bias winding is used exclusively for sensing, while the control winding is dedicated to levitation control. This physical and functional separation mitigates the noise in position estimation observed in conventional self-sensing MBs, thereby significantly enhancing self-sensing accuracy (Wang and Binder, 2016).

2. Separate-winding MB system

2.1 Operating principle and system configuration

Figure 1 illustrates the operating principle behind the separation of sensing and control functions in the proposed self-sensing magnetic bearings (MBs). Each electromagnet consists of two windings: a bias winding for position sensing and a control winding for levitation actuation. A bipolar pulse-width modulation (PWM) signal drives each bias winding in open-loop, amplifying the current slope to improve the accuracy of position estimation. The current slope di/dt is calculated using linear regression over multiple current measurements. This slope is determined from the relationship between the current samples and time, as given by

$$\frac{di}{dt}=\frac{1}{N}\sum_{k=1}^{N}\frac{i_k-i_{k-1}}{t_k-t_{k-1}} \tag{1}$$

Where i_k represents the current at time t_k and N is the total number of current samples. This calculation allows for precise estimation of the current slope, which is inversely proportional to the air gap x, as the inductance of the bias winding increases with decreasing gap size.

The control windings were connected in series with opposite polarity and driven with a unipolar PWM and PI current control to minimize the current ripple. The air gap x is then estimated using a calibrated inverse mapping:

$$x=\frac{K}{di/dt} \tag{2}$$

Where di/dt is the average current slope calculated via linear regression over a measurement window, and K is a calibration constant derived from reference measurements

A one-degree-of-freedom (1-DOF) MB system featuring separate bias and control windings was built, as shown in Fig. 2. A commercial AEC PU-09 gap sensor was used as a reference. The system was controlled using a DSP TMS320F28379D with two three-phase drivers (BOOSTXL-DRV8323RS) from Texas Instruments. The system operates with a ±24 V DC power supply, and the PWM switching frequency for both bipolar and unipolar excitation is set to 10 kHz. During testing, the air gap between the rotor and electromagnets is maintained within ±0.5 mm.

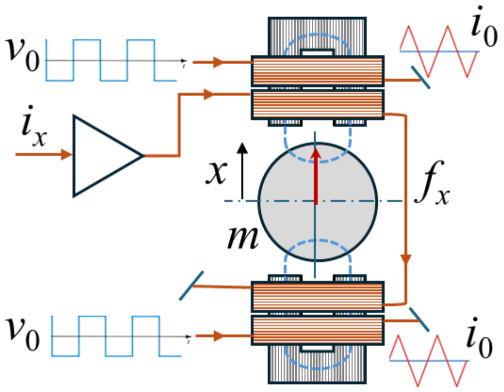

Fig. 1 The proposed self-sensing MB

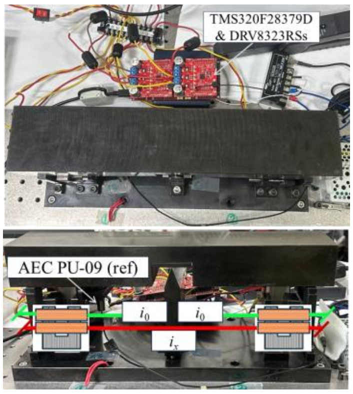

Fig. 2 Experiment setup

2.2 Architectural distinction from previous dual-winding MBs

The primary distinction between the proposed system and previous configurations lies in the complete functional separation of sensing and control operations. While (Matsuda and Tani, 1997) proposed separate bias and control coils based on differential transformer principles, their control winding was still used for both actuation and sensing, introducing signal contamination and mutual interference.

In contrast, the present work dedicates the bias winding exclusively to position sensing and the control winding solely to levitation force generation. This enables independent optimization of each function: bipolar PWM excitation for the bias winding amplifies current slope measurements, while unipolar PWM and PI current control for the control

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winding minimizes current ripple. The complete decoupling eliminates cross-talk between functions, significantly reducing estimation noise compared to previous approaches where both functions competed for the same resources.

2.3 System characteristics and parameter comparison

During levitation with sensor feedback, sensitivity of MBs with the single and separate windings are experimentally measured and compared in Fig. 3. Serial connection of bias and control windings (36 and 64 turns) is converted into single winding equivalent. Control gains for MBs with the single and separate windings are shown in Table 1. Twice control gains and 2.83 times bias current are necessary to have the same characteristics with single winding MB. Higher current control gain for separate winding MB is required due to mutual inductance effects between the physically separated windings.

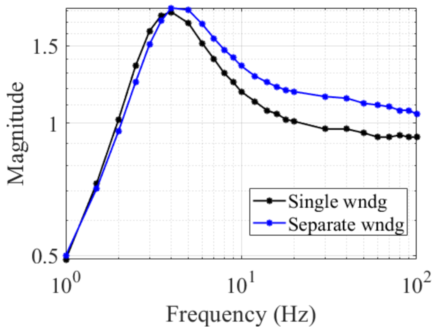


Fig. 3 Sensitivity functions of MBs

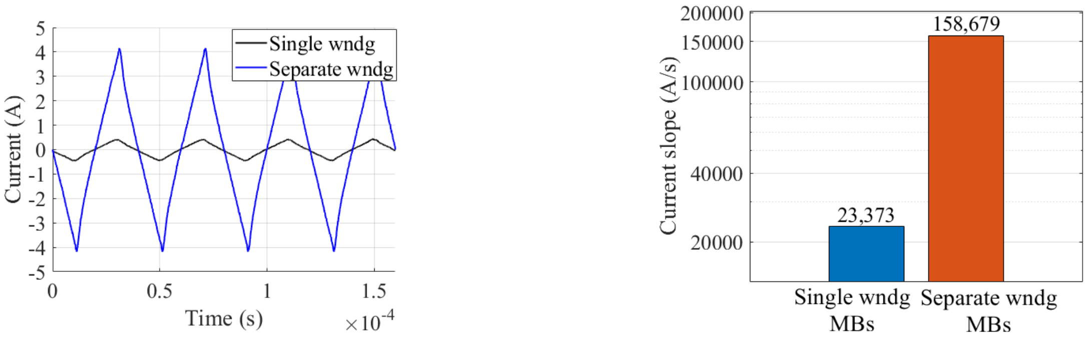
Table 1. Parameters

Item.		Single wndg	Separate wndg
PID	K_p	2	4
	K_i	2	4
	K_d	0.9	0.18
Bias	I_b	1A	2.83A

3. Experimental results and discussion

3.1 Current slope and noise characteristics

The current slope and noise characteristics of single and separate winding MBs are measured and compared, as shown in Fig. 4. In Fig. 4(a), the bias current of the separate winding MB exhibits larger and sharper variations under bipolar excitation, resulting in a significantly increased current slope. As depicted in Fig. 4(b), the average current slope increases by 6.8 times, from 23.4 kA/s to 159 kA/s. Simultaneously, the current slope noise decreased by 37%, from 1705 to 1076 A/s, which corresponds to 327 and 12.5 µm in gap estimation, respectively, as shown in Fig. 5. The gap estimation noise of the separate winding is only 1.66 times higher than that of the commercial gap sensor, indicating a substantial improvement over conventional self-sensing approaches.



(a) Bias current
(b) Current slope

Fig. 4 Bias current and current slope of the single and separate winding MBs

The significant improvement in current slope magnitude results from the dedicated bias winding being specifically optimized for sensing through bipolar PWM excitation. This excitation allows for larger current variations, enhancing the sensitivity of slope detection. The reduction in noise is attributed to the minimal influence of the control winding's switching activity on the sensing signal, due to the complete physical and functional separation of sensing and actuation.

The effect of control coil current on the estimated gap is shown in Fig. 6. Variations in the estimated gap occur as the control coil current is adjusted, even when the position is fixed. These fluctuations, caused by mutual inductance

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between the coils, can be compensated, ensuring accurate gap estimation. The correction algorithm accounts for the control coil's influence, stabilizing the gap measurement despite control current fluctuations.

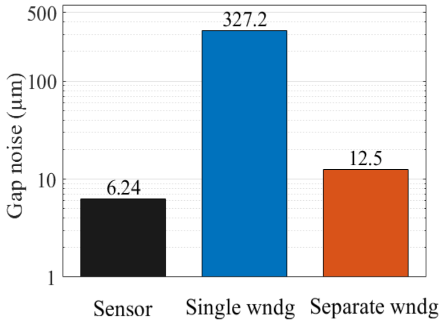


Fig. 5 Gap estimation noise

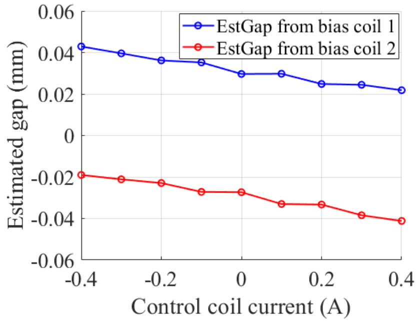
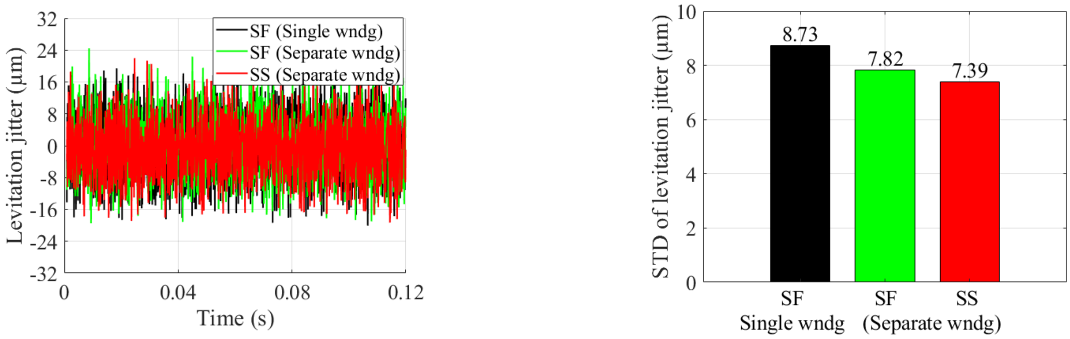


Fig. 6 Effect of control coil current on estimated gap

3.2 Levitation characteristics using self-sensing signals

To verify the self-sensing performance, levitation jitters and their standard deviation are compared with sensor feedback (SF) system as shown in Fig. 7. The proposed self-sensing MB demonstrates comparable performance without additional filtering, indicating sufficient position estimation accuracy for stable levitation control.

The system achieves stable levitation performance under various operating conditions with minimal drift, demonstrating reliability across different bias current levels and control gains. The levitation noise under self-sensing control is only marginally higher than the sensor-feedback system, confirming that separate windings provide sufficient accuracy for practical applications while eliminating sensor-related failure modes.



(a) Levitation jitter (b) Levitation noise

Fig 7. Levitation jitter and levitation noise of conventional and proposed MBs.

3.3 Bandwidth analysis of self-sensing measurement

The bandwidth of the self-sensing position estimation has not been directly measured in this study. However, system bandwidth under self-sensing control was evaluated via sensitivity function analysis (Fig. 3). The gain peak remains below 3, satisfying the ISO 14839-3 stability criterion (ISO, 2006), and confirming stable closed-loop operation.

Future work will focus on characterizing the frequency response of the estimation signal to determine its effective measurement bandwidth.

4. Conclusion

This study presents a novel self-sensing magnetic bearing system that employs separate bias and control windings to enhance position estimation accuracy. By dedicating the bias winding exclusively to sensing and the control winding solely to levitation control, the proposed approach eliminates signal interference and mutual inductance effects that plague conventional single-winding designs.

Experimental validation demonstrates significant performance improvements: a 6.8-fold increase in average current slope (from 23.4 to 159 kA/s), a 37% reduction in current slope noise, and gap estimation noise only 1.66 times higher than commercial gap sensors. The system achieves stable levitation performance comparable to sensor-based feedback systems.

The complete functional separation of sensing and control operations represents a promising advancement in self-sensing magnetic bearing technology, enabling cost-effective operation without external sensors. While bandwidth characteristics remain to be quantified in future work, current results clearly demonstrate substantial improvements in noise reduction and closed-loop stability under self-sensing control.

Acknowledgement

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