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Trade-off between resolution and response time of frequency-modulated (FM) eddy-current displacement sensor for active magnetic bearing (AMB)

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KEYWORDS: Active magnetic bearing, Eddy-current sensor, Response time, Resolution

Active magnetic bearing (AMB) system is increasingly used in high-speed rotating machinery applications due to its high rotating speed, high efficiency, and energy savings over conventional bearings. Since AMB systems are open-loop unstable, they require displacement sensors to provide real-time position feedback of the suspended object and the displacement sensors' performance directly affects the AMBs' performance. Eddy-current displacement sensors are widely used for position feedback in the AMB system due to their simple structure, high sensitivity, and low cost. Although ordinary eddy current displacement sensors detect amplitude changes in oscillation circuits (AM sensors), a frequency modulation (FM) eddy-current sensor is occasionally used to improve the noise susceptibility. This paper presents trade-off between resolution and response time of frequency-modulated (FM) eddy current displacement sensor for active magnetic bearing (AMB). First, a one DOF AMB system with FM eddy-current displacement sensor is built. Then, a prescale combination based on an external counter chip and an internal prescale of a DSP (TMS320F28069M) is implemented to adjust the resolution and response time of the FM eddy-current displacement sensor. Finally, both static and dynamic performance are measured experimentally to evaluate the trade-off between resolution and response time of the system.

NOMENCLATURE

AMB = Active magnetic bearing
AM = amplitude modulation
FM = Frequency modulation
DSP = Digital signal processing
IC = Integrated Circuit

1. Introduction

Active magnetic bearing used position feedback from displacement to levitate the rotor.[1-5] Due to noncontact, the AMB system has an advantage in energy efficiency and reduces maintenance costs of high-speed motors. The AMB system is an essential component for high-speed and high-efficiency rotating machines, wind turbines, flywheels, and compressors[6-8].

The controller in the AMB system requires a displacement sensor for position feedback, then converted the feedback into current control signal. The current feedback is also implemented in the AMB system to adjust the current error[9]. The displacement sensor can be considered a compulsive component in any AMB system. Several types of displacement sensors have been applied to the AMB system. However, they can be divided into four types: laser, inductive, capacitive, and eddy current displacement sensor[10-11].

In real-time application, the sensor's static and dynamic characteristics are essential to evaluate the system's effectiveness. The static characteristics are the response parameters of the sensors for slowly varying inputs and steady error, while the dynamic characteristics are the performance parameters for the rapid change in the input signal[12-13].

This paper presents a trade-off between resolution and response time of a frequency-modulated (FM) eddy current displacement sensor for active magnetic bearing (AMB). First, a one DOF AMB system with FM eddy-current displacement sensor is built. Then, a prescale combination based on an external counter IC, and an internal prescale of a DSP (TMS320F28069M) is implemented to adjust the resolution and response time of the FM eddy-current displacement sensor. Finally, both static and dynamic performance are measured experimentally to evaluate the system's trade-off between resolution and response time.

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2. Eddy-current displacement sensor for AMB system

2.1 Working principle

The eddy current sensor works on the inductive eddy-current principle[14], as shown in Fig. 1. When a metallic target is near the sensor head, this magnetic field will cut the target surface and produces an eddy current. An alternative magnetic generated by this eddy current will affect the coil's magnetic field and change the coil's impedance. By measuring these changes, we can determine the displacement between the sensor and the target.

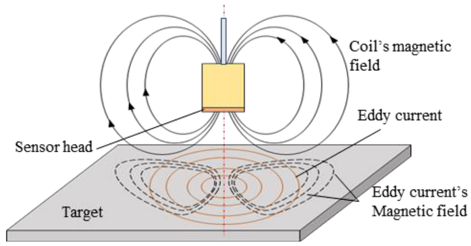

Fig. 1 Principle of eddy current sensor

The eddy current sensor can be divided into three types based on the modulation methods: amplitude modulation, frequency modulation, and phase detection[14]. The frequency modulation eddy current displacement sensor has the advantage of better noise immunity than the amplitude modulation and phase detection displacement sensor[15]. For this reason, we implement an FM eddy current sensor for the AMB system. The detail of this FM eddy current sensor can be referenced as shown in the Table. 1.

Table. 1 Properties of FM eddy current sensor

Parameters	Value
Outer / Inner diameter (mm)	14 / 8 mm
Number of turns	57.5 turns
Resonant frequency	930 kHz
Measurement range	0.25 – 4.00 mm

2.2 Prescale combination for eddy-current displacement sensor

In the AMB system, we implement a commercial DSP from Texas Instrument TMS320F28069M. The DSP supports an enhanced capture module which can be used to detect the timestamps between two rising/falling edges of the input pulse signal.

The FM eddy current sensor signal is about 1.1 MHz to 1.7 MHz and the sampling rate for position feedback exceeds 1 MHz. Even with the internal prescale (up to 62) of the DSP, the sampling rate is still over several ten thousand kHz. Therefore, an external prescale or a counter IC 74HC93 is introduced to decrease the sampling rate.

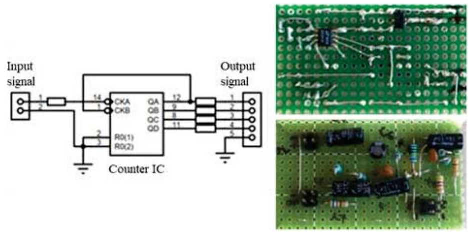

Fig. 2 Principle and circuit of external prescale

3. Static and dynamics analysis of AMB system

3.1 Experiment setup

The experiment setup consists of an AMB system with two electromagnets a balance beam, a pivot, a commercial DSP TMS320F28069M, an FM eddy current sensor, and a commercial AM displacement sensor (AEC-7609/PU09) for reference, as shown in Fig. 3. The specifications of the AM displacement sensor (sensor head PU-09 and a converter AEC-7609) are summarized in Table. 2.

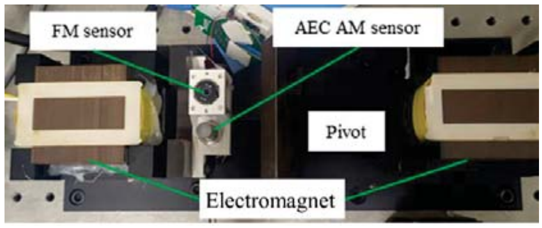

Fig. 3 AMB system

Table. 2 Properties of AEC-7609/PU09 displacement sensor.

Parameters	Value
Sensor/Converter	PU09 / AEC-7609
Sensor diameter	9 mm
Dead zone	0.2 mm
Measurement range	0 – 4.00 mm

3.2 Resolution

First, we measure the frequency and voltage (amplitude) variation of both the FM eddy current sensor and AM sensor. The displacement between each sensor and the target is adjusted, starting from 0.25mm to 4.00mm, with a changing step of 0.5mm.

Fig. 4 shows the sensor calibration results of the FM eddy current and AM displacement sensor. In the operating range, the frequency variation of the FM sensor is from 1.5 MHz to 1.7 MHz, while the voltage variation of the AM sensor is from 1.2 to 2.5 V.

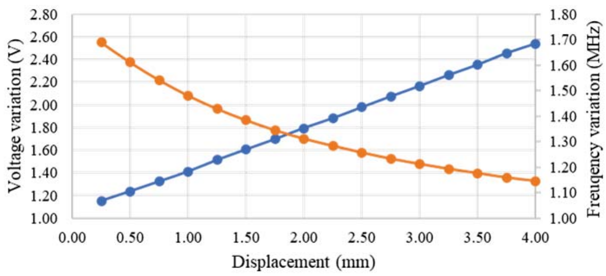

Fig. 4 Sensor calibration (Orange: FM, Blue: AM)

The resolution (static noise) of the FM eddy current sensor was

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also measured with the different sampling rates and compared to the static noise of the AM sensor at the sampling rate of 10 kHz, as shown in Fig. 5. The static noise of the FM sensor is much lower than that of the AM sensor. The static noise of the FM sensor is one tenth (9.55%) of the AM sensor at 10kHz sampling time.

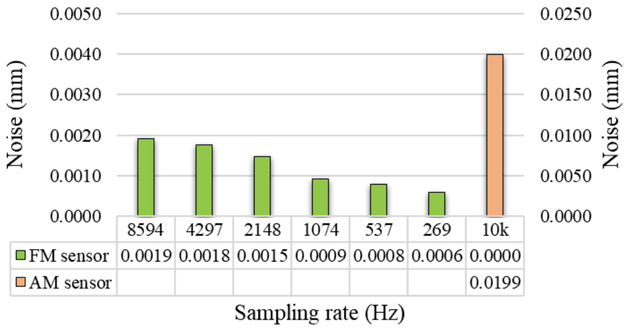

Fig. 5 Static noise (Resolution)

The levitation jitter of the FM eddy current sensor at a sampling rate of 8594Hz and 269 Hz also equal only 8.43% and 3.37% compared with that of the AM sensor at 10 kHz, as shown in Fig. 6.

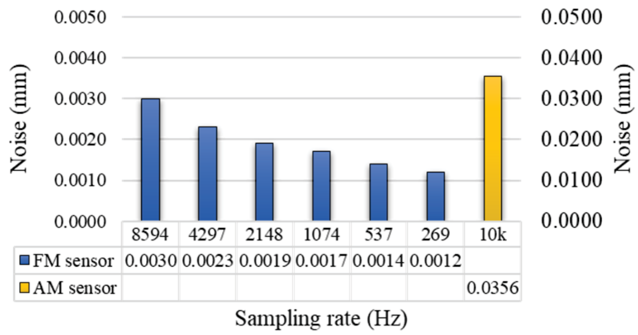

Fig. 6 Levitation jitter

3.3 Response time

The closed loop sensitivity functions of the one-DOF AMB system with the FM sensors are measured and compared with that with AM sensor, as shown in Fig. 7. The higher prescaler of the FM sensor sampling rate, the higher the FM sensitivity function's peak. In the range of sampling rate from 537 Hz to 8594 Hz, the peak of sensitivity functions is under 3 and in the stable zone, while the that at sampling rate 269 Hz is slightly over 5 and still in the acceptable zone.

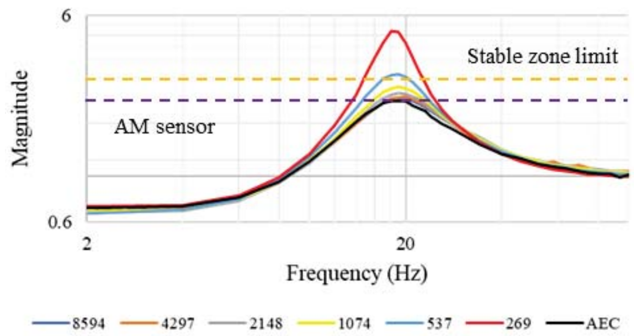

Fig. 7 Sensitivity function of one-DOF AMB system with AM (black) and FM sensors of different prescles

4. Conclusion

This paper presents a trade-off between resolution and response time of frequency-modulated (FM) eddy-current displacement sensors for active magnetic bearing (AMB). The resolution and response time of the FM eddy-current are measured experimentally and compared with a commercial AM displacement sensor. Due to the direct digital interface, the FM eddy-current gap sensor shows much higher static performance than AM gap sensor. In the stable zone, the static noise and levitation jitter of the FM sensor are lower than those of the AM sensor by up to 25.4 and 29.7 times, respectively. Moreover, the static and dynamic performances of the FM gap sensor can be balanced by adjusting the prescaler.

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