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Diagnosis of Lamination Short-Circuit Faults in a Magnetic Bearing via High-Frequency Inductance

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1. Introduction

Electrically excited radial magnetic bearings (MBs) are a category of active MBs, which the rotor is typically constructed by multiple layers of electrical steel sheets. Due to the small air gap in MBs, their performance is highly sensitive to manufacturing tolerances of the rotor [1]. Therefore, the rotor surface of MBs must be precisely machined to meet accuracy requirements. However, improper operations will damage the insulation of the iron core, leading to localized lamination short-circuit faults (LSCFs) on the rotor surface, which ultimately results in excessive losses in the bearing rotor [2]. To address this issue, researchers have proposed methods such as core loss test [3] and electromagnetic core imperfection detector [4] to identify this fault. However, both methods require winding a certain number of excitation coils around the core, making them unsuitable for the unique structure of MBs. In this paper, a high-frequency inductance-based diagnosis method is proposed. The effectiveness of the method is experimentally validated using typical samples.

2. Effect of LSCFs on rotor surface

The stator of an electrically excited radial MB is designed with slots and teeth. During operation, the air-gap flux density contains significant harmonics. When observing a specific point on the rotating rotor surface as a reference coordinate, the magnetic flux density at that point is not constant but varies periodically with the rotation of the rotor.

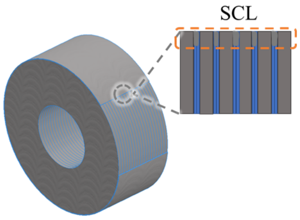

Fig.1 LSCFs on the rotor surface.

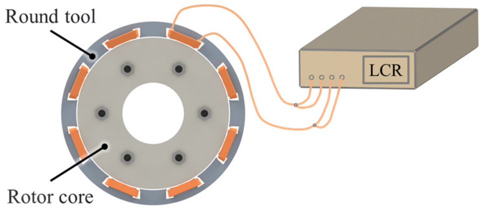

Fig.2 Proposed diagnostic device.

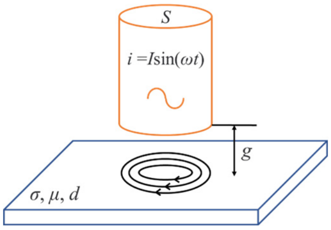

Fig.3 Working principle of the device.

If the rotor core surface experiences LSCFs due to improper machining methods, as illustrated in Fig. 1, the resulting magnetic field variations will induce eddy current losses and hysteresis losses on the rotor surface. These losses are confined to an extremely thin layer of the rotor surface and are therefore commonly referred to as surface losses. Based on our previous research [5], the surface losses of the MB rotor can be expressed as

$$P_{\text{surface}} = \sum_{v=1}^{\infty}(1-e^{-2d/\Delta_v})\sqrt{\frac{\sigma}{\pi\mu}}(B_v\tau_v)^2 f_v^{1.5} A \tag{1}$$

where B_v, τ_v, f_v and Δ_v represent the amplitude, pole pairs, frequency, and penetration depth of the vth order magnetic field, respectively, while A denotes the surface area of the rotor. Additionally, σ, μ, and d correspond to the conductivity, permeability, and thickness of the short-circuit layer (SCL), respectively. Different machining methods produce varying levels of burrs, leading to differing degrees of LSCFs. The primary focus of this study is to develop a straightforward method for the rapid diagnosis of the severity of LSCFs on the surface of MB rotors.

3. Diagnostic device and its principle

The proposed diagnostic device is illustrated in Fig. 2. The device features a round tool resembling the stator of a MB, with multiple slots uniformly distributed along the circumference of the stator and wound with coils. During measurement, the rotor passes through the inner circumference of the stator, and inductance testing is conducted using an LCR meter. The excitation source of the LCR meter can be regarded as an adjustable-frequency AC voltage source.

The working principle is shown in Fig. 3. During operation, the diagnostic device employs an LCR meter to supply a high-frequency current signal to the coil, generating an alternating magnetic field. The SCL on the surface of the iron core, under the influence of electromagnetic induction, produces an eddy current field. This field, in turn, generates an alternating magnetic field that opposes the magnetic field created by the coil. Consequently, the amplitude and phase of the current in the coil are affected by this opposing field, leading to a change in the coil's impedance. The extent of the impedance change is related to the intensity of the induced current. Within the system, the primary variables include the facing area S between the device and the iron core, the air gap g, the amplitude I and frequency ω of the high-frequency current, as well as the σ, μ, and d. The impedance of the coil can be expressed as a function of these variables:

$$Z = f(S, g, I, \omega, \sigma, \mu, d) \tag{2}$$

Variations in the coil impedance reflect the impact of different machining processes on the severity of surface LSCFs on the rotor. When the resistance of the eddy current path increases, the equivalent inductance of the coil also increases. Since the resistance of the eddy current path is closely related to the degree of LSCFs, detecting the equivalent inductance of the coil enables the assessment of the insulation condition on the surface of the radial MB rotor.

4. Experimental verification

We fabricate three typical rotor core samples in order to validate the effectiveness of the proposed device. The severity of LSCFs in these samples follows the order: light-feed turning < heavy-feed turning < grinding. The experimental test setup is demonstrated in Fig. 3. Multi-layer 6650 insulating paper is used to separate the rotor core from the diagnostic device in four directions, ensuring a uniform air gap.

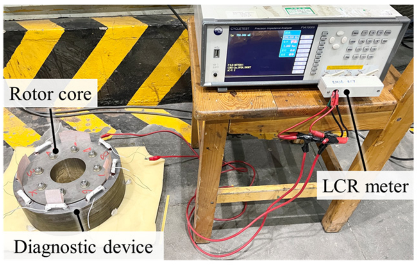

Fig.3 Test platform.

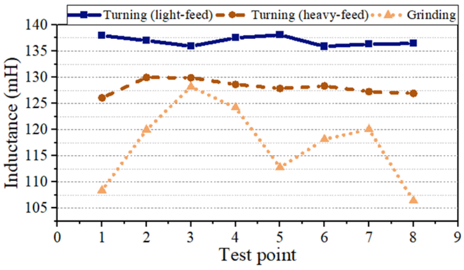

Fig.4 Test results.

Finally, the high-frequency inductance at 10 kHz is selected as the criterion for determining the qualification of the rotor core in radial MBs. The rotor processed with light-feed turning, regarded as the standard rotor produced by a qualified machining method, serves as the reference, and its high-frequency inductance is used as the baseline value. Further measurements of the 10 kHz inductance are conducted at multiple circumferential points on the three typical samples, with the results shown in Fig. 4. The proposed device effectively identified the rotors processed by the other two machining methods as unqualified. The 10 kHz inductance of the rotor which was machined by grinding method is significantly lower than that of the other two rotors, and the non-uniformity of LSCF distribution could also be measured.

5. Conclusion

The diagnostic device and method proposed in this study enable the evaluation of the surface insulation condition of the rotor core in radial MBs by measuring high-frequency inductance. Compared to existing methods, the proposed device offers advantages such as a simple structure and a streamlined testing process. As a result, it is particularly well-suited for the diagnosis of LSCFs during the mass production of radial MBs.

References

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