Structural analysis and design of radial magnetic bearing rotor considering skin effect

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Abstract
This paper investigates the structural design of solid rotors, which are commonly used in small-sized radial magnetic bearings, focusing on the eddy current-induced skin effect as a means for optimization. Unlike laminated silicon steel rotors where eddy currents are suppressed, the performance of solid rotors is significantly influenced by this effect, rendering this study particularly relevant. The primary objective is to reduce the rotor's volume and weight for high-speed applications without significantly compromising its load-bearing capacity. The methodology integrates theoretical analysis, Finite Element Method (FEM) simulations, and experimental validation. A custom test platform was built to measure the dynamic electromagnetic force on various rotor specimens. The simulation and experimental results consistently demonstrate that for a solid rotor, the electromagnetic force decays as speed increases due to the skin effect, which concentrates the magnetic flux near the rotor surface. A key finding from the experiments is that at a high speed of 12000 rpm, a thin-walled solid rotor exhibits a load capacity nearly identical to that of a much thicker one. This result provides strong evidence that the inner material of a solid rotor becomes less effective for force generation at high speeds. In conclusion, this study validates the feasibility of designing thinner, lighter solid rotors for high-speed magnetic bearings by leveraging the skin effect, offering a practical approach to developing more compact and efficient small-sized rotating machinery supported by magnetic bearings.

Keywords : Radial Magnetic Bearing, Solid Rotor, Rotor Design, Skin Effect, Eddy Current, High-Speed Machinery, Finite Element Method (FEM), Lightweight Design

1. Introduction

Magnetic bearings are typically employed in rotating machinery operating at ultra-high speeds to eliminate the friction between the shaft and the bearings. They exhibit robust performance in extreme environmental conditions, including vacuum environments, wide temperature ranges (Schweitzer, 2002), and corrosive environments with varying pH levels (Du et al., 2025). Unlike conventional bearings, magnetic bearings do not necessitate the use of lubricating oil, rendering them exceptionally clean and environmentally friendly, with significantly reduced maintenance costs. Common applications can be found in various types of rotating machinery, such as high-speed motors, clinical blood pumps (Hoshi et al., 2006), vacuum turbo-molecular pumps, and flywheel energy storage systems (Li and Palazzolo, 2022).

Despite these advantages, a significant challenge in the design of magnetic bearings is their size. The volume of magnetic bearings is a main optimization objective in many studies. An obvious disadvantage of magnetic bearings over conventional bearings is that they take up more volume, and the rotor of a magnetic bearing is also significantly larger than that of a conventional mechanical bearing. Since maintaining a certain load capacity requires a sufficient amount of magnetic flux and thus a large number of coil turns, reducing the stator size is difficult. Therefore, this paper focused on the rotor design and tries to reduce the volume of the rotor, especially in small size magnetic bearings with solid rotors.

In recent years, several studies have explored the impact of eddy currents on the electromagnetic performance of magnetic bearings. Kim et al. (1995) used a finite element method coupled with a flexible rotor model to quantify how eddy currents degrade system stiffness and stability, especially under high-frequency excitation, where magnetic flux tends to concentrate near the rotor surface. Sun and Yu (2002) developed analytical techniques to estimate eddy current losses in both laminated and solid rotors, demonstrating a direct correlation between increased speed and flux density with higher energy dissipation. More recently, Chittlangia et al. (2018) suggested that using electrically conductive coatings or minimizing rotor thickness can effectively reduce eddy current losses, providing design guidance for compact systems. These findings form the theoretical and simulation basis for the rotor skin effect proposed in this paper.

During FEM simulation, a phenomenon was discovered where large enough eddy currents cause the magnetic inductance to concentrate on the surface of the rotor, suggesting the interior of the rotor is no longer necessary. This implies that the thickness of the rotor can be reduced appropriately without a significant loss of bearing load capacity. This phenomenon is similar to the skin effect in round conductors and is referred to as the rotor skin effect in this paper.

This paper begins with an analysis of the mechanism of the skin effect, presents theoretical calculations and simulation analysis, and finally conducts experimental verification to validate the concept.

2. Nomenclature

The main symbols used throughout this paper are defined in Table 1.

Table 1 Nomenclature.

Symbol	Definition	Unit
t	Width of the magnetic poles	mm
c_1	Thickness of the rotor sleeve	mm
c_2	Thickness of the yoke	mm
D_0	Inner diameter of the rotor	mm
D_1	Outer diameter of the rotor	mm
B	Magnetic flux density	T
E	Electric field intensity	V/m
F_m	Electromagnetic force	N
J	Eddy current density	A/m^2
n	Rotational speed	rpm
σ	Electrical conductivity	S/m

3. Mechanism and Theoretical Analysis

To accommodate the diverse requirements of different applications, which may entail varying demands for rotor diameter, load capacity, and maximum rotational speed, magnetic bearings are typically custom designed for each specific demand (Mancuzo et al., 2023). In a conventional structural design scenario, the power requirements of the rotating machinery dictate the motor design. To suit the motor design, the motor’s spindle diameter is usually chosen as the outer diameter of the magnetic bearing rotor. The determination of the levitation gap, based on empirical knowledge and load capacity requirements, subsequently determines the inner diameter of the magnetic bearing stator. Next, the number of poles is chosen, followed by the determination of pole width.

Figure 1 shows the topology of a classic eight-pole radial magnetic bearing. Its main mechanical structure consists of a stator fixed on a housing, a rotor fixed on a shaft, and coils on the magnetic poles of the stator. The rotor is magnetically conductive and provides the electromagnetic force required for levitation. To optimize the utilization of material magnetization intensity, the thickness of the rotor sleeve (c_1) and the yoke (c_2) is typically equaled to the width of the magnetic poles (t) (Lijesh and Hirani, 2015). The rotor’s outer diameter (D_1) is geometrically determined by its inner diameter (D_0) and the sleeve thickness (c_1).

Magnetic bearings are usually used in ultra-high speed rotating machinery where the magnetic field generated by the stator is fixed while the rotor rotates rapidly. From the rotor’s frame of reference, it experiences a high-frequency alternating magnetic field, which induces eddy currents within the conductive rotor material according to Faraday’s law of induction.

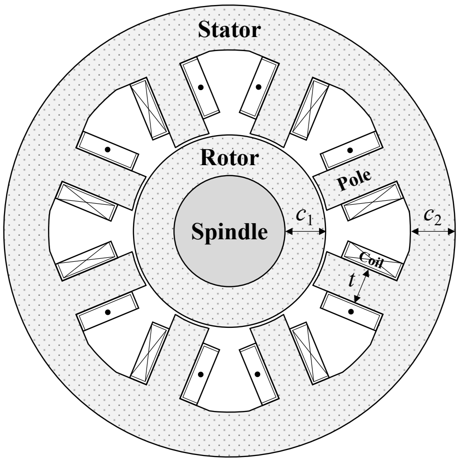

Fig. 1 Topology of a classic eight-pole radial magnetic bearing. The diagram illustrates the main structural components and defines the key geometric parameters discussed in this study: the rotor sleeve thickness (c_1), the stator yoke thickness (c_2), and the magnetic pole width (t).

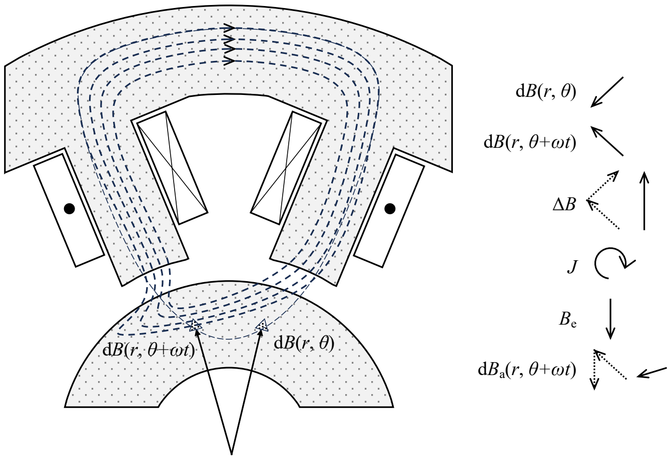

Fig. 2 Mechanism of the time-varying magnetic field experienced by a point on the rotating rotor. As the rotor turns, a single point on its surface at an initial position (r, θ) moves through the stationary magnetic flux from the stator poles. This results in the point experiencing a local magnetic field that changes over time (from $B(r, \theta)$ to $B(r, \theta+\omega t)$), which is the fundamental source of induced eddy currents.

This process is illustrated in Fig. 2. The figure shows that a point on the rotor at coordinates (r, θ) experiences a magnetic field $B(r, \theta)$. As the rotor rotates with an angular velocity ω, after a time t, this point moves to a new angular position and experiences a different magnetic field, $B(r, \theta+\omega t)$. For any given point on the rotor, this continuous change in the local magnetic field over time, $\partial B/\partial t$, induces an electromotive force and subsequently drives eddy currents within the conductive rotor material.

The generation of these eddy currents is governed by Faraday's law of induction. The direction of the currents, according to Lenz's law, creates a secondary magnetic field that opposes the original field from the stator. This interaction forces the resultant magnetic flux to concentrate near the surface of the rotor, a phenomenon analogous to the skin effect in AC-powered round conductors. Consequently, this phenomenon is also referred to as the rotor skin effect in this paper.

This can be described more formally by Maxwell's equations. The time-varying magnetic field (B) experienced by the rotor induces a spatially varying electric field (E) as described by Faraday's law of induction:

$$\nabla \times \mathrm{E} = -\,\partial B \,/\, \partial t \tag{1}$$

This induced electric field drives eddy currents (J) within the conductive material of the rotor, with the current density being proportional to the material's electrical conductivity (σ) and the electric field strength, following Ohm's law:

$$J = \sigma\, E \tag{2}$$

In turn, these eddy currents generate their own magnetic field, which interacts with the original field, leading to the redistribution of magnetic flux. This interaction ultimately causes the magnetic flux lines to bend in the direction of rotation, as depicted in Fig. 2. The depth to which the magnetic field penetrates the rotor is known as the skin depth, which is inversely related to the frequency of the magnetic field variation (i.e., the rotational speed), the material's conductivity, and its magnetic permeability. At very high speeds, the skin depth becomes very small, and most of the magnetic flux is confined to a thin layer on the rotor's surface, making the inner material of the rotor less effective.

4. Simulation and Experimental Results

To quantitatively analyze the influence of the skin effect on the rotor's performance, a finite element method (FEM) simulation model was established to calculate the electromagnetic force at different rotational speeds and with various rotor sleeve thicknesses.

The simulation results visually confirm the mechanism discussed in the previous section. As shown in Fig. 3, the eddy currents generated by high-speed rotation cause the magnetic flux lines to bend and concentrate on the rotor surface in the direction of rotation.

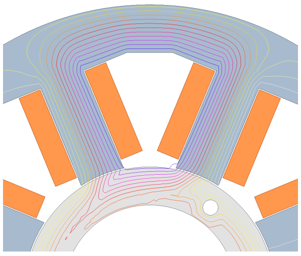

Fig. 3 Magnetic flux lines in the rotor bend towards the direction of rotation.

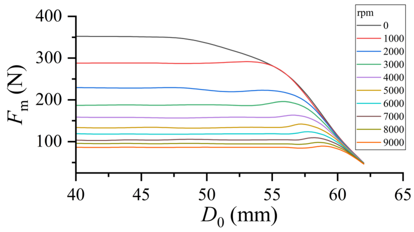

Fig. 4 Electromagnetic force variation with rotor sleeve thickness at different rotational speeds.

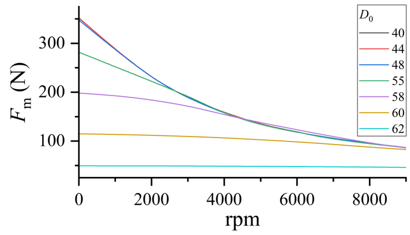

Fig. 5 Electromagnetic force variation with rotational speed at different rotor sleeve thicknesses.

Further parametric simulations were conducted. Figure 4 shows the relationship between the electromagnetic force (F_m) and the rotor's inner diameter (D_0) at various rotational speeds (rpm). At different rotational speeds, the electromagnetic force decreases as the rotor sleeve thickness decreases (i.e., as D_0 increases). However, the critical thickness at which the force begins to drop significantly (the turning point) varies with speed. The higher the rotational speed, the smaller the required rotor sleeve thickness to maintain a high load capacity.

Figure 5 illustrates the electromagnetic force as a function of rotational speed for rotors with different sleeve thicknesses. For rotors with larger sleeve thicknesses, the electromagnetic force decreases as the rotational speed increases. This simulation forms the theoretical basis for redesigning the rotor sleeve thickness based on the skin effect.

To verify these simulation predictions, a magnetic bearing load capacity test platform, as shown in Fig. 6, was designed and built. This platform clamps one magnetic pole of the stator with a force sensor and uses a motor and coupling to drive the rotor, allowing for the measurement of the rotor's load capacity under dynamic conditions at various speeds. Since the magnetic flux inside the rotor cannot be directly measured, the load on rotors with different sleeve thicknesses (c_1) at different rotational speeds is measured to determine whether the material inside the rotor is effectively utilized.

The results for the laminated silicon steel rotors are presented in Fig. 7. Due to the insulating layers between the laminations, eddy currents are largely suppressed. Consequently, the load capacity of each rotor remains nearly constant as the rotational speed increases from 0 to 12000 rpm. For instance, with a 3 A excitation current, the rotors with a 50 mm inner diameter maintain a stable load capacity above 80 N. Furthermore, no significant performance difference is observed between the rotors with 0.35 mm and 0.5 mm lamination thicknesses, as both configurations effectively suppress eddy currents. As predicted by electromagnetic theory, the load capacity decreases as the rotor sleeve thickness decreases (i.e., as D_0 increases to 60 mm). The stability of these load capacities confirms that when eddy currents are suppressed, the speed-dependent force decay phenomenon does not occur, isolating eddy currents as the root cause of the decay seen in solid rotors.

In contrast, the test results for the solid electrical iron rotors, shown in Fig. 8, exhibit correlation with the simulation predictions. For the solid rotor, significant eddy currents were generated and concentrated on the surface, and as a result, the load on the rotor rapidly decreased as the rotational speed increased. The figure compares three solid rotors with the same outer diameter (65 mm) but different inner diameters (45mm, 55mm and 60mm). At low speeds, the thicker rotor provides a higher load capacity. However, as the speed increases to 12000 rpm, their load capacities all converge to a narrow range around 30 N. Notably, the performance difference between the rotors becomes negligible at high speeds, which strongly validates the skin effect theory.

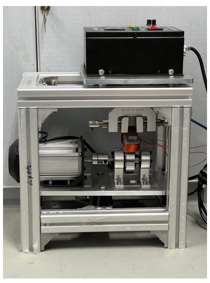

Fig. 6 Magnetic bearing load capacity test platform.

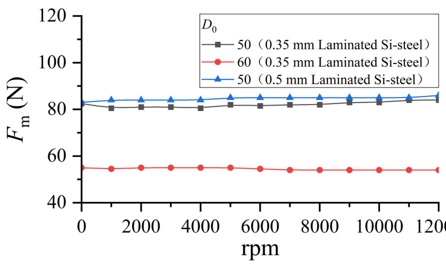

Fig. 7 Electromagnetic force variation with rotational speed at different rotor sleeve thicknesses for laminated silicon steel rotors.

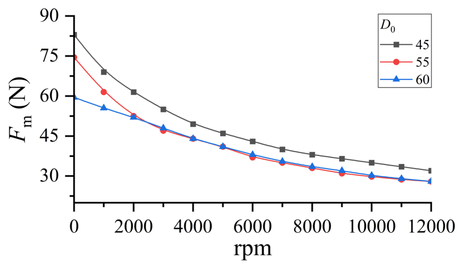

Fig. 8 Electromagnetic force variation with rotational speed at different rotor sleeve thicknesses for solid electrical iron rotors.

The experimental results provide strong evidence for the rotor skin effect. The convergence of load capacity at high speeds for thick and thin solid rotors demonstrates that the inner material of the thicker rotor does not contribute significantly to the force generation. This validates the core hypothesis that for high-speed applications, the rotor sleeve can be made thinner and lighter without a substantial loss of performance.

5. Conclusion

This paper investigated the structural analysis and design of a radial magnetic bearing rotor, with a focus on leveraging the eddy current-induced skin effect for miniaturization. The study combined theoretical analysis, finite element simulations, and experimental verification to explore the feasibility of reducing rotor volume in high-speed applications.

The key findings are summarized as follows:

Both theoretical analysis and FEM simulations confirmed that at high rotational speeds, eddy currents concentrate the magnetic flux on the rotor's surface, causing a significant decay in load capacity for solid rotors.

Experimental tests validated these findings. A control group of laminated silicon steel rotors showed negligible force decay, isolating eddy currents as the primary cause. In contrast, solid iron rotors exhibited force decay that closely matched simulation predictions.

Crucially, the experiment demonstrated that at a high speed of 12000 rpm, the load-bearing capacity of a thin-walled solid rotor (60mm inner diameter) was nearly identical to that of a much thicker one (45mm inner diameter).

In conclusion, this work successfully demonstrates that the rotor skin effect is a dominant factor in the performance of solid rotors at high speeds. This phenomenon renders the inner material of the rotor redundant for force generation under such conditions. Therefore, it is feasible to design thinner and lighter rotors for high-speed magnetic bearings without significantly compromising their load capacity, which provides a valuable design guideline for developing more compact and lightweight magnetic bearing systems. Future work will focus on developing an analytical calculation method to precisely determine the optimal rotor sleeve thickness for various operating conditions and materials.

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