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Five-Axis Rotation Control of Lorentz Force Type Radial Gap Self-Bearing PMSM with Hexagonal Winding and Two-Pole Rotor

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Abstract

This paper introduces a five-axis active control of a self-bearing permanent magnet synchronous motor (PMSM) that using the Lorentz force. Recently, there has been an increased demand for the miniaturization and high performance of self-bearing motors that integrate magnetic bearings and motors. To meet this demand, a small self-bearing motor with a hexagonal stator winding and a two-pole rotor has been developed. The stator consists of two slotless, six-phase, distributed windings stacked in the axial direction. Designing one of the coil ends of the stator winding so that it does not overlap with the rotor PM generates an axial force. The radial force is controlled by supplying a four-pole current to the stator windings. Although the Lorentz force is smaller than the magnetic attractive force, it improves the performance due to its good linearity and reduced eddy current loss. Previous research used a four-pole rotor and diamond-shaped windings; however, this research uses a two-pole rotor and hexagonal stator windings to enhance axial force and radial force generation. This paper introduces the structure and the principles of the axial force and radial force generation. It also confirms the feasibility of the proposed motor through a levitation experiment with a prototype motor.

Keywords :

PMSM, Magnetic levitation, Self bearing motor, Five axis suspension control, Lorentz force, Distributed winding

1. Introduction

A magnetic bearing is a bearing that uses the electromagnetic force to suspend the shaft without mechanical contact (The Japan Society of Mechanical Engineers, 1995). Advantages of magnetic bearings include a long life due to the absence of friction and wear, maintenance-free operation due to the absence of lubricants and dust, low noise, and low energy loss. Additionally, a self-bearing motor (SBM) that integrates a motor and magnetic bearings has been proposed to reduce size and improve performance.

The purpose of this study is to develop a small self-bearing motor that uses the Lorentz force (LSBM). By adopting a slotless structure, the design is simplified, and cogging torque is eliminated, which is expected to improve control performance. LSBMs typically employ thin rotors to ensure axial stability (Kim et al., 2003, Steinert, 2024). We developed a LSBM with slotless distributed windings to reduce the motor's size; however, the axial direction is supported by an axial magnetic bearing (Ueno et al., 2009, Arakawa, 2012). Next, we proposed a five-axis active control LSBM including the axial direction, and the feasibility of the proposed motor has been demonstrated by a protype motor with a four-pole rotor and diamond-shaped stater windings (Ueno et al., 2023). To enhance the axial and radial force generation, we propose a two-pole rotor and hexagonal stator windings. (Kitazawa et al., 2025). This paper introduces the structure and the principles of the axial force and radial force generation in a two-pole rotor and diamond-shaped windings. It also confirms the feasibility of the proposed motor through a levitation experiment with a prototype motor.

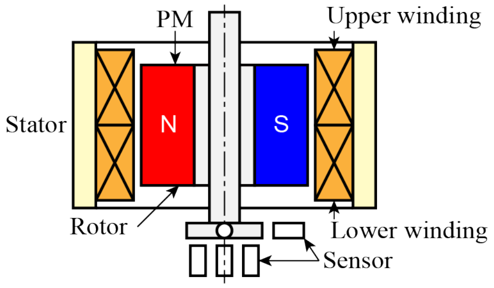


Fig.1 Structure of Lorentz force type self-bearing motor.

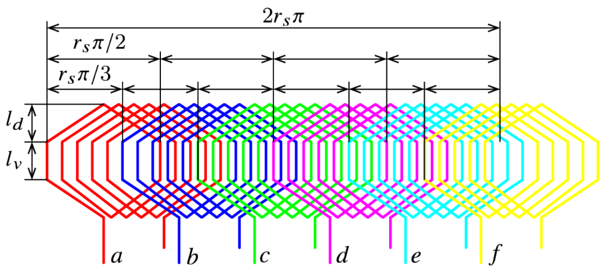


Fig.2 Developed view of 6-phase winding.

2. Structure and principles of the Lorentz force type self-bearing motor

2.1 Structure

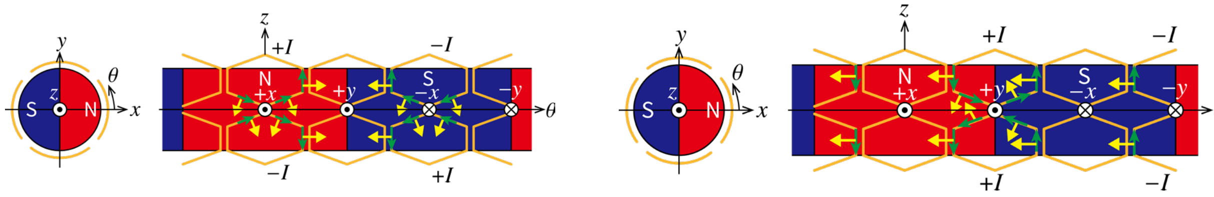
Figure 1 shows the structure of the LSBM proposed in this study. Two slotless, distributed windings are arranged vertically on the stator. A permanent magnet (PM), which overlaps the lower side of the upper coil and the upper side of the lower coil, is attached to the rotor. The back yoke is omitted to eliminate the unstable pull of the rotor permanent magnet.

Figure 2 shows the development view of the stator winding. A six-phase, hexagonal shaped winding is used.

2.2 Principle

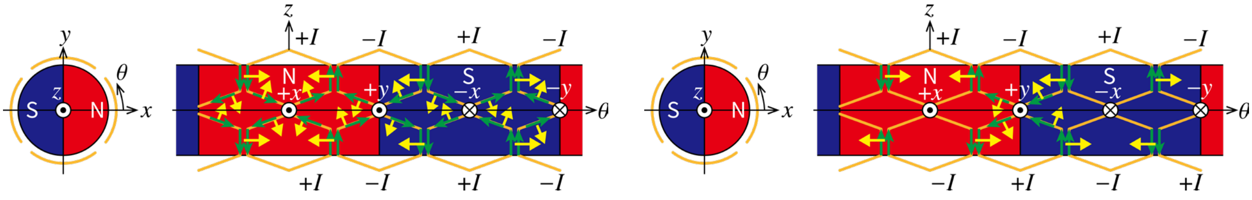
Figure 3 illustrates the principle of generating control forces for the rotor and stator in this study. The left side of each diagram is a top view of the PM rotor. The right side is a developed view of the rotor and stator windings. For simplicity, only one winding is shown. The Red and blue areas represent the magnetic poles of the PM, and the red part generates magnetic flux from the back to the front of the paper, and the blue part generates magnetic flux from the front to the back. Orange lines represent the hexagonal windings. Green arrows indicate the direction of current flow. Yellow arrows indicate the direction of the Lorentz force.

Figure 3 (a) shows the axial force generated by a two-pole d-axis current. When the current is supplied to the winding, Lorentz forces are generated as indicated by the yellow arrows. At positions where the direction of the magnetic fields is reversed, the direction of the current is also reversed, and the axial levitation force is generated. Additionally, supplying currents in opposite directions to the upper and lower windings, the axial levitation force is generated from both windings. The axial force is only generated at the diagonal parts of the winding. The two-pole d-axis current only generates the



(a) Axial Force (2-pole d-axis)

(b) Motor Torque (2-pole q-axis)



(c) Radial Force (x: 4-pole d-axis y: 4-pole q-axis)

(d) Tilt Torque (θ_x: 4-pole d-axis , θ_y: 4-pole q-axis)

Fig. 3 Principle of control force generation axial force because the radial force and motor torque cancel out.

Figure 3 (b) shows the motor torque generated by a two-pole q-axis current. The motor torque can be generated by supplying the current in the same direction to the upper and lower windings. The motor torque is generated by the straight and diagonal parts of the windings. Since the axial force generated by the diagonal parts cancels out, only the motor torque is generated.

Figure 3 (c) shows the radial force generated in the x-direction by a four-pole d-axis current. The radial force is generated by supplying currents in the same direction to the upper and lower windings. The radial forces are generated at the straight and diagonal parts of the windings. This current generates not only the radial force but also tilt torque around the y-axis, however, this torque cancels out in the upper and lower windings. The y-axis force is generated by the four-pole q-axis current.

Figure 3 (d) shows the tilt torque generated in the θ_y-direction by a four-pole d-axis current This tilt torque is generated by supplying the opposite currents to the upper and lower windings. The tilt torque generated at the diagonal parts of the windings is in the same direction as the tilt torque generated by the radial forces, then the tilting torque is enhanced. The θ_x-axis torque is generated by the four-pole q-axis current.

2.3 Coil Current

Figure 4 shows the layout of the six-phase windings relative to the rotor. Phase a generates magnetic flux in the x direction. Phases b through f generate magnetic flux shifted by 60 degrees. Each phase current is expressed as

$$\boldsymbol{i_k = I_z \cos\left(\psi - \frac{\pi k}{3}\right) - I_m \sin\left(\psi - \frac{\pi k}{3}\right) + I_x \cos\left(\psi - \frac{2\pi k}{3}\right) - I_y \sin\left(\psi - \frac{2\pi k}{3}\right)} \tag{1}$$

where k is the phase index, ranging from 0 to 6 for phases a to f, and ψ is the rotation angle of the rotor. Equation (1) is represented with three-phase current as shown in Table 1. A two-pole flux is generated by supplying opposite currents to opposite windings. On the other hand, a four-pole flux is generated by supplying the same currents to opposite windings. Since the rotation is counterclockwise, the phase currents are given in Table 1.

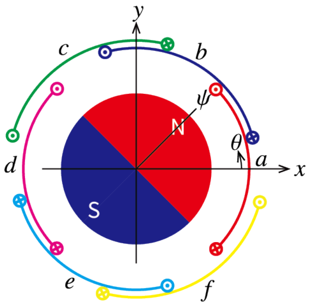


Fig. 4 Layout of 6 phase windings

Table.1 Coil current and phase angle

	Torque & Axial	Radial
$a\ (k=0)$	U	U
$b\ (k=1)$	-W	V
$c\ (k=2)$	V	W
$d\ (k=3)$	-U	U
$e\ (k=4)$	W	V
$f\ (k=5)$	-V	W

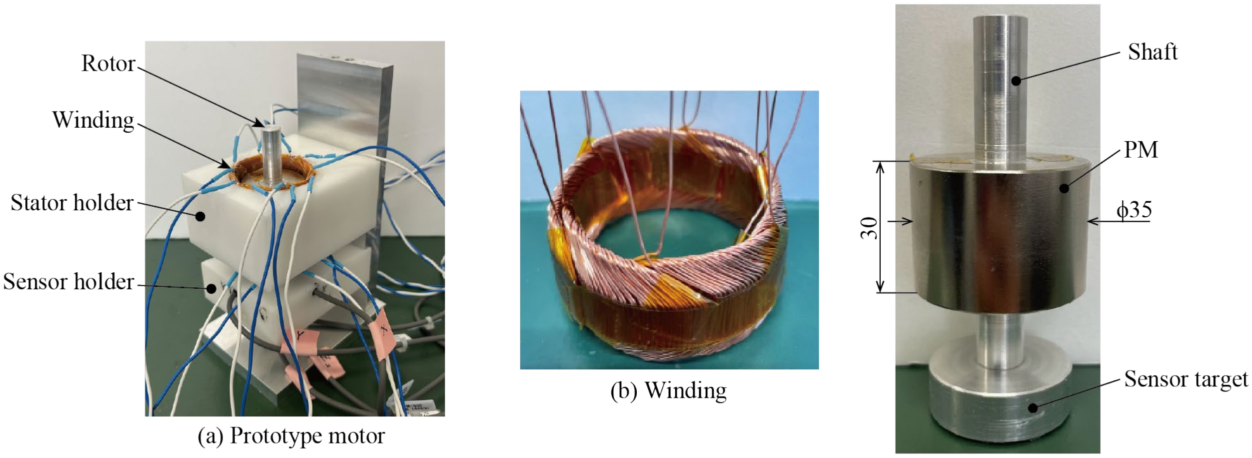
3. Experimental verification

3.1 Prototype motor

To confirm the possibility of levitation control, a prototype motor was manufactured and tested. Figure 5 (a) shows a photograph of the prototype motor. As in Fig. 1, five eddy current sensors are attached to the bottom of the rotor to measure the displacement and posture of the rotor.

Figure 5 (b) shows a photograph of the winding. To ensure that an inner diameter of at least 40 mm, the winding has 49 turns of 0.4 mm diameter wire. It has an inner diameter of 41 mm, an outer diameter of 44 mm, and an axial length of 32 mm. The angle of the diagonal part is 30°.

Figure 5 (c) shows a photograph of the rotor. A two-pole, radially magnetized, cylindrical neodymium magnet with an inner diameter of 15 mm, an outer diameter of 35 mm, and a height of 30 mm is attached to the rotor shaft.



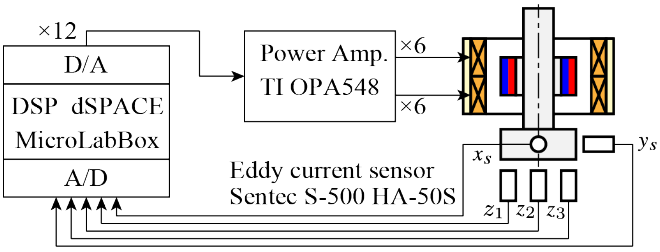
(a) Prototype motor (b) Winding (c) Rotor

Fig. 5 Prototype motor.

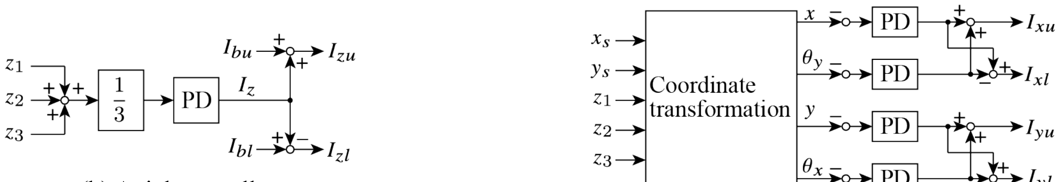
3.2 Controller

Figure 6 (a) shows the control system. A digital signal processor (DSP) is used. The DSP reads sensor signals via A/D converters and calculate each phase current. Then, it outputs the current commands to the power amplifiers via D/A converters.

Block diagrams of the controller are shown in Figs. 6(b) and 6(c). For axial position control, the average value of the three displacement sensor values is applied to a PD controller. Bias current is supplied to support the rotor weight. Positive bias current is supplied to the lower stator while negative bias current is supplied to the upper stator. For radial position control, the center of gravity position and posture of the rotor is calculated from five sensors. Then, the PD controllers calculate the control current. The currents of the upper and lower windings are obtained by adding or subtracting of these values. The gains were tuned by trial and error, and the values are shown in Table 2.



(a) Control system.



(b) Axial controller.

(c) Radial and tilt controller.

Fig. 6 Controller.

Table.2 Gains of the PD controllers.

	z	x	y	θ_x	θ_y
K_P	11	0.05	0.2	1.5	3.5
K_D	0.1	0.0015	0.00015	0.5	0.5

3.3 Levitation test

The startup response is shown in Fig 7. Contactless levitation was achieved in both the axial and radial directions.

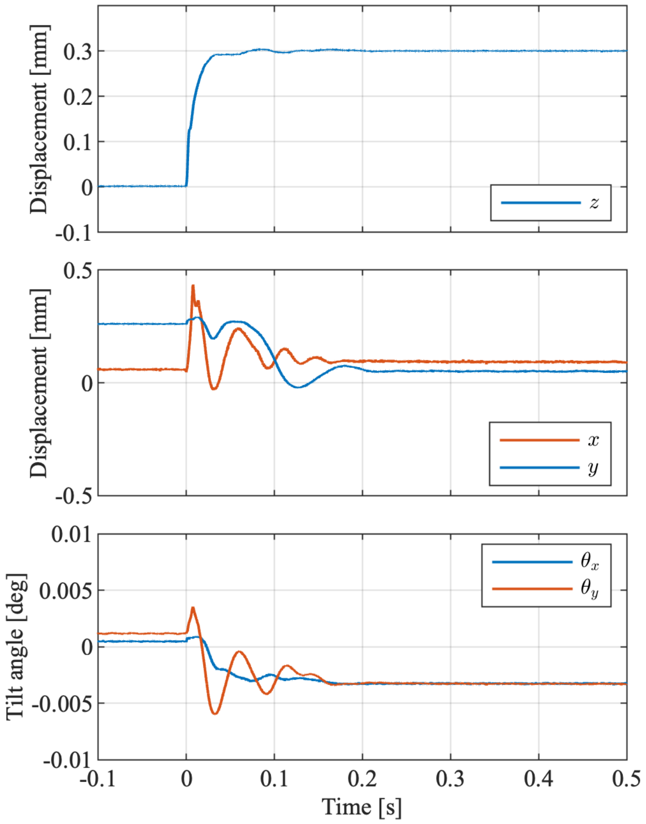


Fig. 7 Startup response.

4. Conclusion

In this paper, we proposed a configuration of a two-pole rotor and hexagonal stator windings to enhance the axial and radial forces of a LSBM. The feasibility of this configuration is confirmed through a levitation test. In the future, we plan to address rotation control in the levitated state.

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