5-DOF CONTROLLED SELF-BEARING MOTOR

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ABSTRACT

A novel 5-DOF actively controlled self-bearing motor that combines the functions of a motor, two radial AMBs, and an axial AMB has been developed to achieve smaller size and higher performance simultaneously. In this paper, radial control performance of the developed self-bearing motor is evaluated by static and dynamic experiments. The radial control force and the negative stiffness due to the permanent magnets are measured statically. The dynamic performance was tested by measuring the impulse response and the frequency response and the maximum oscillation amplitude of the suspended rotor during rotation. The developed 5-DOF self-bearing motor displays sufficient radial position controllability.

INTRODUCTION

Active magnetic bearings (AMBs) have been used to suspend rotors without mechanical contact. Contact-free levitation has many advantages such as elimination of lubrication, high rotational speed, clean operation, and low acoustic noise.

Smaller-sized AMB systems are required for applications in various industrial fields. Integration of components is necessary to miniaturize the systems.

Self-bearing motors have been developed to integrate the AMB systems. For example, the functions of a motor and a radial AMB are combined in radial self-bearing motors [1]. Recently, the application of self-bearing motors to long-term artificial hearts has been investigated. Long-term durability could be achieved due to the contact-free levitation. The authors have applied a radial self-bearing motor to a magnetically levitated centrifugal blood pump [2], [3]. This blood pump has the potential to be a long-term artificial heart. In the self-bearing motor, two degrees of freedom (x, y) are controlled actively. The remaining three degrees of freedom are stabilized passively with magnetic reluctance forces. The usage of passive stabilization allows the device to be smaller, have lower power consumption, use simpler hardware, and reduce cost of sensors. However, it is possible that the low stiffness and the low damping characteristics of the passive stability result in instability of the suspension system.

In this study, a 5-DOF self-bearing motor, which controls five degrees of freedom (x, y, z, θ_x, θ_y) actively, has been developed for artificial heart pumps. Functions of a motor, two radial AMBs, and an axial AMB are effectively combined in the self-bearing motor to miniaturize the system with higher performance.

The authors have already presented the theory of the force and torque generation of the 5-DOF self-bearing motor [4], the numerical results of the self-bearing motor [5], and the experimental results of motor and axial control performance [6]. The radial control performance of the self-bearing motor is reported in this paper.

STRUCTURE

Figure 1 shows the structure of the 5-DOF self-bearing motor. Figure 2 shows the cross sectional view of the 5-DOF self-bearing motor.

The stator has twelve poles. The salient poles of the stator overhang past the circumference of the rotor. The salient poles are composed of an overhanging pole section and a central pole section. The four types of coils are wound around the salient pole. Coils for axial position and tilt control are wound around the overhanging pole section. Coils for motor and radial position control are wound around the central pole section.

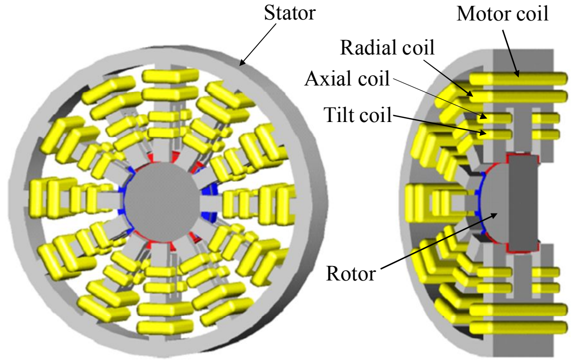

FIGURE 1: Structure of 5-DOF self-bearing motor

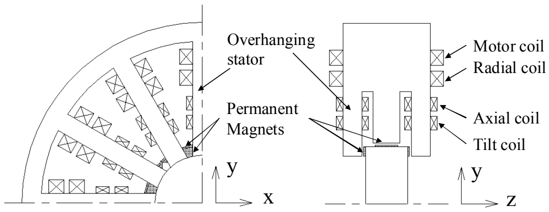

FIGURE 2: Cross sectional view of 5-DOF self-bearing motor

FIGURE 3: Photograph of rotor

Figure 3 shows a photograph of the suspended rotor. Four permanent magnets, which are designated as radial permanent magnets, are mounted on the circumferential surface of the rotor to control the radial position and rotation of the rotor. Four permanent magnets, which are designated as axial permanent magnets, are mounted on both the front and back side of the rotor. The axial permanent magnets enable the device to control the axial position and tilt. The magnetic polarities for each permanent magnet in the same radial position are identical. The edges of the permanent magnets are tapered to generate sinusoidal flux density waveform. Figure 4 shows the dimensions of the 5-DOF self-bearing motor. The size of the stator is calculated to have sufficient winding space and to prevent saturation. The thickness of the permanent magnets is 1 mm. The diameter of the rotor made of laminated silicon steel is 60 mm.

Figure 5 shows a photograph of a divided stator made of laminated silicon steel with excitation coils. The diameter of the coil wire is 0.5 mm.

OPERATION PRINCIPLE

Figure 6 to 8 shows the regulation principle of the radial position, axial position, and tilt of the levitated rotor. The pathways of the bias magnetic flux produced by the permanent magnets and the regulation magnetic flux produced by the electromagnetic coils flux are shown in the figures. When a force is generated to control the rotor position, the magnetic flux in one air gap is increased and the flux in the opposite air gap is decreased by excitation of the electromagnetic coils.

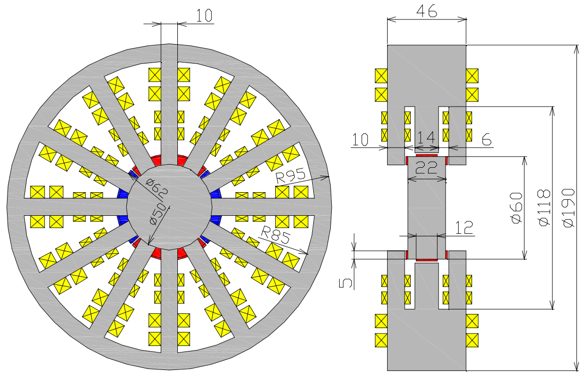

FIGURE 4: Dimensions of 5-DOF self-bearing motor

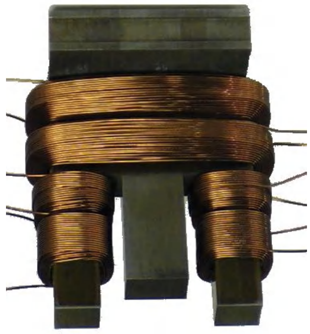

FIGURE 5: Photograph of divided stator

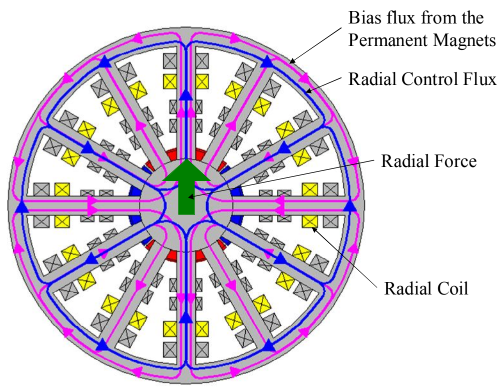

FIGURE 6: Principle of radial position control

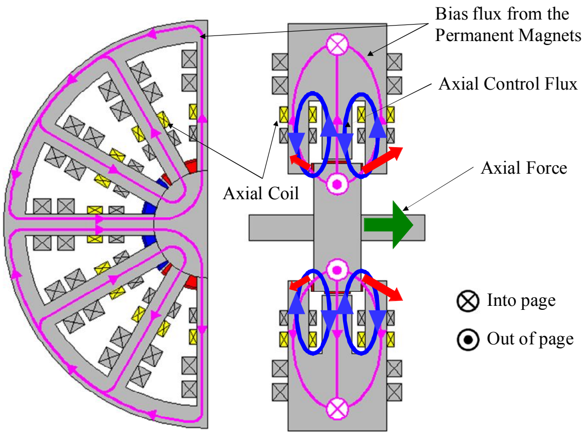

FIGURE 7: Principle of axial position control

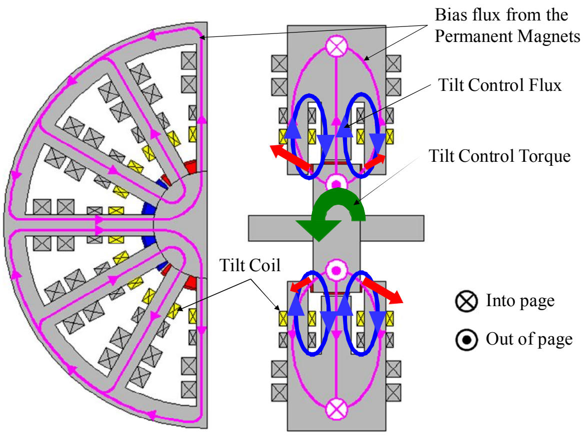

FIGURE 8: Principle of tilt control

EXPERIMENTAL SETUP

Table 1 summarizes the parameters for the 5-DOF self-bearing motor. Figure 9 shows a photograph of the experimental setup to evaluate the radial position control performance. The right end of the rotor shaft is supported by a mechanical ball bearing, and the left end of the shaft is supported by the developed self-bearing motor. The mass of the rotor is 890 g. The controllability in the two radial degrees of freedom (x, y) is examined independently with the experimental setup. A touchdown bearing is installed to avoid direct contact between permanent magnets and the stator.

The movable range of the rotor is restricted from 0.66 mm to −0.66 mm from the center position in the radial direction with the touchdown bearing. Two eddy current displacement sensors are used to measure the x and y position of the rotor. The frequency bandwidth at −3 dB of these sensors is 20 kHz. An optical encoder is used to measure the rotor angle θ_z.

TABLE 1: Design parameters

Parameters	Units	Value
Stator Diameter	*(mm)*	190
Stator Width	*(mm)*	46
Rotor Diameter	*(mm)*	60
Rotor Width	*(mm)*	22
Nominal Air gap	*(mm)*	1
Thickness of Permanent Magnets	*(mm)*	1
Width of Radial Permanent Magnets	*(mm)*	12
Width of Axial Permanent Magnets	*(mm)*	5
Number of turns of Motor Coil and Radial Coil	*(Turns)*	150
Number of turns of Axial Coil andTilt Coil	*(Turns)*	100
Supply Voltage	*(V)*	±36

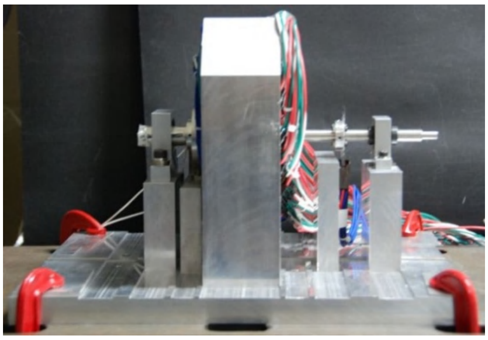

FIGURE 9: Photograph of experimental setup

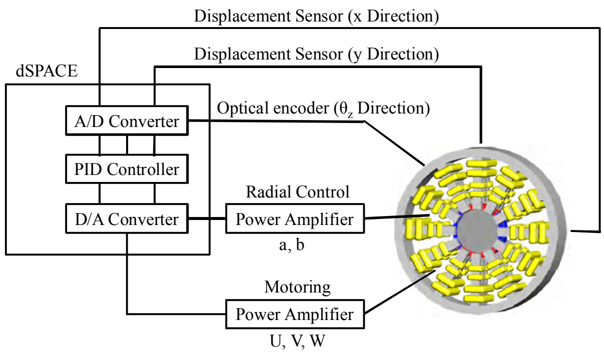

FIGURE 10: Schematic of radial control system

Figure 10 shows the schematic of radial control system. Digital PID controllers are implemented on the dSPACE controller board (DS 1104). The control current is applied to the electromagnetic coils with the power amplifier (PA12, APEX). The supply voltage of the power amplifier is ±36 V. Rotational speed is also controlled by the digital PID controller. The control parameters are summarized in table 2.

TABLE 2: Control parameters

Parameters	Units	Value	
		x	y
Proportional Gain	A/mm	10	10
Integral Gain	A/(sec · mm)	8	8
Derivative Gain	A · sec/mm	0.03	0.03
Sampling interval	msec	0.1	
Derivative time constant	msec	0.18	

EXPERIMENTS

Static and dynamic experiments were carried out to evaluate the radial control performance of the 5-DOF self-bearing motor.

In the static experiments, the radial control force is measured by changing the radial control current while the rotor is fixed at the center position ($y = 0$ mm). Also, negative stiffness due to the permanent magnets is measured by changing the rotor position.

In the dynamic experiments, impulse response, frequency response, and the maximum ocsillation amplitude of the suspended rotor during rotation are measured to evaluate the dynamic performance of the 5-DOF self-bearing motor. The impulse response is measured by hammering the rotor when it is suspended at the center position with the radial position feedback. The frequency response is measured by the frequency sweeping method. Sinusoidal disturbance with the amplitude of 0.005 mm is added to the levitation current and the disturbance frequency is varied from 1 Hz to 400 Hz. The back electromotive force (EMF) is measured at the terminal of the motor coils when the rotor is driven by an external DC motor. Both ends of the rotating shaft were supported with mechanical ball bearings for the back EMF measurement.

EXPERIMENTAL RESULTS

Static performance

Figure 11 shows the relationship between radial control force and excitation current. The estimated force by the three-dimensional magnetic field analysis using finite element methods is also shown for comparison. The rotor position is set at the center in the analysis. The experimental results of the radial control force are 49 % of the numerical results. The ratio of radial control force to excitation current for the experimental results is about 15 N/A and is constant with different rotor positions.

Figure 12 shows the characteristic of the radial negative stiffness due to the permanent magnets which

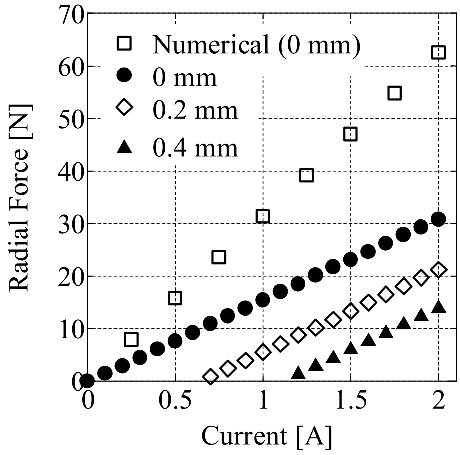

FIGURE 11: Relationship between radial control force and excitation current with different rotor positions ($y = 0$ mm, 0.2 mm, 0.4 mm)

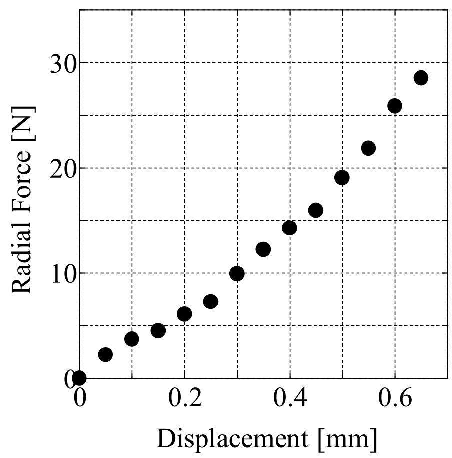

FIGURE 12: Radial negative stiffness by permanent magnets ($I = 0$ A)

is measured by changing the rotor position while keeping the excitation current zero ($I = 0$ A). The ratio of force to displacement is about 38 N/mm.

Dynamic performance

Figure 13, 14 shows the impulse response in the x and y direction, respectively. The settling times of 0.03 sec for both directions imply sufficient controllability for the radial direction.

Figure 15 shows the frequency response of the system in the x and y directions. Similar results in the x and y directions are obtained. The first resonant peak is observed at about 80 Hz and the amplitude of the resonant peak is successfully suppressed. Sufficient controllability of the rotor position in the radial direction is displayed in the results.

Figure 16 shows the maximum oscillation amplitude of the suspended rotor during rotation in the x and y

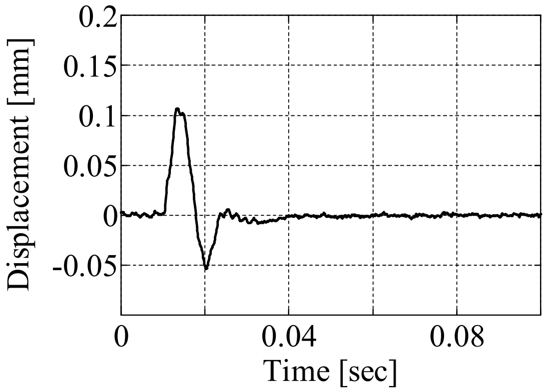

FIGURE 13: Impulse response (x direction)

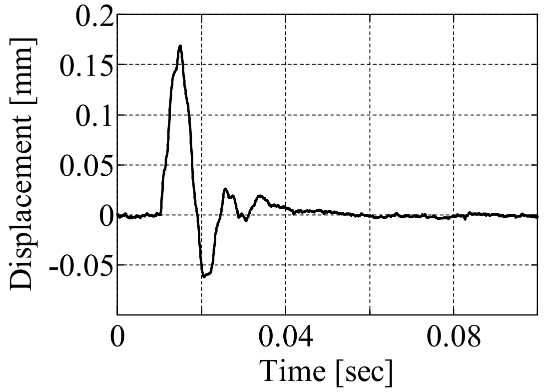

FIGURE 14: Impulse response (y direction)

directions with the no load condition. Similar maximum oscillation amplitude in the x and y directions is obtained. Figure 17 shows the trajectory of the rotor position. Steady rotation of the rotor at low frequency is observed while the maximum oscillation amplitude increases as the rotational speed increases. The radial position control becomes impossible as the rotational speed increases to more than 800 rpm. This limit is caused by the back EMF.

Figure 18 shows the relationship between the back EMF and the rotational speed. The back EMF increases proportionally to the rotational speed and reaches a supplied voltage of 36 V at a rotational speed of 1,200 rpm. This large back EMF is caused by a large magnetic flux density generated with permanent magnets mounted on the rotor.

Figure 19 shows the back EMF waveform at 1,200 rpm. Due to the tapered edges of the permanent magnets, high harmonic component is decreased and the more sinusoidal waveform is obtained, while the maximum voltage of the back EMF waveform reaches 36 V at 1,200 rpm. The back EMF should be decreased by changing the PM configuration to achieve higher rotation.

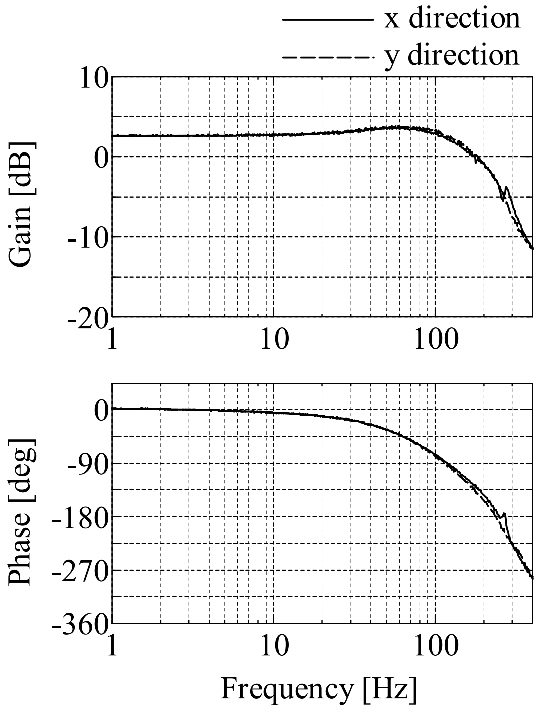

FIGURE 15: Frequency response

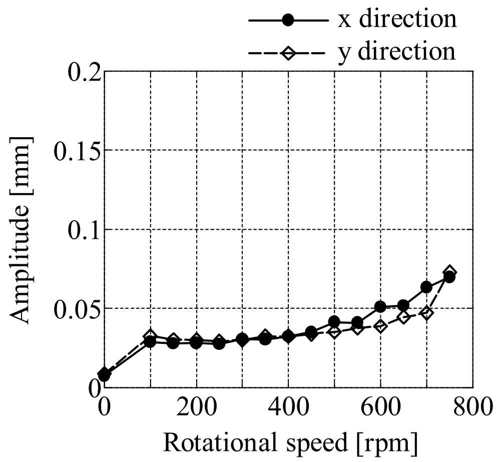

FIGURE 16: Maximum oscillation amplitude of the suspended rotor during rotation

CONCLUSIONS

A novel 5-DOF actively controlled self-bearing motor that combines the functions of a motor, two radial AMBs, and an axial AMB has been developed to achieve smaller size and higher performance simultaneously.

The radial control performance of the developed self-bearing motor was evaluated. From the static experiments, the ratio of radial control force to excitation current is about 15 N/A. In the dynamic experiments, the impulse and frequency response

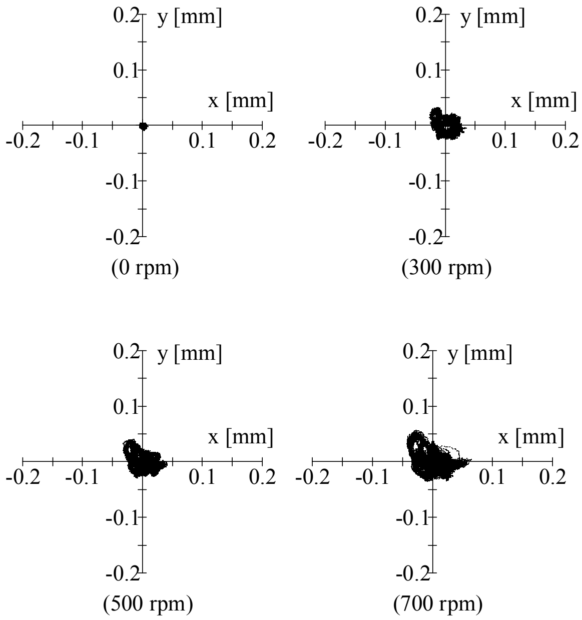

FIGURE 17: Trajectory of radial rotor position

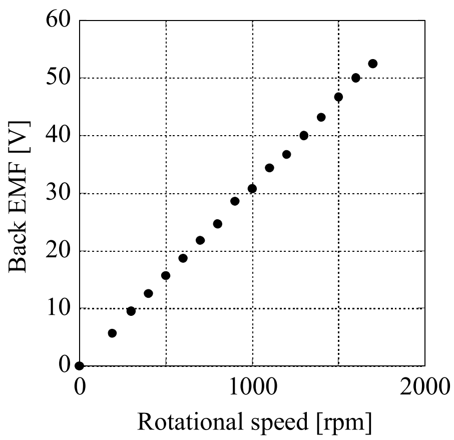

FIGURE 18: Back EMF with the rotational speed increased

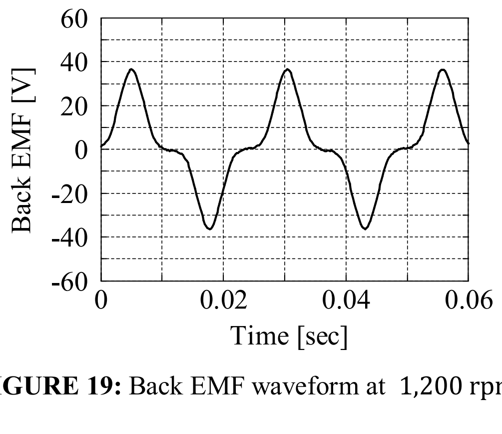

FIGURE 19: Back EMF waveform at 1,200 rpm

exhibit good performance and adequate damping. The oscillation amplitude with low speed rotation was very stable. The results show sufficient radial position controllability and a possibility to achieve a smaller size and higher performance 5-DOF actively controlled self-bearing motor.

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