

Prototype Fabrication of Reluctance-Type Combined Radial-Axial Magnetic Bearing with Multi-Disk

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Abstract

Magnetic bearings (MBs) can support a rotating shaft without any contacts using electromagnetic force. A typical five-degree-of-freedom magnetic levitation system uses two radial MBs and one axial MB. However, such a configuration tends to become large due to the combination of three MBs, and it poses an issue of reduced critical speed as the shaft length increases. Therefore, combined radial-axial MBs (CRAMBs) have been proposed to address these challenges. CRAMB can generate support forces in three degrees of freedom using a single unit. In our study, we have proposed an innovative reluctance-type CRAMB with multi-disk (CRAMB-MD) to enlarge the opposing surface area where magnetic attractive force acts, enabling three-degree-of-freedom support with a high support force density. Since the proposed CRAMB-MD does not require permanent magnets, it offers advantages such as ease of assembly and suitability for cryogenic or high-temperature environments. This paper presents the design and fabrication of a prototype. The axial and radial support force characteristics are calculated using three-dimensional finite element method, and experimental measurements are conducted using a load cell. A qualitative agreement was observed between the analytical and experimental results. The findings demonstrate the validity and effectiveness of the proposed structure, offering a promising approach for compact and high-performance magnetic levitation systems.

Keywords : Combined radial-axial magnetic bearing, Multi-disk, Reluctance-type magnetic bearing, Support force characteristics, High support force density, Magnetic levitation.

1. Introduction

A typical five-degree-of-freedom magnetic levitation system comprises two radial MBs and one axial MB. In this system, the reduction of critical speed due to an increase in shaft length becomes a significant issue (Ayuzawa et al., 2025). Therefore, to reduce the shaft length, combined radial-axial MBs (CRAMBs) have been proposed to generate triaxial support force with a single unit. A CRAMB with a permanent magnet (PM) ring was proposed (Imoverdorf et al., 2007). However, PMs are difficult to assemble due to their strong magnetic attraction force. In combustion systems, PM demagnetization occurs in high-temperature environments. Moreover, hydrogen embrittlement of PMs occurs in environments where liquid hydrogen is used. Heya et al. proposed reluctance-type CRAMBs without PMs (Heya et al., 2021). However, the low support force per unit volume (support force density) is a problem.

To address this issue, we proposed a reluctance-type CRAMB with multi-disk (CRAMB-MD), which can support three degree of freedom without using PMs and have a high support force (Ayuzawa et al., 2024). In the proposed structure, the opposing surface on which the magnetic attraction force acts can be enlarged to achieve a high support force density. The novelty and main contributions in this paper are as follows:

1. A prototype of the proposed reluctance-type CRAMB-MD was designed and fabricated to verify the practical feasibility of the structure.
2. Experimental measurements of the axial and radial support forces confirmed qualitative agreement with finite element analysis results.

This study demonstrates the prototype of proposed CRAMB. First, a comparison between the conventional structure and the proposed structure and operating principle are described. Then, analytical and experimental results regarding the

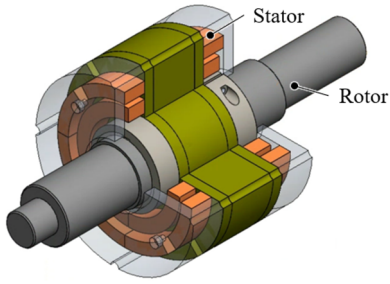


Fig. 1 Conventional CRAMB structure is referred to as the CRAMB-OD. This structure replaces the PM part with a soft magnetic material, making it a reluctance-type CRAMB (Imoverdorf et al., 2007).

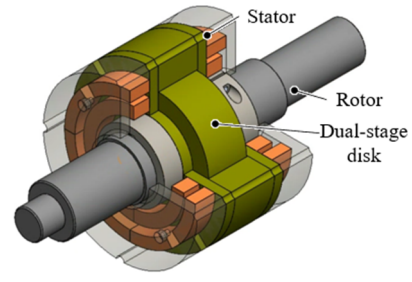


Fig. 2 Proposed CRAMB structure is referred to as the CRAMB-MD. This structure is a dual-disk structure with a thinner disk added to the conventional CRAMB-OD disk. (Ayuzawa et al., 2024)

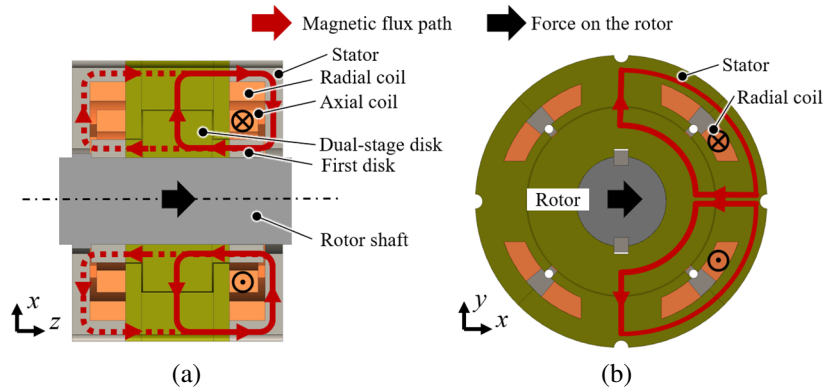


Fig. 3 Operating principle of the proposed CRAMB-MD. (a) Axial support force is generated by energizing the axial control coil. (b) Radial support force is generated by energizing the radial control coil.

axial and radial support force are compared to evaluating the performance of the prototype.

2. Reluctance-type CRAMB structure

A conventional CRAMB structure is shown in Fig. 1. This structure replaces the PM part with a soft magnetic material, making it a reluctance-type CRAMB (Imoverdorf et al., 2007). Since the conventional structure has only one disk on the rotor, it is referred to as the CRAMB with one disk (CRAMB-OD) in this paper. The CRAMB stator comprises axial and radial stator sections. In the axial stator section, two axial control coils are wound in the winding direction around the rotor axis. The rotor has a disk, which is the source of the axial and radial support forces. The support force of a typical MB is based on the magnetic attractive force between the rotor disk and stator core, which can be expressed in a simplified form as in Eq. (1).

$$F = \frac{B^2}{2\mu_0} S \quad (1)$$

where B denotes the magnetic flux density, μ_0 denotes the magnetic permeability in vacuum, and S denotes the opposing surface area between the rotor disk and the stator core. The radial stator section features a four-slot structure and includes four radial control coils to generate radial support force. The radial stator section forms a magnetic circuit in the radial (x - y) section.

The proposed CRAMB-MD structure is shown in Fig. 2. The CRAMB-MD is a dual-disk structure with a thinner disk added to the conventional CRAMB-OD disk. Figure 3 illustrates the principle of the magnetic attraction force. The axial support force is produced by energizing the coil in the direction required to create force between the two axial control coils (Fig. 3 (a)). Similarly, the radial support force is generated by energizing the coil in the direction required to create force among the four radial control coils (Fig. 3 (b)).

The prototype of proposed structure is shown in Fig. 4, and its design parameters are listed in Table 1. The rotor shaft is made of NCF718 (JIS), which is a non-magnetic material, as shown in Fig. 4 (a). The disk attached to it is made of 35A300 (JIS), a type of silicon steel sheet. The radial stator is also made of 35A300 (JIS). The axial stator is made of

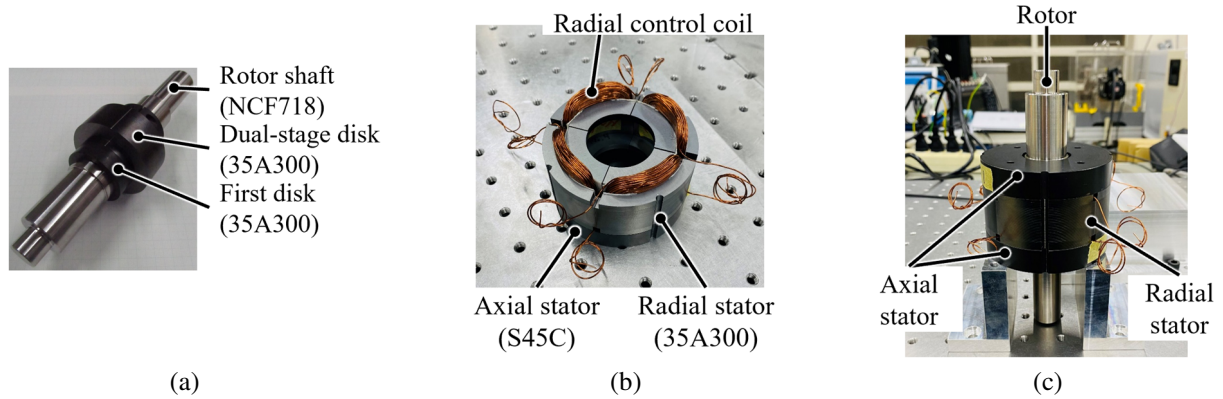


Fig. 4 Prototype of the proposed CRAMB-MD.
(a) Rotor. (b) Stator. (c) Rotor and stator.

Table 1 Design parameters of reluctance-type CRAMB.

Rotor	Shaft diameter	24.7 mm
	Shaft length	166 mm
	First disk diameter	69.5 mm
	First disk length	35 mm
	Center disk diameter	51.5 mm
Stator	Outer diameter	80 mm
	Length	60 mm
Coil	Wire diameter	0.65 mm
	Axial coil turn	95 Turns
	Radial coil turn	75 Turns
	Maximum current density	7 A/mm ²
Air gap	Length in radial direction	0.30 mm
	Length in axial direction	0.55 mm

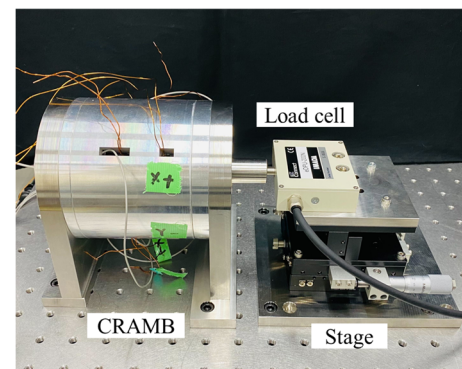


Fig. 5 Experimental setup for measuring the axial support force. The rotor is fixed at one end by the housing, and the support force is measured using a load cell. The load cell is mounted on a stage that allows movement along three axes. A non-contact displacement sensor is used to monitor the rotor's position.

S45C (JIS). The radial stator is divided into four segments in the circumferential direction, and the axial stators are arranged to sandwich it from both axial sides.

3. Analysis and Experimental conditions

The axial and radial support force characteristics are compared through analysis and experiment. A magnetic field analysis is performed using the three-dimensional finite element method. The rotor is placed at the origin, and the support force is defined as the force acting on the rotor when current is applied to a single coil in the desired support force direction. The current density varies up to 7 A/mm² (2.32 A).

Experimental setup for the axial support force is shown in Fig. 5. One end of the rotor is fixed at the origin by the housing. The support force is measured using a load cell (DPU-200N, IMADA Co., Ltd.) connected to the rotor. The load cell can be moved along three axes using a stage. The rotor's position can be monitored using a non-contact displacement sensor for MBs (1195-510, SHINKAWA Electric Co., Ltd.).

4. Analysis and Experimental results

Analytical and experimental results are shown in Fig. 6. Magnetic flux density distribution diagrams analyzed in three-dimensional finite element method are shown in Fig. 7. The axial support force is proportional to the square of the current (Fig. 6 (a)). At 7 A/mm², axial support force is 28.0 N. On the other hand, the experiment also showed an increase as the current increased. However, at 7 A/mm², the axial support force decreased to 18.3 N. One possible reason for this is the increase in magnetic reluctance in the magnetic circuit due to the presence of air gaps between the components of

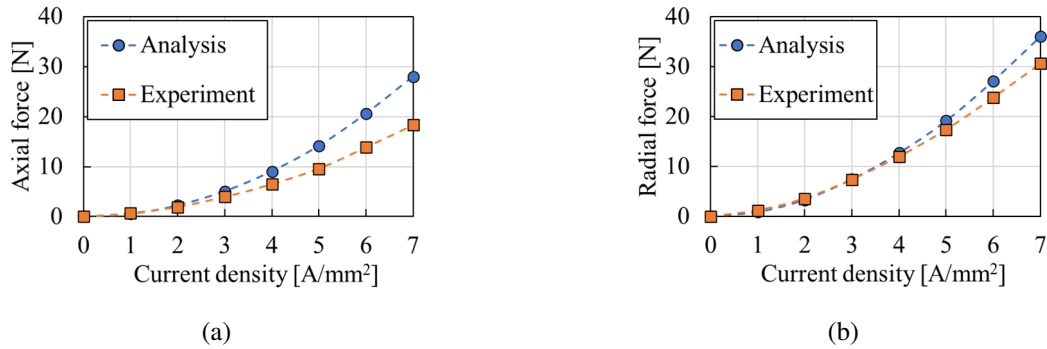


Fig. 6 Comparison of support force characteristics obtained by analysis and experiment. (a) Axial force. (b) Radial force. The blue lines represent the analysis results, and the orange lines represent the experimental results.

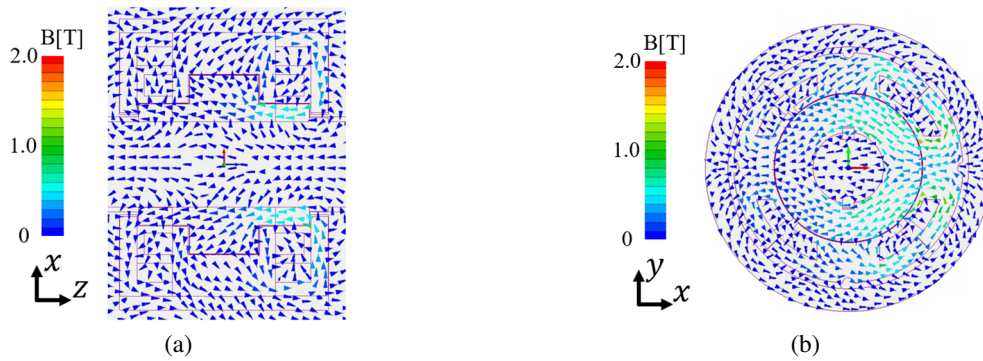


Fig. 7 Magnetic flux density distribution diagram during generation of support force. (a) Axial direction: 7 A/mm² current applied to the axial coil. (b) Radial direction: 7 A/mm² current applied to the radial coil support force.

the rotor and stator, which were likely caused by assembly errors. Similarly, the radial support force is also proportional to the square of the current (Fig. 6 (b)). At 7 A/mm², the radial support force is 36.0 N. However, in the experiment, the radial support force decreased to 30.6 N. One possible cause of this difference is the characteristic stator structure of this design. A section of the stator, made of silicon steel sheets, is divided into four sections in the circumferential direction to improve the manufacturability of the winding and ease of assembly. However, the small gaps between these stator sections in the circumferential direction likely increased the magnetic reluctance, resulting in a reduction in support force.

5. Conclusion

In this study, we conducted an experimental verification of the proposed CRAMB-MD, which integrates radial and axial MBs. This structure aims to increase critical speed by reducing the shaft length and achieve high support force. In the experimental setup, the generation of both radial and axial support forces was confirmed. Although the static support force characteristics obtained from the analysis and experiments were influenced by assembly errors, they showed qualitative agreement.

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