

Evaluation of passive stability through structural ingenuity for an ac ampere-type magnetic suspension system

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Abstract

This paper describes the successful realization of a fully non-contact magnetic levitation (maglev) system by incorporating the concept of the rotational center (RC) and applying structural modifications to the levitating object in an AC Ampere-type maglev configuration. The proposed AC Ampere-type maglev system is an enhanced version of conventional AC induction-type maglev. In contrast to the conventional one, this system integrates an AC electromagnet (EM1) that induces repulsive forces and additional electromagnets (EM2) that generate Ampere forces. The Ampere force is generated as the cross product of the induced current in the levitating object and the magnetic flux produced by EM2. By appropriately adjusting the phase difference between the induced current and the magnetic flux, it is possible to realize a magnetic levitation system in which the object is suspended beneath a stator composed of multiple electromagnets. The levitating object is an aluminum (Al) ring, referred to as a “squirrel-cage Al ring.” To set the RC at a location far below the Al ring, a pair of permanent magnets is used. One of the magnets is connected to the Al ring via three lightweight threads. The relationship among the electromagnetic forces—namely, the alternating repulsive force and Ampere force—generated in the Al ring, the attractive force produced by the pair of permanent magnets, and the gravitational force of the levitating object were experimentally investigated. In the levitation experiment, the object was suspended near the equilibrium point, with a vibration amplitude of approximately 0.1 mm and a magnetic stiffness of 19.1 mN/mm. Thus, with a touch of structural ingenuity—suspending permanent magnets from the squirrel-cage Al ring—we have successfully realized a non-contact, passive, and pendulum-style AC Ampere-type maglev system.

Keywords: Magnetic suspension, AC Ampere-type, AC electromagnets, Aluminum ring, Passive stability

1. Introduction

In the general AC induction-type magnetic levitation (maglev) system, AC electromagnets (EM1) installed under a conducting levitating object provide an alternating repulsive force to the object (J. L. He et al, 1992, N. Kawada et al., 1993, and Karl, H. et al., 1997). In other words, in conventional AC induction-type maglev systems, the levitating object should be placed above the EM1 to balance with the gravity of the object. The main advantage of this system is that it enables non-contact levitation of the object without any active control.

The AC Ampere-type maglev system we have proposed is an enhanced version of the conventional AC induction-type maglev system (T. Ohji et al., 2007). In this system, in addition to EM1, AC electromagnets (EM2) are installed on the sides of a levitating object. The system produces an alternating Ampere force, which is the cross product of the current induced in the object by the excitation of EM1 and the magnetic flux from EM2, as well as the alternating repulsive force. We have previously developed AC Ampere-type magnetic levitation systems in which the stator structure is tailored to the shape of the levitating object (T. Ohji et al., 2014 and T. Sato et al., 2015). Using these systems, we successfully achieved non-contact and stable levitation and transport of aluminum objects, such as thin rectangular plates and hollow cylindrical shells, by generating upward alternating repulsive force and Ampere force. The direction of the Ampere force

can be changed by adjusting the phase difference between the induced current in the object and the magnetic flux from EM2; therefore, by appropriately adjusting this phase difference, it is possible to configure a suspended-type maglev system in which the object is levitated below EM1. Through preliminary experiments and FEM analysis using the electromagnet arrangement shown in Fig. 1, we have demonstrated that an upward force can be generated on the levitating object even when it is located below EM1. However, fully stable non-contact magnetic levitation in all directions of the levitating object has not yet been achieved. In this paper, we introduce the concept of a rotational center (RC) of the levitating object and propose a novel configuration that utilizes a pair of cylindrical permanent magnets. We report the achievement of fully non-contact levitation based on experimental validation.

2. Structural Features and Definitions

Figure 1 shows a schematic diagram and the dimensions of a suspended-type maglev system based on the AC Ampere-type principle. The levitating aluminum (Al) ring has a squirrel-cage shape, resembling a circular ring made by connecting ladder-like elements. An electromagnet (EM1) is installed above the squirrel-cage Al ring to generate an alternating repulsive force. Additionally, six electromagnets (EM2) are mounted on the lateral side of the Al ring to generate alternating Ampere forces. These six EM2 units are evenly arranged around the circumference of the Al ring at 60-degree intervals.

The coordinates is defined as follows: the central axis of the EM1, which is the vertical direction, is z ; the radial direction (r) along the magnetic pole face of EM2 is x ; and the perpendicular direction to x is y . Additionally, the rotation angle about the y -axis is defined as θ_y , the rotation angle of the Al ring about the RC is defined as θ_{Ry} , the distance from the bottom surface of EM1 to the top surface of the Al ring is defined as the gap d , and the displacement of the RC from the center of gravity (GC) of the Al ring is defined as l . Let i_1 denote the current flowing through the EM1, and i_2 denote the current flowing through the series-connected circuit of the six EM2 units. Furthermore, let f denote the frequency of the excitation current, θ the phase difference of i_2 relative to i_1 , and m the mass of the Al ring.

In addition, let m_p denote the mass of lightweight threads and the suspended permanent magnet (including mounting jigs) described later. In the levitation experiment, the initial position of the levitating object is defined as the initial gap of the ring d_0 , and the initial distance between a pair of permanent magnets is defined as d_{p0} . In addition, the average electromagnetic force acting on the Al ring is denoted by f_{z_ave} , and the average torque acting around the RC is denoted by T_{Ry_ave} .

3. Torque evaluation by finite element analysis

In preliminary levitation experiments conducted using only the squirrel-cage Al ring, meaning that the center of gravity (GC) of the Al ring coincides with its rotational center (RC), a consistent phenomenon was observed in which

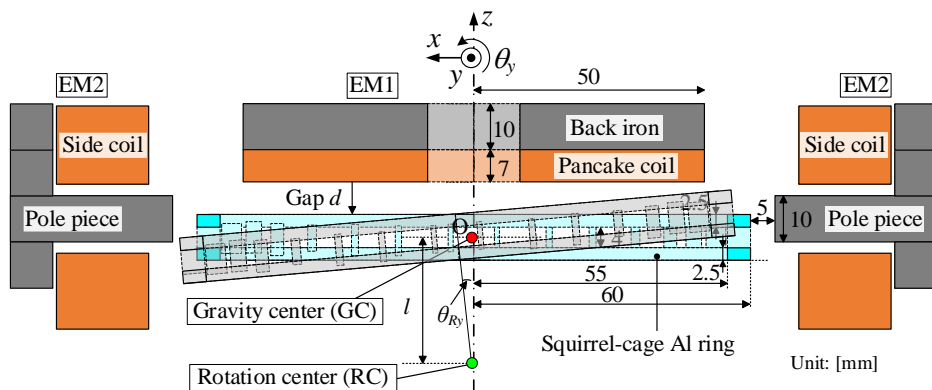


Fig. 1 The dimensional relationship between the levitating object and stator electromagnets (EM1, 6-EM2). The displacement of the rotational center (RC) from the center of gravity (GC) of the squirrel-cage Al ring is defined as l , and it is assumed that the levitating object rotates around the RC. By setting the RC at a different position from the GC, a restoring torque is expected to act on the Al ring when it tilts, depending on the position of the RC.

the Al ring was attracted toward the direction of EM2 and lifted upward, regardless of the number of trials.

Accordingly, we conducted a finite element analysis to evaluate the average torque T_{Ry_ave} acting around the RC when the RC was virtually changed upward and downward along the central axis. By calculating the torque T_{Ry_ave} , it becomes clear whether a lift-up torque or a restoring torque acts on the levitating object. Consequently, the feasibility of its levitation can be investigated. Fig. 2(a) shows the finite element analysis model with the air layer hidden. Fig. 2(b) shows the torque T_{Ry_ave} acting around the RC with varying displacement l from the RC. The analysis conditions are listed in Table 1.

The initial position of the Al ring was set with a gap of $d = 1$ mm and a horizontal displacement of the GC $x = 0$. According to Fig. 2(b), when l is positive, that is, when the RC is positioned above the GC, a lift-up torque acts to further promote rotation of the levitated body. In contrast, when l is negative, meaning that the RC is set below the GC, a restoring torque acts upon rotation, working to return the levitated body to its original position. These findings suggest that placing the RC below the levitating object is key to achieving stable levitation.

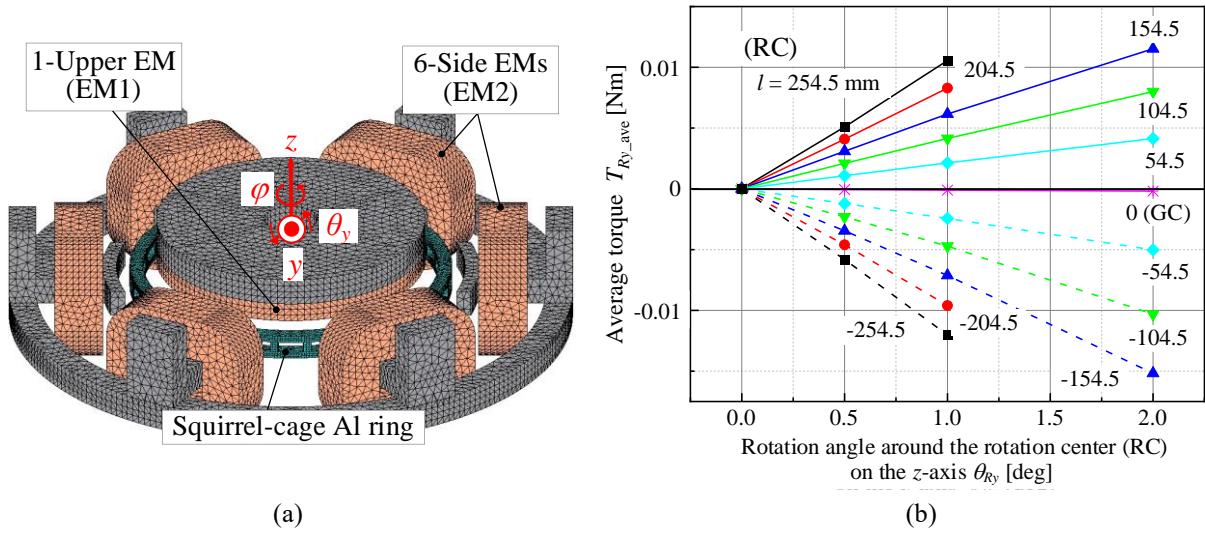


Fig. 2(a) FE analysis model (mesh view). The geometry, dimensions, material properties, and excitation conditions are all identical to those in the experimental setup. The air layer is not displayed.

Fig. 2(b) Relationship between the average torque T_{Ry_ave} acting around the RC and the parameter θ_{Ry} when the position of the RC is varied. When the RC is positioned above the GC of the Al ring ($l > 0$), a lift-up torque acts to enhance the rotation of the Al ring. In contrast, when the RC is located below the GC ($l < 0$), a restoring torque is generated even when the Al ring tilts. When the RC and GC are at the same position ($l = 0$), the torque is nearly zero. However, even a slight horizontal slide causes the Al ring on the slid side to approach the magnetic pole of EM2, which increases the upward Ampere force and results in the Al ring being lifted unintentionally.

Table 1 Parameters of FE analysis.

Squirrel-cage Al ring	Dimensions: $\varnothing 120$ mm \times $\varnothing 110$ mm \times (2.5+4+2.5) mm Mass: $m = 28.6$ g
Coil	A1050 (Conductivity: $3.77e^7$ S/m)
Iron core	Copper (Conductivity: $5.98e^7$ S/m)
Excitation conditions	20JNEH1200 (JFE Steel Corp.) EM1: $\sqrt{2}i_1 \cdot \exp(j2\pi ft)$ EM2: $\sqrt{2}i_2 \cdot \exp(j(2\pi ft + \theta))$ ($i_1 = i_2 = 3.0$ A _{rms} , $\theta = 60$ deg., $f = 180$ Hz)
Software	JMAG-Designer (x64) (Ver. 22.1.01v)
No. of elements	About 650,000 (Tetrahedral mesh)
CPU, Calc. time	Intel(R) Core(TM) i9-10980KE CPU @ 3.00 GHz, 70 min.

4. Implementation of a Permanent Magnet Pair

This study proposes using the attractive force between a pair of permanent magnets to position the rotational center of the Al ring below its center of gravity. The attractive force acting between a pair of cylindrical permanent magnets (NdFeB(N40), $\phi 10 \text{ mm} \times 5 \text{ mm}$) was measured. Fig. 3(a) shows the experimental setup for measuring the attractive force. In the measurement, the gap d_p between the permanent magnets was adjusted from 10 mm to 40 mm in 1.0 mm increments. The attractive force was measured using a digital force gauge (IMADA, ZTS-5N). A portion of the measured attractive force results, along with the secondary scale, is presented in Fig. 4. It is important to obtain the attractive force characteristics of permanent magnets in advance. By adjusting the distance between the permanent magnet suspended from the Al ring and the counterpart permanent magnet mounted on a stator base, the desired attractive force can be achieved. Furthermore, when this attractive force is generated, a radial restoring force acts on the pair of permanent magnets, allowing the suspended permanent magnet to potentially serve as the rotational center.

Figure 3(b) presents the actual configuration of the entire maglev device. Three lightweight threads of equal length are suspended at 120-degree intervals from the squirrel-cage Al ring, and the permanent magnet is attached to these threads. The other permanent magnet is embedded in a nonmagnetic base whose height can be adjusted as desired. In addition, a laser displacement sensor (Omron, ZX-LD40) was installed using the underside of the Al ring as the reflective surface to detect the gap d .

Figure 4 shows the average electromagnetic levitation force acting on only the squirrel-cage Al ring, the attractive force of the permanent magnets, and the total levitation force acting on the levitating object. The method for measuring the electromagnetic levitation force acting solely on the Al ring has already been established by the authors (T. Ohji et al., 2020). In this method, the Al ring is fixed to a horizontal acrylic base equipped with a vertical rod. By canceling the weight of the base using a counterweight, the Al ring can be positioned at an appropriate gap d . The equilibrium gap d is then measured with additional weights. In Figure 4, when the total levitation force equals the weight of the levitating

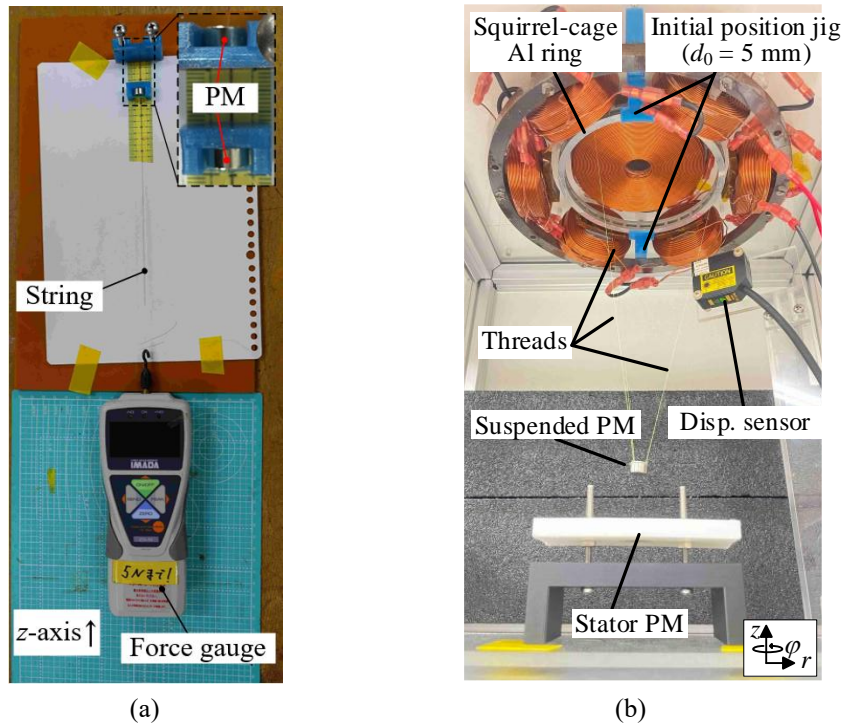


Fig. 3(a) Attractive force measurement between a pair of permanent magnets. The permanent magnets are NdFeB (N40) ($\phi 10 \text{ mm} \times 5 \text{ mm}$).

Fig. 3(b) Experimental setup. The levitating object consists of a squirrel-cage Al ring, three strings, a permanent magnet, and their fixture. Here, the value of l is set to -204.5 mm . The vertical displacement of the Al ring is measured with a laser displacement sensor. The initial distance d_{p0} between the suspended PM and stator PM is set to 23 mm .

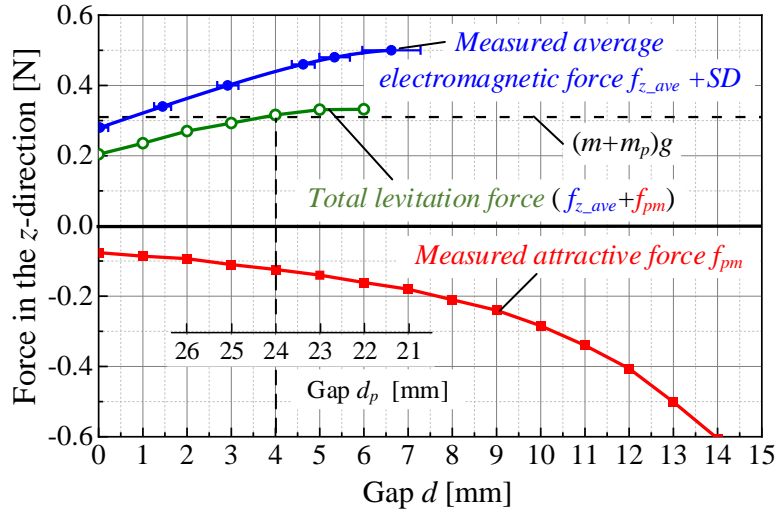


Fig. 4 Measurement results of the average electromagnetic force in the z -direction acting on the Al ring. The electromagnetic force f_{z_ave} (blue solid line) is the sum of the upward AC Ampere force and the downward AC induced repulsive force. The red solid line represents the measured permanent magnet attractive force f_{pm} . Therefore, the total levitation force (green solid line) acting on the levitating object is the sum of the upward electromagnetic force f_{z_ave} and the downward attractive force f_{pm} . The intersection of the total weight $(m+m_p)g$ of the levitating object and the total levitation force ($d = 4$ mm) is the stable equilibrium point. ($m = 28.6$ g, $m_p = 3.2$ g)

object $(m + m_p)g$, the forces in the z -direction are balanced. Under this condition, the equilibrium gap is $d = 4$ mm.

5. Levitation Experiments

Levitation experiments were performed using the setup shown in Fig. 3(b) under the excitation conditions summarized in Table 1, with the displacement l set to -204.5 mm. The target gap d for the levitating object is expected to be 4 mm, as mentioned above. Accordingly, a jig was installed to position the Al ring with an initial gap of $d_0 = 5$ mm. In addition, the initial distance d_{p0} between the permanent magnets was set to 23 mm.

Figure 5 shows the levitation test result of the squirrel-cage Al ring with the suspended permanent magnet. When a step current was applied at 5 seconds, the Al ring levitated immediately and exhibited damped vibration with an initial amplitude of approximately 1.3 mm and a vibration frequency f_1 of 4.06 Hz. At 5 seconds after the current was applied, the vibration of the levitating object converged to the target gap, resulting in stable levitation with a vibration amplitude

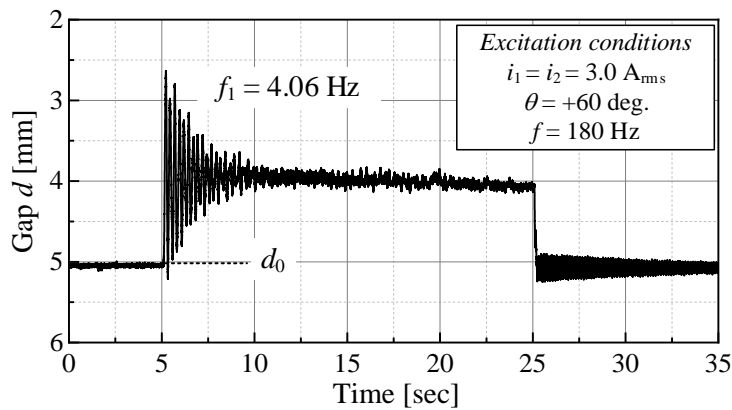


Fig. 5 Startup response characteristics of the levitated object's displacement in the z -direction. In the first 5 seconds after current application, the Al ring exhibits pronounced oscillations as it approaches the target gap of 4 mm. After settling, it oscillates slightly with an amplitude of approximately 0.1 mm, indicating stable levitation at the target gap. Based on the initial oscillation waveform, the vibration frequency f_1 was calculated to be 4.06 Hz.

of approximately 0.1 mm. Based on the vibration frequency f_1 , the vertical magnetic stiffness k_z of the levitating object was 20.6 mN/mm. On the other hand, the average magnetic stiffness k_{z_ave} estimated from the slope of the tangent at $d = 4$ mm in Fig. 4 was 19.1 mN/mm. These stiffness values are in good agreement, supporting the validity of the experimental results.

6. Conclusion

In this report, we achieved contactless and passive AC Ampere-type magnetic levitation by adding a small pair of permanent magnets to the squirrel-cage Al ring. A passive AC magnetic levitation technology that levitates only a conductive metallic object has not been previously reported. We plan to evaluate the magnetic stiffnesses of the levitating object in all directions during stable levitation. Furthermore, we intend to investigate approaches to stabilize the levitating object without the aid of permanent magnet pairs in the future.

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