

Analysis of Magnetic Force Characteristics for a Zero-Power Hybrid Maglev Actuator with Variable Permanent Magnetic Offset Mechanism

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Abstract

This paper presents the design and magnetic field analysis of a novel hybrid zero-power magnetic levitation system capable of a constant air gap under varying loads. Finite element simulations confirm that the linear superposition of sinusoidal permanent magnet flux and current-dependent electromagnetic flux enables active control of magnetic force while maintaining a constant gap. The simulation results validate the feasibility of constant-gap, zero-power levitation and demonstrate the systems capability to support ferromagnetic objects of different masses through coordinated control of the permanent magnet angle and coil current.

Keywords : Zero-power levitation, Hybrid magnetic levitation, Finite element method, Permanent magnet

1. Introduction

Magnetic levitation is an advanced mechatronics technology that is widely used to achieve non-contact support, such as magnetic levitation bearings, high-speed trains (Hyung-Woo et al., 2006; Maslen and Schweitzer, 2009; Zhou and Wu, 2022). However, a constant offset current is used in conventional electromagnetic (EM) levitation systems to balance gravity or to regulate levitation stiffness, and it will result in significant power consumption and temperature increase. It is not permitted in special industrial situations with vacuum, high precision or power limitations. The structure of a conventional maglev system makes it impossible to fully address these situations, even if advanced control strategies are proposed (Yao et al., 2023).

With the development of the 2nd generation of rare-earth permanent magnet materials, NdFeB can provide a huge maximum magnetic energy product (Coey, 2020). So, permanent magnet (PM) is being utilized in the magnetic circuit of the maglev system to minimize power consumption, such as maglev flywheels and hybrid maglev bearings (Kim et al., 2024; Xu et al., 2022). Unfortunately, the structure never achieved large-scale industrial application due to unsolvable contact adsorption in case of circuit failure. Meanwhile, due to the non-adjustable permanent magnet offset, the zero-power levitation is only achievable with a unique air gap in the current hybrid levitation system. What it means is that the air gap must change when the external load changes or the zero-power levitation will be broken (Lin et al., 2021; Zhao et al., 2022a). This shortcoming originates from structural characteristics that cannot be solved by innovative control strategies.

Directly controlling the motion of the PM is another method for achieving zero-power levitation. Feedback-controlled linear motion of the PM using a voice coil motor enables zero-power stabilized levitation (Oka et al., 2012; Sun and Oka, 2009). Also, rotation motion is used in a variety of systems to vary flux paths, and quasi-zero power levitation is realized (Sun et al., 2010; Zhao et al., 2020). By using a diametrically magnetized cylindrical PM and the variable flux path mechanism, quasi-zero-power levitation with a constant air gap under varying loads is achieved (Sun et al., 2022; Zhao et al., 2022b). However, compared with the coil current in the EM or EM-PM hybrid system, the motion control

of PM is a higher order system. As a result, it is hard to reach an available bandwidth comparable to that of coil current control (Gunter, 2003). Thus, the levitation of these systems is affected, and they typically exhibit low robustness and poor transient performance.

Based on the great contributions of the previous researchers, a new maglev actuator is proposed in this paper. The variable flux path mechanism is utilized in EM-PM hybrid maglev system, providing variable PM offset capability. It indicates that zero-power levitation with variable loads can be achieved while maintaining a constant air gap. First, the structure and components of the system are described. Then, its working principle is illustrated. Finally, the magnetic field and flux path are calculated using the FEM (finite element method). Simultaneously, the curve of the magnetic field density and reluctance force are obtained, and their characteristics are analyzed.

2. Working principle

2.1. Variable permanent magnetic offset mechanism

The variable permanent magnetic offset mechanism comprises a diametrically magnetized two-pole cylindrical PM, two F-type iron cores, a ferromagnetic levitated object, and a pair of EM coils. As shown in Fig. 1(a), When the magnetization direction of the PM is oriented vertically upward, the external magnetic flux generated by the PM flows through both F-type iron cores and returns directly from the N pole to the S pole. Because the soft ferromagnetic levitated object is excluded from the flux path, leading to negligible the magnetic flux density in the air gap. As shown in Fig. 1(b), once the PM is rotated to a certain angle, for example 30° , some of the magnetic flux still closes the loop through the F-type cores. In contrast, the rest of the flux is diverted through the ferromagnetic levitated object, thereby enhancing the air-gap magnetic flux density.

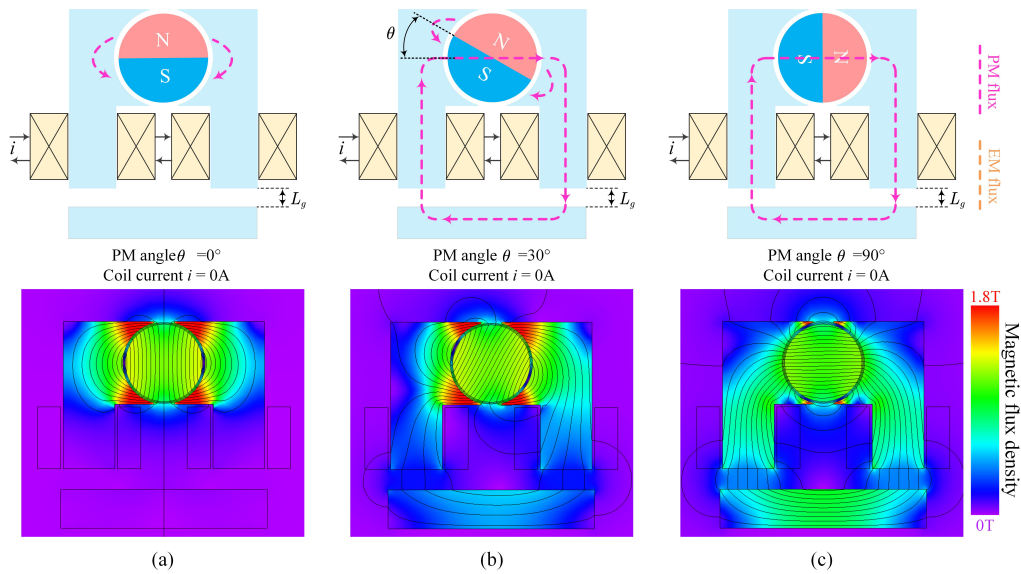


Fig. 1 Variable permanent magnetic offset mechanism

As the rotation angle of the PM continues to increase, a larger proportion of the generated magnetic flux closes the loop through the ferromagnetic levitated object and the F-type cores. Meanwhile, a decreasing portion of the flux returns directly through the iron cores without passing through the levitated object. As shown in Fig. 1(c), when the rotation angle of the PM reaches 90° , almost all of the magnetic flux generated by the PM passes through the ferromagnetic levitated object, except for a small portion of leakage flux. If the rotation angle of the PM continues to increase beyond 90° , the PM flux begins to decrease. When the angle exceeds 180° , the magnetic poles at the pole shoes of the F-type cores are reversed. This indicates that, for magnetic levitation purposes, the usable rotation range of the PM in this mechanism is limited to 0° to 90° .

2.2. Principle of hybrid magnetic levitation and zero-power control

In a magnetic levitation system, stable levitation is achieved when the upward magnetic force acting on the ferromagnetic levitated object balances its gravitational force. Due to the inherent limitations in the transient response of PM rotary actuation, levitation systems that rely on direct control of rotational actuators generally exhibit weak robustness

and low transient characteristics. Therefore, to achieve high-performance levitation control, EM coils are integrated into the magnetic flux path to enable real-time control of the magnetic force.

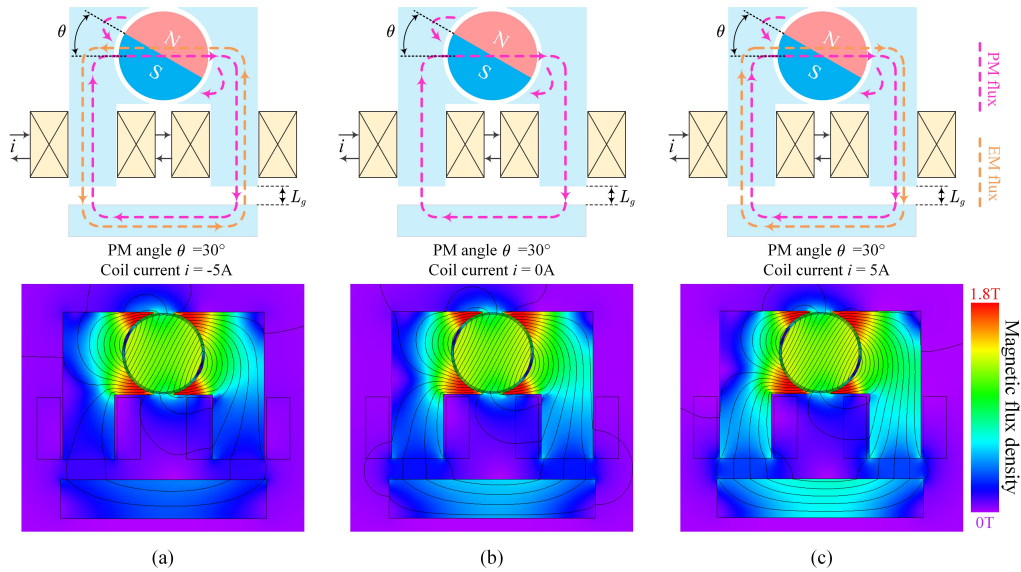


Fig. 2 Real-time control principle of the magnetic force

The fundamental configuration and working mechanism of the proposed system resemble those of typical EMPM hybrid magnetic levitation systems. As shown in Fig. 2(b), when the PM is rotated to a certain angle of 30° and the control current is zero, the levitation system operates in a zero-power state. To maintain stable levitation and constant air gap under a reduced load, the magnetic force must be correspondingly decreased. As illustrated in Fig. 2(a), applying a reverse current to the coil produces magnetic flux opposite in direction to that of the PM. Consequently, the magnetic flux passing through the ferromagnetic levitated object decreases, reducing the air-gap magnetic flux density and thus the magnetic force. To maintain a constant levitation air gap and return to the zero-power condition, the PM angle is decreased with feedback control, enabling the system to reconstruct the zero-power state.

Under increased load conditions, a stronger magnetic force is required. As shown in Fig. 2(c), applying a forward current aligns the coils magnetic flux with that of the PM, enhancing the overall flux through the levitated object and increasing the magnetic flux density across the air gap. To reestablish the zero-power levitation condition under increased load while maintaining a constant air gap, the rotation angle of the PM is progressively decreased. This adjustment compensates for the additional magnetic force and reconstructs the equilibrium state without consuming additional power.

3. Design of prototype system

To realize the zero-power and constant-gap levitation described in Section 2, a prototype system has been designed. As shown in Fig. 3, the magnetic unit is composed of two F-type iron cores, a diametrically magnetized two-pole PM, and a pair of EM coils. To enable precise control of the PM angle, a servo system consisting of a brushless DC motor, a planetary reducer, and an incremental encoder is employed for rotational actuation and feedback control. Sudden increases or decreases in current can cause abrupt changes in the torque acting on the permanent magnet. Therefore, the ability to lock the PM angle is critical to the feasibility of the prototype system. Without PM angle locking, the PM flux lead to unpredictable magnetic force behavior, potentially causing instability or divergence of the levitation system. Therefore, a worm reducer is employed in the indexing mechanism of the PM to ensure angle locking. This design leverages the self-locking characteristic of the worm reducer. Once zero-power levitation is achieved, the servo motor can be disabled to eliminate motor power consumption. Without a self-locking mechanism, a servo motor with extremely high stiffness and control performance would be required, resulting in increased structural size and power consumption.

In addition, a laser displacement sensor is employed to measure the displacement of the ferromagnetic levitated object, thereby enabling real-time indirect measurement of the levitation air gap length. To achieve stable levitation in one-degree-of-freedom, a linear guideway is employed to provide vertical guidance for the ferromagnetic levitated object. Additionally, a micrometer head is employed to adjust the initial levitation air gap and to limit the maximum allowable gap during operation. Similarly, a mechanical stopper is used to limit the minimum levitation gap. these two structures

serve a protective role similar to that of auxiliary bearings in magnetic suspension systems. For this zero-power hybrid magnetic levitation prototype, a complete experimental system can be established by integrating electronics components including power amplifiers, servo drivers, and control units.

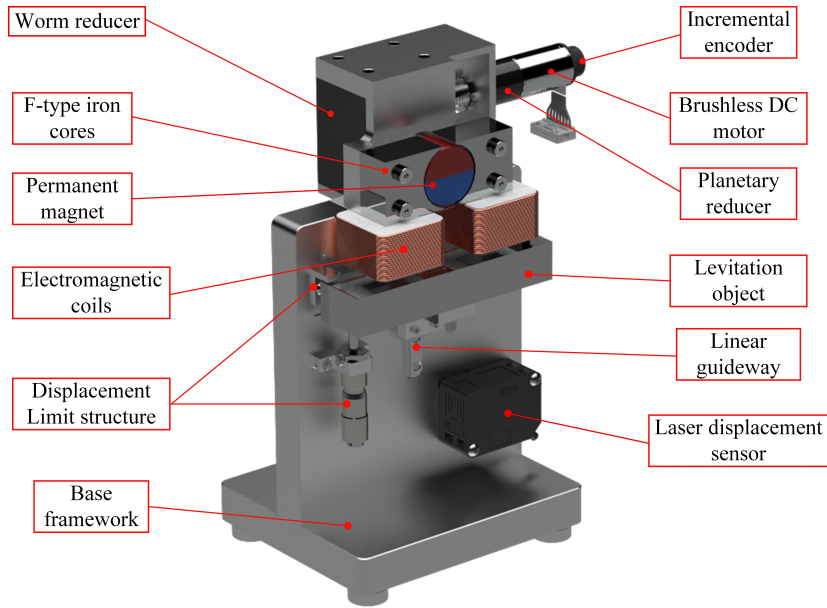


Fig. 3 Structure of prototype system

4. Magnetic field analysis with finite element method

4.1. Magnetic field density simulation

To analyze the magnetic field characteristics of the system, finite element method (FEM) analysis is performed using the JMAG software. Firstly, finite element analysis is conducted to evaluate the air-gap magnetic flux density with the air gap length fixed at 8 mm. As shown in Fig. 4(a), when the rotation angle of the PM increases from 0° to 90° with zero current in the EM coils, the magnetic flux density exhibits a sinusoidal increase. At a PM angle of 0° , the magnetic flux density approaches zero, while at 90° , it reaches its peak value. Applying a forward current to the electromagnetic coil generates an additional magnetic field, which introduces a bias to the flux density produced by the PM. As shown in graphic of the simulation results, the application of a forward current results in an upward translation of the magnetic flux density profile induced by the PM.

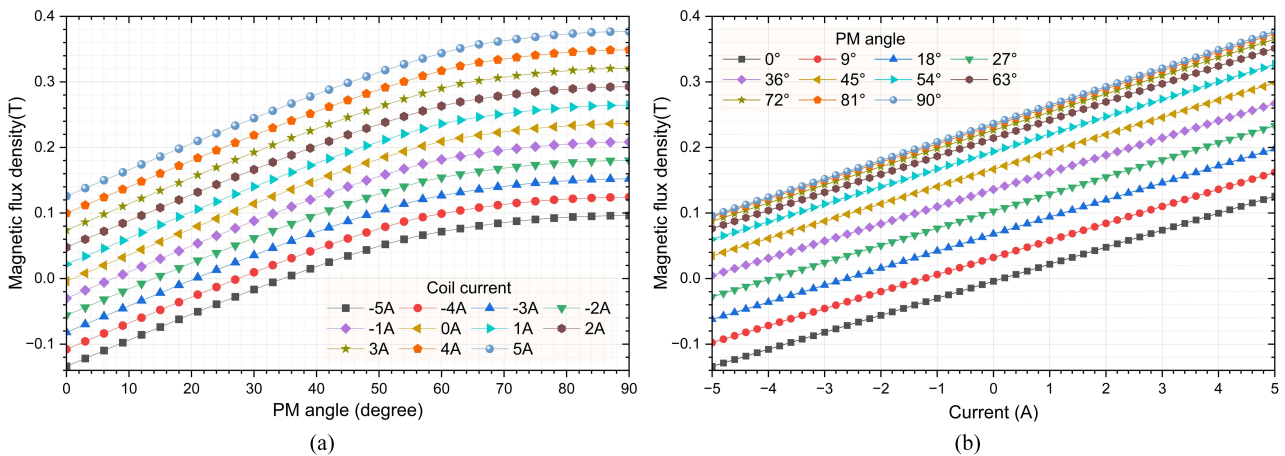


Fig. 4 Magnetic flux density simulation

Under reverse current excitation, the magnetic flux density is biased in the opposite direction, which is reflected as a downward translation of the flux density curve in the simulation results. Moreover, the simulation currents are set

as arithmetic increments. At a certain PM angle, the resulting magnetic flux density profiles exhibit uniform spacing along the vertical axis. In other words, under all current conditions, the magnetic flux density varies sinusoidally with the increasing PM angle.

As shown in Fig. 4(b), at a fixed PM angle, the magnetic flux density exhibits a linear relationship with the current of EM coil in the range from -5 A to 5 A. Meanwhile, it can be observed from the figure that, under a fixed current, the differences between adjacent magnetic flux density curves are not uniform. In conjunction with Fig. 4(a), it can be concluded that this non-uniform spacing results from the sinusoidal variation of the PM magnetic flux. Based on the two subfigures in Fig. 4, it can be concluded that the magnetic flux generated by the PM varies sinusoidally with the rotation angle, while the flux generated by the EM coil increases linearly with current. Furthermore, the PM flux and the EM flux are linearly additive in the magnetic flux path.

4.2. Magnetic force simulation

In the above mentioned magnetic levitation systems, the magnetic force arises from the variation of magnetic energy stored in the air gap. In other words, variations in magnetic flux and air gap length lead to changes in magnetic energy. The resulting force can be theoretically derived using the Maxwell stress tensor or the principle of virtual work. Magnetic force simulation with FEM is performed as well, employing the same setup and parameters described in Section 4.1. As shown in Fig. 5(a), when the current is zero, the magnetic force exhibits an approximately sinusoidal curve shaped as the PM angle increases from 0° to 90° . This curve represents the capability of achieving zero-power levitation for ferromagnetic objects of varying mass under a constant air gap of 8 mm.

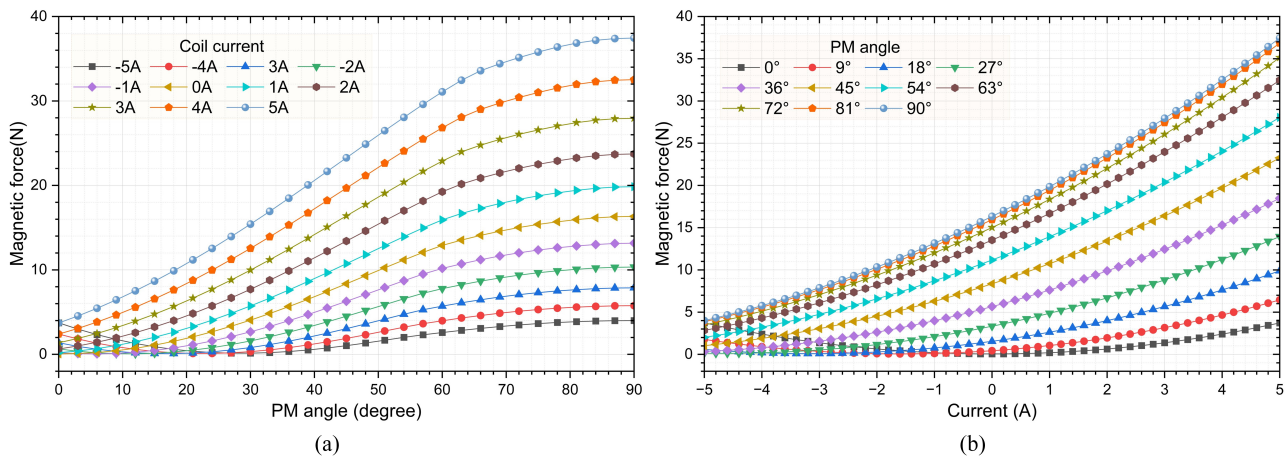


Fig. 5 Reluctance force simulation

Since the magnetic force is proportional to the square of the magnetic flux density, its variation with current no longer exhibits a linear offset along the vertical axis. Additionally, under small PM angles with reverse EM current excitation, the magnetic flux reverses polarity, thereby still producing magnetic attraction. Such behavior poses challenges for feedback controller design. Therefore, the reverse current should be limited based on the PM angle, or the system should avoid operating within the reverse flux region. For magnetic levitation feedback control, the real-time magnetic force control simulation results with variable current are shown in Fig. 5(b). At a fixed PM angle, the magnetic force increases with forward EM current and decreases with reverse EM current. On the same horizontal axis, points represent equal magnitudes of magnetic force. By moving along this axis to the intersection with zero current, zero-power levitation can be achieved.

5. Conclusions and further works

In this study, a novel zero-power hybrid magnetic levitation system was proposed and analyzed. By integrating a diametrically magnetized PM, F-type iron cores, and EM coils, the system achieves controllable magnetic force through the linear superposition of PM and EM flux. Finite element simulations demonstrated that the PM flux varies sinusoidally with the rotation angle, while the EM flux exhibits a linear relationship with coil current. An experimental prototype was developed, the prototype validated the feasibility of constant-gap, zero-power levitation across varying loads. Simulation

and control results confirmed that effective force regulation can be achieved through coordinated control of PM angle and coil current. Future research will focus on the optimization of the prototype design, the development of a predictive mathematical model, and the design of robust feedback control strategies.

Acknowledgments

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