

Analysis and Design of Hybrid Excitation Axial-Flux Electrodynamic Wheels for Maglev Transportation

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In this paper, a new Hybrid Excited Axial Electrodynamic Wheel (HEAEDW) for Electrodynamic Suspension (EDS) maglev systems is proposed and investigated. The HEAEDW simultaneously generates both propulsion and levitation forces through a moving magnetic rotor above a conductive guideway. This hybrid excitation machine not only enables active control of the thrust force but also reduces the risk of permanent magnet (PM) demagnetization, improving system reliability. The field distribution and forces generated by the HEAEDW are analyzed using both analytical methods and the finite element method (FEM). Key parameters influencing performance are investigated and adjusted to optimize machine operation. A prototype of the HEAEDW is developed, and experimental results are presented to validate the predicted outcomes. The results demonstrate that the proposed machine can generate an equivalent levitation force to basic axial electrodynamic wheels (EDWs) while providing additional thrust and controllability.

Index Terms—Hybrid Excited, EDS, analytical, FEA, axial flux.

I. INTRODUCTION

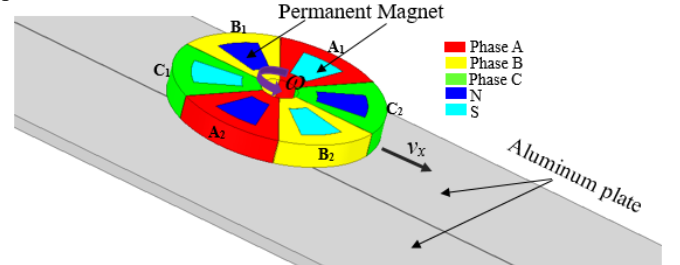
MAGLEV trains have garnered renewed interest due to their numerous advantages over conventional wheel-on-rail systems, such as reduced maintenance costs, lower noise and vibration levels, and the ability to navigate steeper grades and tighter curves [1]. However, the primary drawbacks of maglev systems are the significantly higher initial capital costs and increased guideway complexity compared to traditional iron-rail systems. A promising alternative that is still in the research and development phase is the Electrodynamic Wheel (EDW) maglev system, which offers a potentially lower-cost solution [2].

The EDW integrates lift, thrust, and braking capabilities into a single device. There are two main types of EDW technologies: radial and axial. The radial magnetic configuration, as considered by Bird, offers the advantage of having the traveling field aligned with the direction of translational motion. However, the radial EDW suffers from lower force density, as the area interacting with the conductive plate is much larger compared to that of an axial wheel at any given instant. In contrast, the axial configuration can produce lift even without translational speed, but it cannot generate thrust when the rotor's axis is orthogonal to the track.

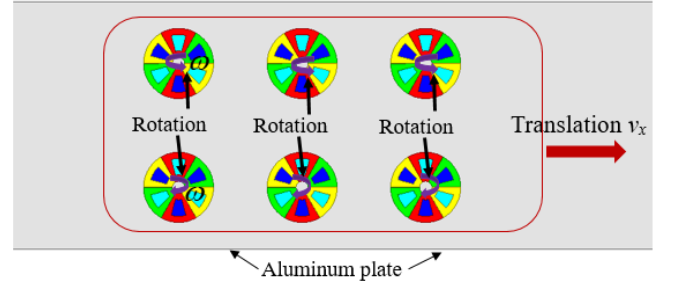
Fujii and Ogawa proposed two types of rotating axially placed PMs for simultaneously generating thrust and lift. These configurations are difficult to operate due to asymmetric rotation of the PMs over a conductive sheet. An additional disadvantage of PM-based EDW systems is their susceptibility to vertical oscillation under external disturbances, which may lead to unstable suspension at high speeds [2].

In this paper, a new PM and electromagnetic hybrid-excited axial EDW topology is introduced. This design aims to generate thrust force with a constant airgap while simultaneously controlling the levitation force, as illustrated in Fig. 1. The proposed hybrid axial EDW consists of alternating polarity permanent magnets and three-phase electromagnet coils. The main objective of this paper is to derive the 3D spatial magnetic field and the 3D eddy current forces, validate the analytical

model through 3D FEA, and investigate the effects of key parameters on the generated forces. A prototype of the HEAEDW is fabricated and tested to validate the theoretical predictions.



(a) 3D schematic of a single rotor above an aluminum plate



(b) Top view of a 2D schematic of the maglev vehicle.

Fig. 1. The configuration of the HEAEDW.

II. COFIGURATION AND OPERATION PRINCIPLES

A 3D schematic of the proposed HEAEDW is shown in Fig.1(a), and a schematic of the maglev vehicle is depicted in Fig.1(b). The HEAEDW utilizes a simple, flat guideway, potentially as cost-effective as high-speed rail. It consists of three isolated-phase concentrated windings and axial flux PMs. The PMs, with alternating polarities, are symmetrically arranged circumferentially. The three-phase concentrated windings, shown in Fig. 1, are wound alternately on the PMs and supplied with alternating current (AC) in a 120° phase sequence.

In the absence of a time-varying field, the rotation of the PM arrangement with a constant airgap generates no thrust due to symmetric flux. However, when three-phase windings are energized, a traveling magnetic field is created in the airgap,

which can enhance or weaken the PM flux asymmetrically, as shown in Fig. 2. This asymmetry generates both thrust and lift forces. The rotor's motion and the traveling wave's speed must match to maintain asymmetric flux, resulting in thrust and lift forces.

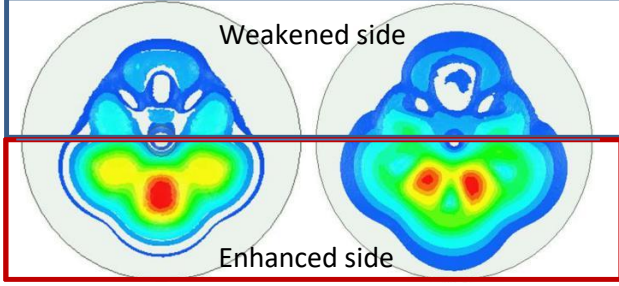


Fig. 2 The flux density of propose motor : (a) Rotor position =0 degree; (b) Rotor position =180 degree;

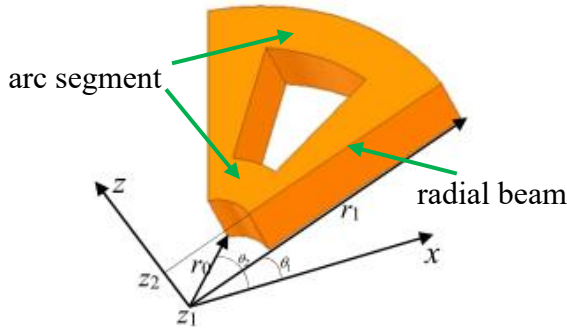
The magnetic field produced by the system can be actively controlled by adjusting the AC excitation current, enabling dynamic control over thrust and levitation. The relationship between the current frequency f and rotor speed n is governed by:

$$n_r = \frac{120 f}{p} \quad (1)$$

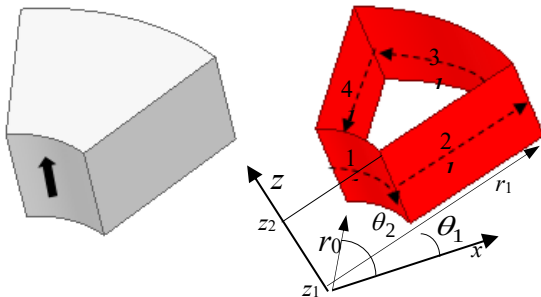
where p is the number of pole pairs in the armature winding.

III. MODELLING OF HEAEDW

In this context, a 3D analytical approach is developed, based on the volume integral method and SOVP, to calculate the steady-state and transient performance of the HEAEDW. The Biot-Savart law is employed to compute the magnetic field generated by the coils and PMs.



(a) 3-D analytical model for coils

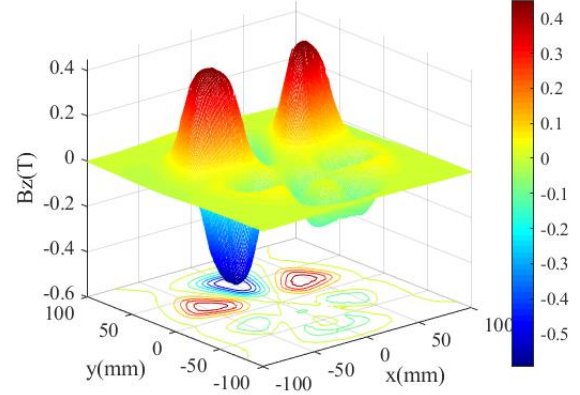


(b) Equivalent current sheet model for an axial magnet piece

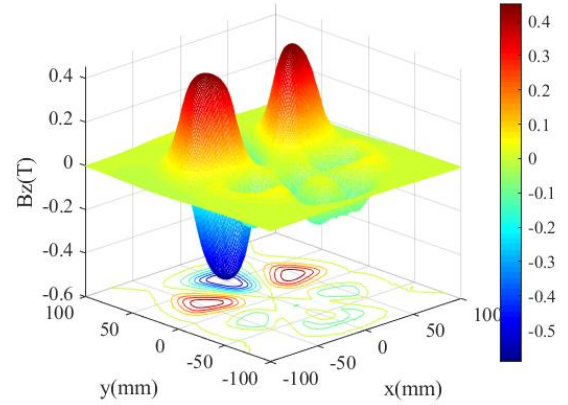
Fig. 3. 3-D analytical model

The 3D analytical model for the coils is illustrated in Fig. 3. As shown, the coils are discretized into radial beam or circular

arc segment volume elements. The magnetic flux produced by the Halbach rotor is modeled using equivalent current sheets, calculated via the Biot-Savart law. The equivalent surface current is determined by the circumferential component of coercivity on the surface of the magnet pole, based on the theory of magnetization in magnetic media.



(a) 3-D analytical model



(a) 3-D FEA model

Fig. 4. The comparison of the z-component field

IV. RESULTS

A comparison of the z-component field, calculated using the 3D analytical model, with results from an Ansys Maxwell 3D finite-element model of the HEAEDW is presented in Fig. 4. The results show close agreement between the two methods. A HEAEDW prototype has been designed and constructed in the laboratory, and the experimental results have been validated against both the FEA and the proposed analytical approach. The full paper will provide a more in-depth analysis and optimization of the parameters that influence performance, including force and efficiency values.

REFERENCES

- [1] Hyung-Woo, K. Ki-Chan, and L. Ju, "Review of maglev train technologies," *IEEE Transactions on Magnetics*, vol. 42, no. 7, pp. 1917-1925, 2006.
- [2] N. Fujii, G. Hayashi, and Y. Sakamoto, "Characteristics of magnetic lift, propulsion and guidance by using magnet wheels with rotating permanent magnets," in *2000 IEEE Industry Applications Conference*, 2000, vol. 1, pp. 257-262..