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PERFORMANCE AND COST ANALYSIS OF HALBACH ARRAYS IN ELECTRODYNAMIC LEVITATION FOR HIGH-SPEED TRANSPORT

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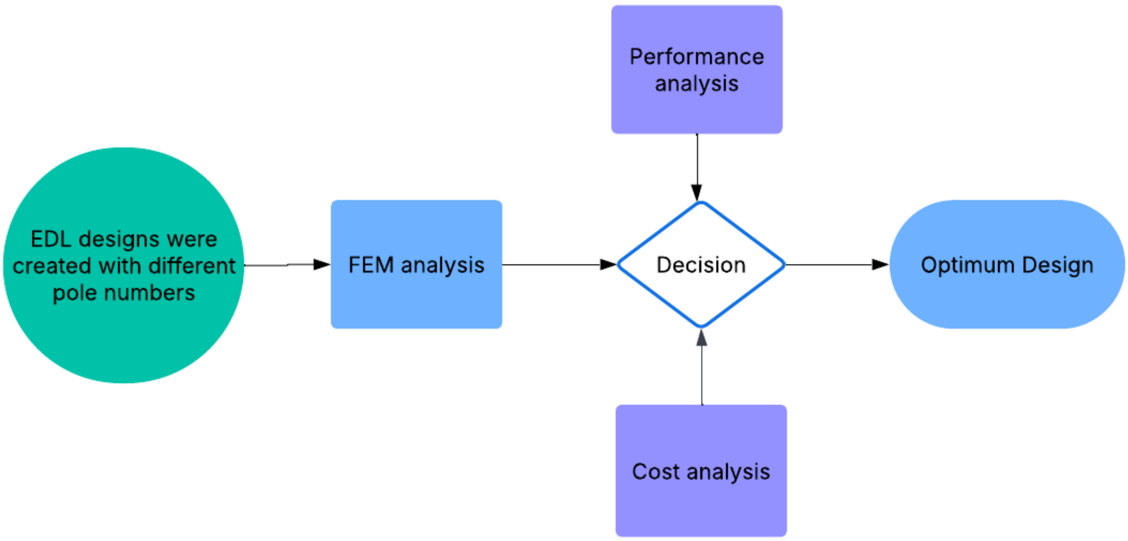
Highlights

- Performance evaluation of rotating Halbach arrays with 8 to 16 pole configurations.
- Comparative analysis covered Halbach variants and the conventional N/S configuration.
- Cost analysis included NdFeB, Ni-Cu-Ni coating, and assembly-related complexity.
- 12-pole Halbach array identified as optimal in performance and cost balance.
- Recommendations offered for cost-effective design of high-speed levitation systems.

Graphical Abstract



Flowchart of the proposed method

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ABSTRACT: This study evaluates the performance and cost implications of rotating Halbach magnet arrays in electrodynamic levitation systems used in high-speed transportation applications such as Maglev and Hyperloop. Four different Halbach configurations (8, 10, 12, and 16 poles) are investigated and compared with a conventional N/S magnet arrangement. Finite Element Method simulations are employed to analyze key parameters including lift force, drag force, torque, and magnetic flux density. In addition, a cost analysis is conducted, considering raw material usage, Ni-Cu-Ni coating requirements, and assembly complexity. The findings indicate that Halbach arrays significantly enhance levitation performance, with higher pole numbers generating stronger lift and magnetic flux. However, they also lead to increased drag force and a reduced lift-to-drag (L/D) ratio, slightly impacting system efficiency. While NdFeB material consumption remains relatively stable across configurations, coating and manufacturing costs rise with increased pole count. Among the examined configurations, the 12-pole Halbach array offers the most balanced trade-off between performance and cost. Specifically, the 12-pole configuration achieves a lift force of 1399.36 N with a corresponding drag force of 332.28 N and an L/D ratio of 4.21, indicating a favorable efficiency-to-cost balance. These results demonstrate that optimized Halbach configuration can reduce the transition speed compared to 8 and 10 pole Hallbach configirations, highlighting their suitability for next-generation high-speed transportation systems. An effective balance between levitation performance and cost depends on the choice of pole configuration, which plays a key role in guiding future high-speed transportation system designs.

Keywords: *Electrodynamic Levitation, Halbach Arrays, Maglev Trains, Hyperloop, Transportation Systems*

1. INTRODUCTION

Electrodynamic levitation (EDL) is a fundamental suspension mechanism used in high-speed transportation systems, particularly in technologies like Hyperloop and Maglev trains. Furthermore, it plays a crucial role in space and aerospace applications, including the removal of space debris and stabilization of satellites. Magnetic levitation is the core principle of Hyperloop technology, enabling frictionless suspension and effective integration with electromagnetic propulsion systems. In the industrial sector, EDL is used for vibration isolation in high-precision instruments and particles analysis. This system operates based on the repulsive force generated by the interaction between a conductor and magnetic field. The force counteracts the weight of the moving object, allowing it to remain suspended in the air. Specialized magnet arrangements such as Halbach arrays are employed to enhance the efficiency of EDL systems. Halbach arrays concentrate the magnetic field in one direction while weakening it in the opposite direction, thereby increasing the levitation force and optimizing energy efficiency. Due to these properties, Halbach arrays significantly improve system performance in electrodynamic levitation by balancing lift and drag forces [1, 2].

In EDL systems, eddy currents are induced when a moving conductive body (track) is exposed to a magnetic field generated by coils. However, for the system to function, a certain transition speed must be exceeded [3]. Once this speed is surpassed, the vehicle can remain levitated. Therefore, at low speeds or

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when stationary, the vehicle requires landing wheels. This characteristic highlights the dynamic and speed-dependent nature of EDL systems.

In recent years, passive electrodynamic suspension (PEDL) systems, where the magnetic field is provided by permanent magnets (PM), have gained significant attention due to their simple structure and cost advantages. The emergence of innovative transportation concepts such as Hyperloop has further increased interest in PEDL systems. Since these systems do not require superconducting coils, cooling facilities, or complex power conversion systems, they significantly reduce both installation and operational costs [4, 5]. The repulsive forces generated by varying magnetic fields enable the vehicle to move at high speeds with minimal friction [6].

In a linear Halbach array, lift force gradually increases with speed and asymptotically reaches a maximum value [7]. However, if the speed falls below a specific transition, the drag force becomes more significant than the lift force, preventing levitation [8]. To overcome drag at low speeds, either a high-power propulsion system is used at low speeds or a larger air gap is created [9]. In EDLs, not only linear but also rotating Halbach arrays are utilized [10]. The varying magnetic field generated by the permanent magnets in a rotating Halbach array induces eddy currents in a conductive plate. These eddy currents create a secondary magnetic field, resulting in a repulsive lift force. If the rotational speed of the magnet rotor remains above a minimum transition, the rotor can remain stably levitated [11].

The primary advantage of a rotating Halbach array over a linear Halbach array is that the levitated vehicle does not need to move linearly. In other words, by simply rotating the permanent magnets, levitation can be achieved even while the vehicle remains stationary. Several studies in the literature have explored electrodynamic levitation and Halbach arrays. Various configurations and materials have been investigated to enhance the performance and feasibility of PM-EDL systems [7, 12]. Beauloye and Dehez [13] provided a comprehensive evaluation of PM-EDL systems by classifying their topologies and discussing experimental validation setups; however, they emphasized that these systems have not yet been integrated into MAGLEV applications and highlighted the need for a comparative performance analysis. Oleszczuk [14] used the Finite Element Method (FEM) to derive the transfer functions of electromagnetic suspension systems in magnetically levitated (Maglev) vehicles. The dynamic interaction between the Maglev track and the vehicle was analyzed through analytical and theoretical examples, and various control laws were evaluated in detail to ensure stable and robust levitation. Galluzzi, et al. [15] developed a multidomain lumped-parameter model to investigate and stabilize electrodynamic levitation systems by capturing the strong interaction between electromagnetic and mechanical dynamics. Hu, et al. [16] designed and developed a frequency-tuned electromagnetic vibration energy harvesting device based on magnetic levitation. Utilizing repulsive forces and adjustable frequencies improved the system's efficiency. Zhu, et al. [17] investigated the optimization of magnetic levitation and damping forces using Halbach arrays. They proposed a passive damping method based on a permanent magnet-damping conductor plate to enhance stability in superconducting Maglev systems. Tang, et al. [18] developed a six-degree-of-freedom (6-DOF) micro-positioning mechanism using Halbach array magnets and electromagnetic direct-drive systems. They suggested that this system could be used in ultra-precise magnetically suspended robotic arms. Li, et al. [19] studied optimized PM rotors with Halbach arrays to improve magnetic coupling in HTS flywheel systems. These optimized PM rotors concentrate the magnetic flux of HTS stacks while maintaining low-temperature operating conditions. Mollahasanoglu, et al. [20] examined the performance and cost effects of different permanent magnet (PM) and aluminum track configurations. They conducted numerical simulations to determine optimal geometric parameters.

In PM-EDL systems, dynamic stability and damping performance remain critical issue for practical implementation. A passive damping configuration that utilizes the end-leakage field of a Halbach array has been shown to reduce vibration amplitude by up to 50%, significantly enhancing the dynamic stability of PMEDL systems [21]. A similar contribution was made through the development of a 3D analytical model that incorporates vertical vibration velocity and experimentally validates a novel passive magnet arrangement for improved system damping [22]. The dynamic properties of propulsion-type Halbach-based levitation systems have also been modeled using coordinate transformation techniques to interpret complex oscillation behavior [23].

To improve performance metrics such as lift-to-weight ratio, a two-stage analytical optimization approach was introduced for Halbach-array-based EDL configurations, supported by validated structural parameters [24]. Another structure, the Traveling Magnetic Electromagnetic Halbach Array, which simultaneously produces lift and thrust, was proposed and confirmed through analytical modeling, 2D FEM simulation, and experimental validation [25]. The electromagnetic design and dynamic behavior of an EDL system intended for Hyperloop vehicles operating in low-pressure environments have been explored, leading to effective passive levitation and guidance solutions[26]. A rotary-magnet-based EDL was developed specifically for a Hyperloop capsule, in which lift and drag forces were optimized via analytical and numerical methods and validated through prototyping[27]. Energy efficiency improvements have also been addressed by introducing adjustable gaps between horizontally arranged Halbach magnets, resulting in reduced magnetic braking force and up to 15% instantaneous power savings [28]. Finally, an electromagnetic actuator based on a Halbach array demonstrated enhanced thrust performance and minimized normal force disturbance, indicating strong applicability for magnetic levitation transport systems [29].

Although some studies on EDL systems exist in the literature, the effects of rotating Halbach arrays on lift and drag forces have been explored only to a limited extent. While most research focuses on the performance of linear Halbach arrays or the general design of magnetic levitation systems, the lift forces generated by rotating Halbach arrays with different pole configurations and their performance variations have not been thoroughly analyzed in detail. In this study, the lift and drag forces of EDL disks with rotating Halbach arrays were examined, as well as the effects of different pole configurations (8, 10, 12, and 16 poles) on performance. Using FEM simulations in Ansys Maxwell, key parameters such as lift force, drag force, magnetic flux density, and torque were evaluated and compared across different pole configurations. In addition to the performance assessment, a comprehensive cost analysis was conducted, considering factors such as NdFeB mass usage, Ni-Cu-Ni coating requirements, and assembly complexity. The results show that increasing the number of poles improves the overall performance of electrodynamic levitation by improving the lift force and magnetic flux density. However, this improvement is accompanied by an increase in drag force, which reduces the lift-to-drag (L/D) ratio and can negatively affect system efficiency. Furthermore, higher pole counts are associated with increased manufacturing complexity and cost, emphasizing the need for a balanced design approach. These findings show the importance of carefully selecting pole configurations in rotating Halbach arrays, particularly for high-speed applications like Maglev and Hyperloop.

2. ELECTRODYNAMIC LEVITATION DESIGN

Magnetic levitation is the core principle of Hyperloop technology, enabling frictionless suspension and effective integration with electromagnetic propulsion systems[30]. EDL is a magnetic suspension method that generates lift force through eddy currents induced in a conductive surface by moving magnetic fields. Since EDL produces magnetic lift without physical contact, it is widely used in high-speed transportation systems. EDL systems operate by inducing eddy currents on a conductive surface under a moving magnetic source, such as a permanent magnet or an electromagnet. According to Lenz's Law, these eddy currents generate a magnetic field opposing the changing magnetic field. As a result, a lift force (F_y) acts against the moving magnetic source, while a drag force (F_z) opposes its motion. Figure 1 shows the basic structure of the designed EDL.

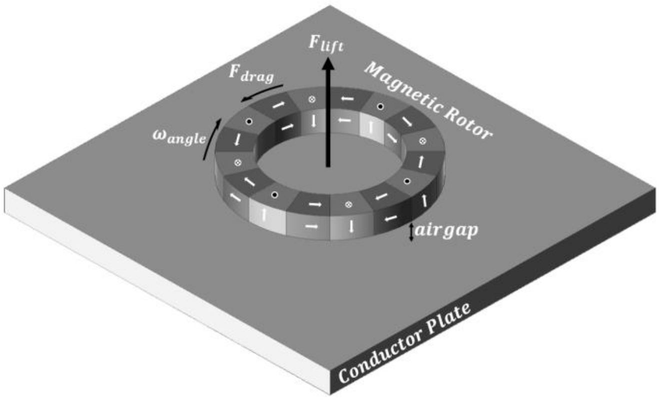


Figure 1 The structure of the designed EDL.

Drag force analysis is conducted using standard circuit theory, where voltage and current can be expressed as follows [3, 8].

$$V = L\frac{di}{dt} + Ri = \omega\emptyset_0 Cos\omega t \quad (1)$$

If this equation is solved here.

$$i(t) = \frac{\emptyset_0}{L}\left[\frac{1}{1+\left({R}/{\omega L}\right)^2}\right]\left[sin\omega t + \frac{R}{\omega L}Cos\omega t\right] \quad (2)$$

To maximize the lift force, the phase of the current is shifted by 90° relative to the voltage, and the lift and drag forces can be defined as follows.

Lift force;

$$F_y = \frac{B_0^2 w^2}{2kL}\frac{1}{1+(\frac{R}{\omega L})^2}e^{-2kg} \quad (3)$$

Drag force;

$$F_z = \frac{B_0^2 w^2}{2kL}\frac{(\frac{R}{\omega L})}{1+(\frac{R}{\omega L})^2}e^{-2kg} \quad (4)$$

Here, w is the transverse width of the Halbach array, B_0 is the peak magnetic field, g is the vertical distance between the lower surface of the Halbach array and the centroid of the upper leg of the circuit, L is the inductance of the circuit, and R is its resistance. ω is the excitation frequency, given by $\omega = (2\pi/\lambda)v$ [3].

The skin depth determines how deeply the eddy currents penetrate the conductive surface and is defined as follows:

Here, ω is the angular frequency of the magnetic field.

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \quad (5)$$

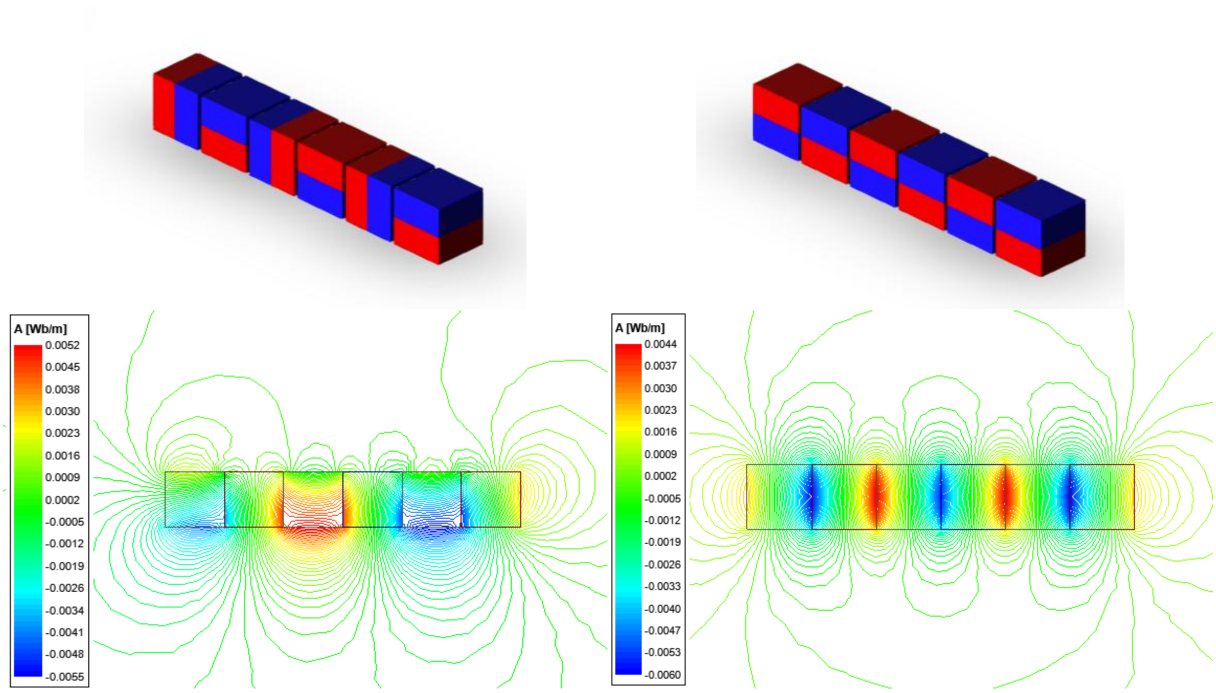
Here, δ is the skin depth, μ is the material's magnetic permeability (Henry/meter), and σ is the electrical conductivity of the material (Siemens/meter).

The lift-to-drag ratio evaluates the performance of such systems, serving as an indicator of the system's efficiency at a given speed.

$$^{L}/_{D} = \frac{F_y}{F_z} = \frac{\omega L}{R} = \frac{2\pi v}{\lambda}\left(\frac{L}{R}\right) \quad (6)$$

Here, λ is the wavelength of the Halbach array fields, and v is the train's velocity.

The research conducted by Halbach [31] on various applications of permanent magnets in accelerators and electron storage rings is described in the literature as the Halbach array. Halbach arrays focus the magnetic field in one direction, increasing the lift force while minimizing magnetic flux leakage on the other side. For this reason, they are commonly used in EDL systems to enhance lift force. Halbach arrays offer several advantages that make them highly suitable for electrodynamic levitation systems. They enable contactless suspension, effectively eliminating mechanical friction and reducing wear. Their configuration ensures stable operation even at high speeds, which is essential for high-performance transportation applications. Additionally, since they utilize permanent magnets, they provide an energy-efficient solution that does not require continuous external power. The inherent magnetic balancing mechanism of the array contributes to a self-stabilizing structure, further enhancing system reliability and efficiency. Figure 2 shows the magnetic field generated by a Halbach array compared to a classical N/S configuration. Magnetic analyses were performed using the finite element method (FEM). As seen in Figure 2, the magnetic flux is more concentrated in one direction.



a) Halbach array b) N/S array

Figure 2 The static magnetic field distribution of the FEM model

Figure 3 shows the geometric structures of the investigated 8, 10, 12, and 16-pole Halbach array magnet disks and an 8-pole N/S array magnet disk. Table 1 displays the physical properties of these structures and the number of magnets in each configuration. All magnet disks are selected to have the same geometric dimensions. There is a 5 mm air gap between the disks and the aluminum plate. An analysis has been conducted considering torque, lift force, drag force, and magnetic flux density for the 8, 10, 12, and 16-pole Halbach array magnet disks, as well as the 8-pole N/S array magnet disk.

Table 1 Physical parameters of PM-EDL system

Parameter	Symbol	Value
Pole Number	p	8 -10 -12 – 16
Magnet Type	-	N35 (NdFeB)
Total Magnet Number	s	8 – 16 – 20 – 24 – 32
Magnet Thickness	l	10 mm
Mechanical Air Gap	g	5 mm
Angular Velocity range	w	0 – 10000 rpm
Angular Velocity	W	5000 rpm
Disk outer diameter	D	150 mm
Disk inner diameter	d	50 mm
Conductor (Rail) Thickness		10 mm
Conductor (Rail) width		200 mm
Conductor (Rail)length		200 mm

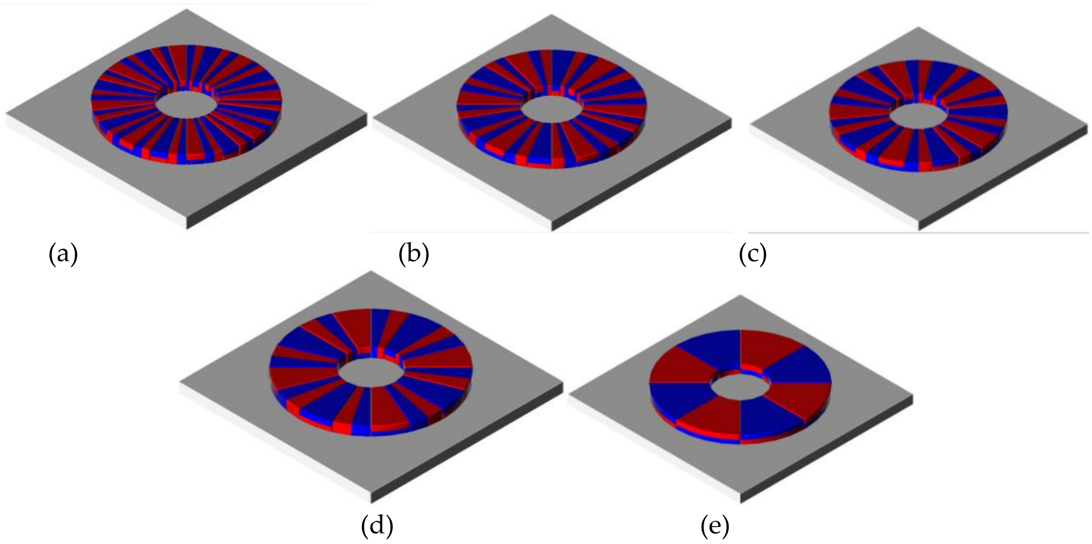


Figure 3 Designed Magnet Disks. a) 16 pole Halbach array b) 12 pole Halbach array c) 10 pole Halbach array d) 8 pole Halbach array e) 8 pole N/S array

3. FEM ANALYSIS

FEM is a numerical technique used to obtain approximate solutions for boundary value problems in the mathematical modeling of physical phenomena. To create a solution using FEM, the solution region is divided into smaller regions, such as triangles, quadrilaterals, or polygons for two-dimensional problems, and cubes or prisms for three-dimensional problems [32]. By assuming that the vector potential within each element vary according to a specific relationship, the vector potential distributions across all elements can be assembled. This process ultimately yields an approximate solution. If the sources in the magnetic field are shown by J and the magnetic resistance by υ , the energy function in such a Poisson field in the Cartesian coordinate system is expressed as follows [33].

$$W = \iint_{\Omega} \left[\frac{1}{2}\upsilon|\nabla A|^2 - JA\right].dxdy \quad |\nabla A|^2 = \left(\frac{\partial A}{\partial x}\right)^2 + \left(\frac{\partial A}{\partial y}\right)^2 \tag{7}$$

In the energy relation in Eq. (7), the $\frac{1}{2}\upsilon|\nabla A|^2 - JA$ term represents the energy density on the surface $d\Omega =$ dxdy. It is possible to obtain more than one vector potential for a solution region, but one of them is.

$$\nabla^2 A = \nabla A = \frac{1}{\upsilon} J = \mu J \tag{8}$$

This solution, which gives Poisson's equation, also minimizes the vector potential energy within the region. To solve Poisson's equation, $\nabla^2 A = 0$ is converted into the Laplas equation.

In this study, the motion of the permanent magnet is considered by the time stepping method. The lifting and drag forces are calculated using the Maxwell stress tensor method. However, since these analytical calculations are very complex, the use of the FEM is inevitable. The geometrical modeling of the EDL is carried out in 3D using a solid model suitable for FEM analysis. Solid modeling ensures accurate representation of all geometric volumes with well-defined regions. When creating a solid model in ANSYS, it is essential to design the geometry carefully using small, uniform regions in sensitive areas and larger ones in less critical zones. The air gap and its surrounding regions require high precision; therefore, fine and consistent meshing should be applied in these areas. Moreover, overlapping volumes and discontinuities must be avoided to prevent errors during the finite element modeling process.

Table 2 Simulation parameters of EDL for ANSYS

Parameters	**Value**
Solution type	Transient
Baundary	Region Insulating
Stop Time	50 ms
Time Step	0.05ms
Motion Type	Rotational
Angular Velocity	((10000/0.04) * time) rpm
Magnet Type	N35 special geometry
Conductor (Rail) material	Aluminum
Air gap	5mm
Mesh Type	Length Based

Table 2 shows simulation parameters of EDL for ANSYS. The remanent magnetization of the permanent magnets is taken as B_r= 1.23T, magnetic field strength is Hc= 876 kA/m, and the electrical conductivity of aluminum is σ = 3.8x10^{-7} S/m. To determine the design parameters, the lift and drag force formulations under static conditions are used. By analyzing these forces through FEM, the comparison of parameters becomes easier. The analysis of five different magnet disks was performed using the Maxwell program. Geometry, air gap, rotational speed, and plate thickness were used under equal conditions for all five disks to better understand the differences between the N/S and Halbach configurations. Specifically, the cost analysis of the N/S array disk and the Halbach array disk were compared. The analysis results highlight the differences in magnetic flux distribution and levitation performance between these two configurations.

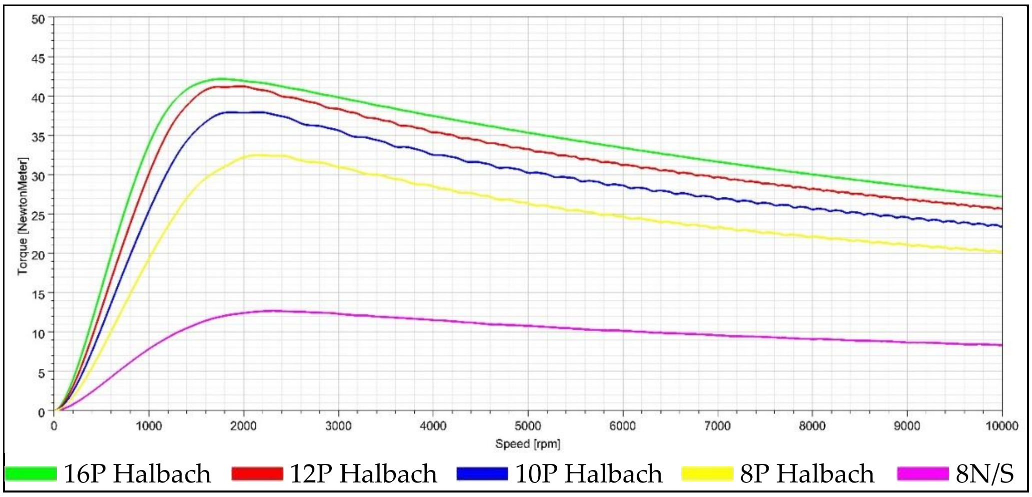


Figure 4 Torque variation for Halbach and N/S arrays

Figure 4 shows the torque variation of the conventional N/S configuration and Halbach arrays. Halbach arrays, especially those with higher pole numbers, require significantly higher torque compared to the traditional N/S configuration. This is due to the more efficient orientation of the magnetic field intensity of Halbach arrays, which offers a significant advantage for lifting systems requiring high efficiency. The variations in lift and drag forces are presented in Figure 5. As the number of poles in the Halbach arrangement increases, the generated lift force correspondingly rises. In all Halbach configurations, the lift force exceeds the drag force at relatively lower rotational speeds, indicating effective levitation performance. In contrast, the conventional N/S configuration requires higher speeds for the lift force to surpass the drag force. The N/S configuration exhibits significantly lower lift force values. Halbach configurations, particularly those with higher pole counts, offer superior magnetic lift and levitation capability at high speeds.

Figure 6 illustrates the magnetic flux density distribution for the 8-pole and 10-pole Halbach configurations. In the 8-pole configuration, the magnetic flux is relatively evenly distributed around each magnet segment, indicating a balanced and practical field orientation. The concentration of flux near the surface is visible, although the overall flux density remains moderate. In contrast, the 10-pole configuration exhibits a more focused and intensified flux pattern, with slightly higher peak values on the magnet surfaces. Figure 7 presents the flux density distribution for the 12-pole and 16-pole Halbach configurations. With a higher pole count, the magnetic field becomes more concentrated and directional. In the 12-pole arrangement, a strong and uniform magnetic field is observed along the outer surface, indicating efficient flux guidance and distribution. The 16-pole configuration further intensifies the flux concentration near the magnet edges, with sharper gradients and higher peak values. Figure 8 shows Magnetic flux density of Eight-pole N/S configuration. In this configuration, the simulation indicates that the magnetic flux density between the disks is higher. The eddy currents exhibit a symmetrical and circular pattern around each magnetic pole, indicating localized energy dissipation regions.

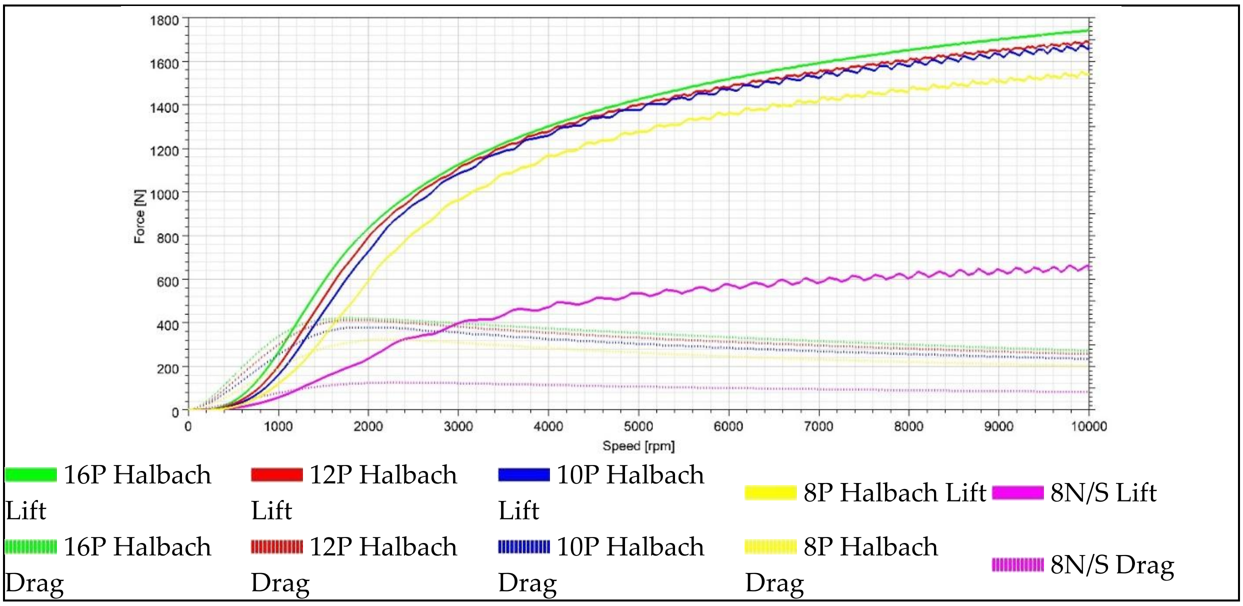
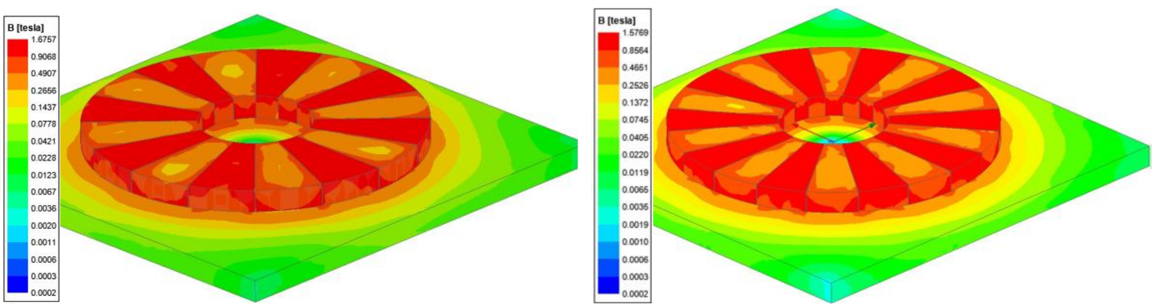
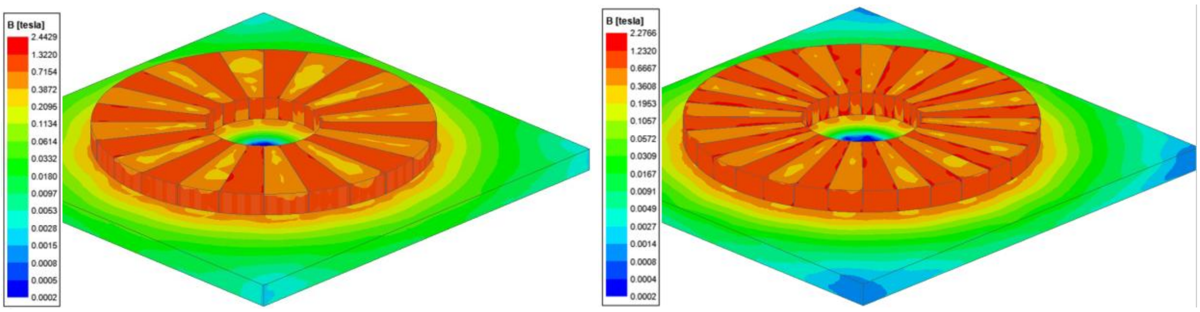


Figure 5 Lift and drag force variation



(a). Eight-pole (b) Ten pole

Figure 6 Halbach configuration magnetic flux density



(a) Twelve pole b) Sixteen-pole

Figure 7 Halbach configuration magnetic flux density

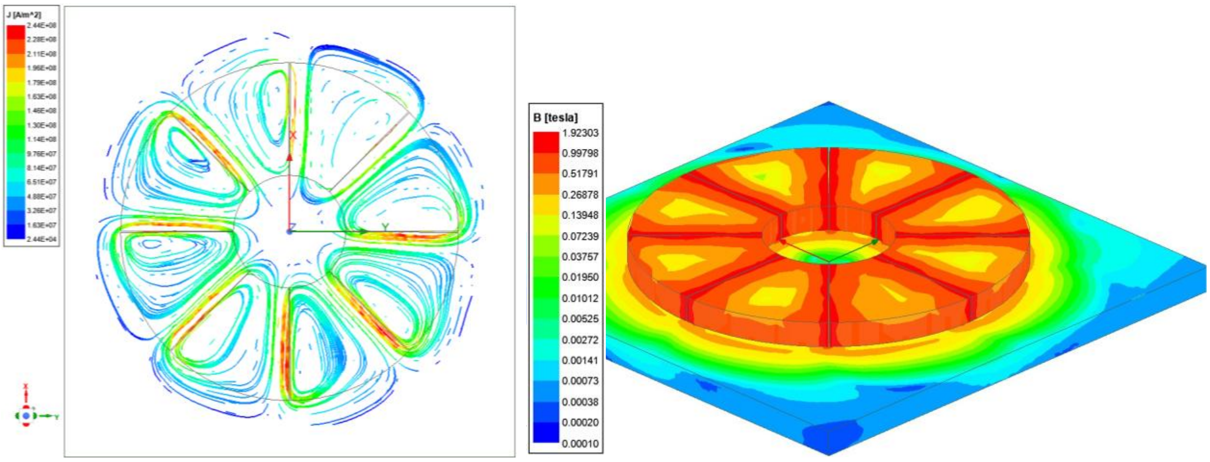


Figure 8 Eddy currents and magnetic flux density for eight-pole N/S configuration

4. PERFORMANCE COMPARISON OF EDL DESIGNS

The performance of EDL systems utilizing Halbach arrays was analyzed through finite element simulations to evaluate their effectiveness in high-speed transportation applications. This section presents a comparative analysis of the torque, lift force, drag force, transition speed, and magnetic flux density for different Halbach array configurations (8, 10, 12, and 16 poles) as well as a conventional 8-pole N/S magnet arrangement. The objective is to determine the influence of pole number variations on system efficiency and levitation performance. The results and findings are detailed in Table 3. The geometric structure, air gap, and plate thickness were kept constant throughout the study, while all analyses were performed at the same set of rotational speed values. The following conclusions can be drawn.

- Simulation results show that the Halbach configuration produces more lift force compared to the N/S configuration.
- The magnetic flux on the surface, which is 0.3179 T for the 8-pole N/S configuration, increases to 0.6347 T for the 8-pole Halbach configuration. This increase indicates that Halbach configurations are more effective in increasing magnetic flux density.
- While the 8-pole N/S configuration produces 535 N of lift force, the 16-pole Halbach configuration reaches the highest lift force of 1425.51 N. Halbach configurations significantly increase the lift force.
- The lift and drag force values were analyzed according to the Halbach configuration (excluding the N/S disk), and the average rate of increase and percentage increase was calculated.
    - When transitioning from the 8-pole configuration to the 10-pole configuration, the lift force increase rate was 7.75%. However, the average increase rate of the lift force is 3.76%.
    - When transitioning from the 8-pole configuration to the 10-pole configuration, the drag force increase rate was 14.79%. The average increase rate of the drag force is 10.33%.

- According to these values, the lift force increases over time, but the drag force increases at a higher rate. If this trend continues, the system's efficiency may decrease because the faster increase in the drag force will result in a larger portion of the energy being spent on friction.

Figure 9 shows L/D rate and Lift force variation. In the Halbach configuration, A higher number of poles leads to a decreased L/D ratio. In the 8-pole configuration, this ratio is 4.85, while in the 16-pole configuration, it drops to 4.03. The average decrease in the lift/drag (L/D) ratio in the Halbach configuration is calculated as 5.90%. Considering the L/D ratio of 4.85, the 8-pole Halbach configuration is regarded as a more efficient design in terms of performance.

Table 3 Values of lift force, drag force, transition speed, and magnetic flux on the surface

	8-pole N/S	8-pole Halbach	10-pole Halbach	12-pole Halbach	16-pole Halbach
Torque	12.68 Nm	32.45 Nm	37.89 Nm	41.19 Nm	42.12 Nm
Lift Force	535 N	1277.55N	1376.53 N	1399.36 N	1425.51 N
Drag Force	107.57 N	263.22 N	302.15 N	332.28 N	352.96 N
Transition speed	1213 rpm	1375 rpm	1300 rpm	1269 rpm	1172 rpm
Magnetic Flux density on the surface	0.31791 T	0.6347 T	0.6667 T	0.7154 T	0.8564 T
L/D rate	4.97	4.85	4.55	4.21	4.03

The torque value presented in Table 3 represents the minimum required torque for the operation of the system. The lift force, drag force, and magnetic flux density on the surface values listed in the table were obtained when the systems reached a rotational speed of 5000 rpm.

Figure 10 illustrates a clear trend among magnetic configurations, indicating that torque, lift force, and drag force increase. Halbach arrays provide a considerable increase in lift and torque compared to conventional N/S configurations, while the drag force increases in parallel. The 16-pole Halbach configuration offers the maximum lifting force and torque but also the highest drag force, which can be explained by the more efficient orientation of the magnetic field in the Halbach arrangement. However, since the increase in drag force brings energy losses, it is a critical design parameter to balance between high lift and low drag in electrodynamic levitation systems.

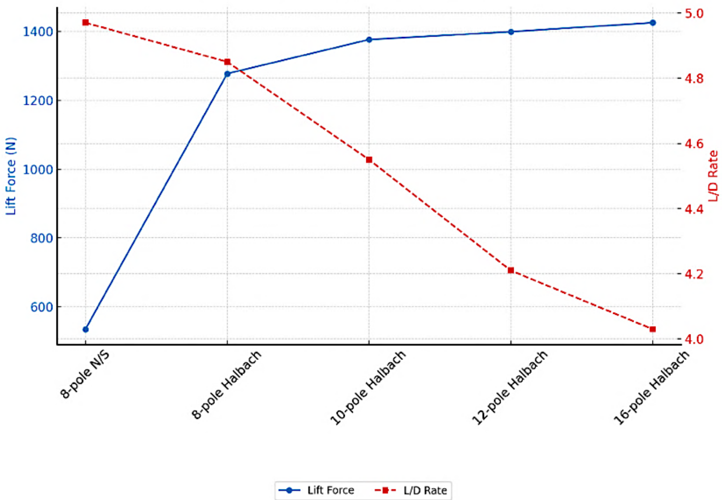


Figure 9 L/D rate and Lift force variation for different configurations

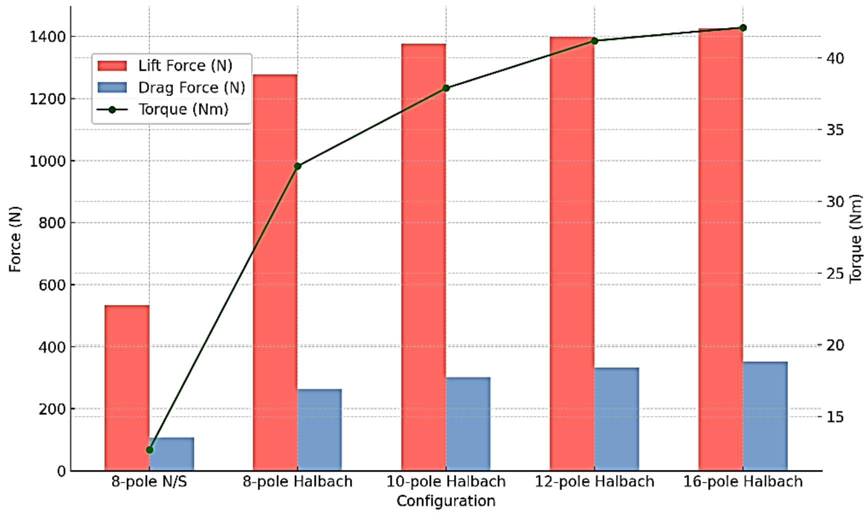


Figure 10 Torque, lift force, and drag force for different configuration

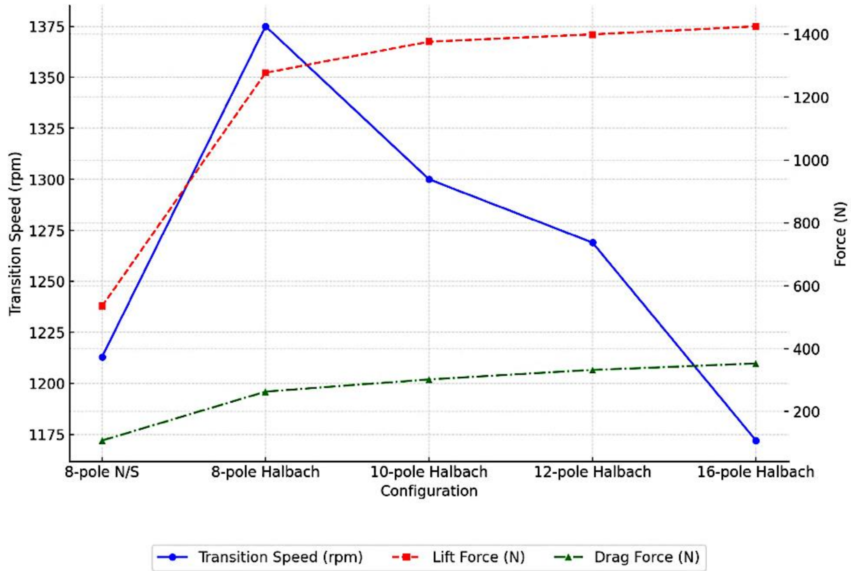


Figure 11 Relationship between transition speed, lift force, and drag force

Before exceeding the critical transition speed, the lift force in the standard N/S configuration remains at a lower level. Beyond a certain speed, the standard N/S configuration becomes less efficient than the Halbach configuration because its magnetic field orientation is not as effective. Halbach configurations are more advantageous in magnetic levitation systems (e.g., Maglev, contactless transportation) because they generate higher lift forces and lower energy losses. However, considering production costs and alignment precision, classic N/S configurations may be more suitable for simpler applications.

Due to its optimized magnetic field orientation, a Halbach-configured disk produces higher lift force and lower drag force. In contrast, a standard N/S-configured disk generates a more symmetrical but weaker lift-producing magnetic field. In the design of Halbach-configured systems, the optimal air gap and magnet dimensions must be carefully selected; otherwise, excessive magnetic saturation or inefficient material usage may occur.

An increasing number of poles in the Halbach configuration leads to higher magnetic flux density; however, beyond a certain point, this may result in magnetic saturation. Initially, increasing the number of poles in a Halbach configuration significantly enhances the lift force, but it also reduces the lift-to-drag (L/D) ratio, slightly diminishing overall system efficiency. This emphasizes the importance of optimizing Halbach configurations, as simply increasing the number of poles does not continuously improve performance. Considering the L/D ratio, the 8-pole Halbach configuration emerges as a more efficient design in terms of performance.

5. COST ANALYSIS OF EDL DESIGNS

Neodymium magnets are composed of the elements Neodymium (Nd), Iron (Fe), and Boron (B) and are usually produced by Sintering or Melt Spinning methods [34]. During the cost analysis, it was assumed that the magnet used was coated with Ni-Cu-Ni and that the surface thickness of the magnets would be exposed to the coating process up to 18 μm. The cost analysis of the disks designed is given in Table 4.

Table 4 Cost analysis of EDL designs

	8-pole N/S	8-pole Halbach	10-pole Halbach	12-pole Halbach	16-pole Halbach
Number of Magnets Used	8	16	20	24	32
Mass of NdFeB Per Magnet (grams)	146,63	73,12	58,42	48,63	36,37
Mass of NdFeB Per Disk (grams)	1173,07	1170,07	1168,57	1167,12	1164,06
Magnet Surface Area (mm^2)	5541,08	3218,59	2754,10	2444,43	2057,35
Disk Total Surface Area (mm^2)	44328,64	51497,44	55082,00	58666,32	65835,2
Ni-Cu-Ni coating mass per magnet (grams)	0,75	0,43	0,37	0,33	0,27
Ni-Cu-Ni Coating Mass Per Disk (grams)	6,00	6,88	7,40	7,92	8,64
Total Mass (grams)	1179,07	1176,95	1175,97	1175,04	1172,704

The results show that increasing the number of poles leads to a rise in both the number of magnets (from 8 to 32) and the total surface area (from 44,328.64 mm^2 to 65,835.2 mm^2), while the total NdFeB mass per disk (≈1170–1173 g) remains nearly constant. This can be explained by the decrease in mass per magnet (from 146.63 g to 36.37 g). Therefore, the cost of NdFeB raw material remains nearly independent of the pole number. However, Ni-Cu-Ni coating costs are directly related to the number of poles. Although the coating mass per magnet decreases (from 0.75 g to 0.27 g), the total coating mass per disk increases by 44% (from 6 g to 8.64 g) due to the increased number of magnets. This increase results from the expansion of the total surface area. Considering the cost per unit area of the coating process, it can be stated that high-pole-number designs significantly increase coating expenses.

With a greater number of poles, manufacturing and assembly processes become more labor-intensive, driving up associated costs. Increasing the number of magnets from 8 to 32 raises the assembly precision and alignment time, making manufacturing tolerances more critical. Additional quality control measures may be required to ensure magnetic field homogeneity in Halbach arrangements, which can further increase production costs. Particularly in the 16-pole configuration, the surface area per magnet (2057.35 mm^2) is at its lowest, necessitating greater precision during manufacturing. In terms of cost optimization, 10-pole or 12-pole Halbach configurations may offer a balanced alternative. These configurations provide higher magnetic efficiency compared to the 8-pole N/S design while requiring lower coating and manufacturing costs than the 16-pole design. For instance, the 12-pole Halbach array results in only 1.92 g more coating material per disk (7.92 g) than the 8-pole N/S (6 g), while saving 0.72 g compared to the 16-pole configuration.

Furthermore, having a more reasonable number of magnets (24) than in the 16-pole configuration (32) may facilitate assembly processes. While the costs of raw materials stay stable as the number of poles increases, the costs of coating and manufacturing are on the rise. The optimal design should be determined by carefully evaluating the magnetic performance requirements against cost factors. Especially in applications that demand high magnetic efficiency, the 12-pole Halbach configuration stands out as a cost-effective and high-performing option. However, in scenarios where labor costs are a significant concern, the 8-pole N/S design may offer a more economical solution. This analysis should also consider potential future shifts in cost dynamics due to fluctuations in rare earth metal prices and advancements in coating technologies.

6. COMPARASION

A comparative analysis was conducted with two recent studies from the literature[27, 35]. Both studies examined EDL systems based on different configurations and parameters. Table 5 presents a comparison of the 8-pole N/S conventional design and the 8-pole Halbach configuration with similar studies in literature.

Table 5 Performance Comparison of 8-Pole N/S and Halbach Configurations

	6-pole N/S [27]	8-pole N/S (Our Study)	4-pole Halbach [35]	12-pole Halbach (Our Study)
Magnet Type	N35	N35	N35	N35
Total Magnet Number	6	8	8	24
Magnet Thickness (mm)	10	10	20	10
Mechanical Air Gap(mm)	8	5	5.5	5
Angular Velocity (rpm)	4000	4000	1000	1000
Disk outer diameter (mm)	145	150	100	150
Disk inner diameter(mm)	70	50	50	50
Conductor (Rail) Thickness (mm)	-	10	3	10
Total Magnet Volume (cm3)	42.4	156.4	117.81	156.4
Lift Force (N)	100	535	8	200
Lift Force Per Unit Volume (N/m^3)	2.36×10^6	3.45×10^6	67923	$1.28\text{x}10^6$

A comparison of the 6-pole configuration and the 8-pole N/S configuration reveals that an increase in the number of poles and a decrease in the air gap have a direct and positive effect on the performance of the EDS system. In particular, the proposed 8-pole N/S disk design has exhibited enhanced efficiency, as evidenced by a higher lift force per unit volume. This enhancement can be attributed to the more effective placement of magnets and the enhancement of magnetic coupling. A comparison of the 4-pole Halbach configuration and the 12-pole Halbach configuration shows that both systems operate with similar magnet volumes and rotational speeds. The proposed 12-pole Halbach disk design, particularly due to the utilization of a thicker conductive plate and a smaller air gap, has resulted in a substantially elevated lift force. This clearly highlights the decisive role of design parameters in the performance of magnetic levitation systems. The comparison further demonstrates that system configuration, magnet volume, and air gap directly influence the lift force. In particular, the difference in plate thickness should be carefully considered when evaluating performance differences between systems.

7. CONCLUSION

This study conducted a comprehensive evaluation of different Halbach array configurations for electrodynamic levitation (EDL) systems, focusing on both performance metrics and cost factors relevant to high-speed transportation applications. The configurations tested—8, 10, 12, and 16 poles—were compared against a conventional 8-pole N/S arrangement in terms of magnetic flux density, lift force, drag force, torque, and transition speed. The simulation results confirmed that Halbach arrays significantly enhance levitation capability compared to the classical N/S configuration. As the number of poles increases, both lift force and magnetic flux density improve; however, this improvement comes with a concurrent rise in drag force, leading to a reduction in the lift-to-drag (L/D) ratio. For instance, while the 16-pole configuration reached the highest lift force of 1425.51 N, its L/D ratio decreased to 4.03 compared to 4.85 in the 8-pole configuration, indicating diminishing efficiency with excessive pole counts. Among all tested geometries, the 12-pole Halbach array emerged as the most balanced configuration. It achieved a lift force of 1399.36 N and a drag force of 332.28 N, corresponding to an L/D ratio of 4.21. This reflects a 9.53% improvement in lift force compared to the 8-pole Halbach array, along with a moderate increase in drag. Additionally, the transition speed was reduced to 1269 rpm, enabling effective levitation at lower rotational speeds—a desirable feature for energy-efficient propulsion. From an economic perspective, the cost analysis revealed that NdFeB usage remains nearly constant due to optimized magnet sizing, while Ni-Cu-Ni coating and assembly costs increase with pole number. The 12-pole configuration requires only 1.92 g more coating material per disk (7.92 g) than the 8-pole N/S configuration (6 g), yet uses 0.72 g less than the 16-pole design, making it a cost-effective and high-performing solution.

These findings show the importance of selecting an optimal pole configuration to balance levitation performance with manufacturing feasibility. The 12-pole Halbach array demonstrates strong potential for integration into next-generation EDL-based systems such as Maglev and Hyperloop. Future research should focus on optimizing magnetic material selection, air gap, and magnet geometry to develop designs that maximize lift force while minimizing drag force.

Declaration of Ethical Standards

As the author of this study, he declares that he complies with all ethical standards.

Credit Authorship Contribution Statement

CK and EY conducted simulations and analyses and contributed to the preparation of the manuscript. MÇ provided supervision, conceptualized and designed the study, and managed the overall research process. All authors reviewed and approved the final version of the manuscript

Declaration of Competing Interest

The authors declared that they have no conflict of interest.

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Data Availability

No datasets were generated or analyzed during the current study.

REFERENCES

[1] C. Luo, K. Zhang, J. Duan, and Y. Jing, "Study of permanent magnet electrodynamic suspension system with a novel Halbach array," *Journal of Electrical Engineering & Technology,* vol. 15, no. 2, pp. 969-977, 2020.

[2] S.-J. Moon, D.-W. Yun, H.-J. Cho, S.-W. Park, and B.-H. Kim, "An Analytical Study on the Magnetic Levitation System Using a Halbach Magnet Array," *Transactions of the Korean Society for Noise and Vibration Engineering,* vol. 17, no. 11, pp. 1077-1085, 2007.

[3] R. F. Post and D. D. Ryutov, "The inductrack approach to magnetic levitation," Lawrence Livermore National Lab.(LLNL), Livermore, CA (United States), 2000.

[4] A. Najjar-Khodabakhsh, "Analytical modeling of passive electrodynamic levitation systems," *Przegląd Elektrotechniczny,* vol. 86, no. 10, pp. 354-358, 2010.
[5] Z. Deng *et al.*, "Permanent magnet electrodynamic suspension system integrated with a car: Design, implementation, and test," *IEEE Transactions on Transportation Electrification,* vol. 10, no. 1, pp. 1101-1115, 2023.
[6] C. Karabulut, E. Yücel, and M. Çunkaş, "Analysis of An Electrodynamic Levitation System Based on The Halbach Magnet Arrays," presented at the Hodja Akhmet Yassawi 8th International Congress On Scientific Research, Konya, Türkiye, 17-19 May, 2024.
[7] Y. Xiang *et al.*, "Design and analysis of guidance function of permanent magnet electrodynamic suspension," *Technologies,* vol. 11, no. 1, p. 3, 2022.
[8] A. Lendek and C. M. Apostoaia, "Investigation of an Electrodynamic Magnetic Levitation Device," in *2020 IEEE International Conference on Electro Information Technology (EIT)*, 2020: IEEE, pp. 297-303.
[9] S. Sadeghi, M. Saeedifard, and C. Bobko, "Dynamic modeling and simulation of propulsion and levitation systems for hyperloop," in *2021 13th International Symposium on Linear Drives for Industry Applications (LDIA)*, 2021: IEEE, pp. 1-5.
[10] E. Chaidez, S. P. Bhattacharyya, and A. N. Karpetis, "Levitation methods for use in the hyperloop high-speed transportation system," *Energies,* vol. 12, no. 21, p. 4190, 2019.
[11] C. A. Gallo, "Halbach magnetic rotor development," 2008.
[12] L. Beauloye and B. Dehez, "Impact of the magnet span on the forces of electrodynamic suspensions with an alternate permanent magnet arrangement," in *2022 25th International Conference on Electrical Machines and Systems (ICEMS)*, 2022: IEEE, pp. 1-5.
[13] L. Beauloye and B. Dehez, "Permanent magnet electrodynamic suspensions applied to MAGLEV transportation systems: A review," *IEEE Transactions on Transportation Electrification,* vol. 9, no. 1, pp. 748-758, 2022.
[14] G. Oleszczuk, "Robustness and control of a Magnetically Levitated Transportation system," 2006.
[15] R. Galluzzi *et al.*, "A multi-domain approach to the stabilization of electrodynamic levitation systems," *Journal of Vibration and Acoustics,* vol. 142, no. 6, p. 061004, 2020.
[16] C. Hu, X. Wang, Z. Wang, S. Wang, Y. Liu, and Y. Li, "Electromagnetic vibrational energy harvester with targeted frequency-tuning capability based on magnetic levitation," *Nanotechnology and Precision Engineering,* vol. 7, no. 4, 2024.
[17] P. Zhu, L. Jie, Q. Chen, Y. Tan, M. Liu, and D. Zhou, "A suspension damping enhancement method based on permanent magnet damping conductive plate for superconducting maglev sled," *IEEE Transactions on Magnetics,* 2024.
[18] X. Tang, Y. Xu, and X. Liu, "Design and control of redundant-actuated Six-DOF micropositioning stage with magnetic gravity compensation," *Engineering Research Express,* 2025.
[19] W. Li, D. Wang, S. Peng, Z. Deng, D. Zhou, and C. Cai, "Optimizing superconducting magnetic bearings of HTS flywheel systems based on 3D H-ϕ formulation," *Cryogenics,* vol. 140, p. 103849, 2024.
[20] H. Mollahasanoglu, M. Abdioglu, U. K. Ozturk, H. I. Okumus, E. Coskun, and A. Gencer, "Numerical Investigation of EDS Maglev Systems in Terms of Performance and Cost for Different PMs-Aluminum Rail Arrangements," *Journal of Superconductivity and Novel Magnetism,* vol. 38, no. 1, p. 52, 2025.
[21] J. Liu *et al.*, "Damping characteristics improvement of permanent magnet electrodynamic suspension by utilizing the end-effect of onboard magnets," *Electrical Engineering,* vol. 106, no. 1, pp. 15-29, 2024.
[22] C. Wu, G. Li, D. Wang, and J. Xu, "Dynamic characterization of permanent magnet electrodynamic suspension system with a novel passive damping magnet scheme," *Journal of Sound and Vibration,* vol. 599, p. 118849, 2025.

[23] F. Zhou, J. Yang, H. Hu, and T. Gao, "Study of repulsive permanent magnetic levitation mechanism and its dynamic characteristics," *Scientific Reports,* vol. 14, no. 1, p. 29859, 2024.
[24] Y. Hu, Z. Long, J. Zeng, and Z. Wang, "Analytical optimization of electrodynamic suspension for ultrahigh-speed ground transportation," *IEEE transactions on magnetics,* vol. 57, no. 8, pp. 1-11, 2021.
[25] W. Qin, Y. Ma, G. Lv, F. Wang, and J. Zhao, "New levitation scheme with traveling magnetic electromagnetic Halbach array for EDS maglev system," *IEEE Transactions on Magnetics,* vol. 58, no. 2, pp. 1-6, 2021.
[26] M. Fumeaux, M. Cailleteau, D. Melly, S. Chevailler, and J. Cugnoni, "Design and simulation of the electrodynamic suspension of an hyperloop test vehicle," in *2023 14th International Symposium on Linear Drivers for Industry Applications (LDIA)*, 2023: IEEE, pp. 1-5.
[27] I. E. Uslu, A. S. Akkas, M. O. Gulbahce, and I. Kocaarslan, "Design of Electrodynamic Suspension System for Hyperloop Pod," *Turk J Electr Power Energy Syst.,* March 10, 2025, doi: 10.5152/tepes.2025.24037.
[28] T. Kublin, L. Grzesiak, P. Radziszewski, M. Nikoniuk, and Ł. Ordyszewski, "Reducing the power consumption of the electrodynamic suspension levitation system by changing the span of the horizontal magnet in the Halbach array," *Energies,* vol. 14, no. 20, p. 6549, 2021.
[29] J. Jin *et al.*, "Characteristics analysis of an electromagnetic actuator for magnetic levitation transportation," in *Actuators*, 2022, vol. 11, no. 12: MDPI, p. 377.
[30] E. Yücel, C. Karabulut, and M. Çunkaş, "Design, implementation, and testing of a propulsion system for the hyperloop transportation system," *Electrical Engineering,* pp. 1-21, 2025.
[31] K. Halbach, "Application of permanent magnets in accelerators and electron storage rings," 1984.
[32] M. A. Şahman, M. Mutluer, and M. Çunkaş, "Design optimization of tubular linear voice coil motors using swarm intelligence algorithms," *Engineering Optimization,* vol. 54, no. 11, pp. 1963-1980, 2022.
[33] Y. Özoğlu, "Magnetic field analysis of direct current motor using finite element method," PhD, Istanbul Tecnical University 1995.
[34] J. Herbst and J. Croat, "Neodymium-iron-boron permanent magnets," *Journal of magnetism and magnetic materials,* vol. 100, no. 1-3, pp. 57-78, 1991.
[35] Q. Xuesong, S. Qianyuan, S. Zikang, L. Yuhang, and W. Bin, "Analysis of the magnetic levitation characteristics of the vertical Halbach array in a permanent magnet rotor," *Nonlinear Dynamics,* vol. 113, no. 1, pp. 397-412, 2025.