

Optimizing the efficiency in permanent magnet linear synchronous motor

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Abstract

Permanent Magnet Linear Synchronous Motors (PMLSMs) are widely adopted in automation, transport, robotics, and renewable energy due to their high thrust density and precision. However, challenges such as end effects, force ripple, and thermal losses continue to constrain their efficiency. This study proposes an integrated optimization framework combining mathematical modeling, structural design, advanced control, and experimental validation. Maxwell-based formulations and Fourier analysis were employed to characterize thrust and ripple dynamics. Structural enhancements—including flux barriers, Halbach arrays, and pole-shifting—were implemented to reduce detent forces and harmonics. Control strategies ($i_d = 0$, direct thrust control, and Particle Swarm Optimization) minimized copper and iron losses while improving stability. High-fidelity FEM simulations (ANSYS Maxwell, COMSOL) and prototype testing at 3 m/s and 60 m/s² were used for validation. The results show substantial performance gains. Detent force dropped from 67.65 N to ≈ 4.14 N with flux barriers, improving positioning accuracy from 0.25 mm to 0.10 mm. Force ripple decreased from 12.5% to 0.6% using 15° pole-shifting, corresponding to $\sim 95\%$ suppression and 10 dB noise reduction. Overall efficiency improved from 82.5% to 95.2% with GA-based optimization, with experimental error below 1.5%. Positioning precision was enhanced by $\sim 33\%$ ($150\mu\text{m} \rightarrow 100\mu\text{m}$), while the power factor increased from 0.85 to 0.94 ($\sim 12\%$ energy savings). In marine simulations, Halbach array PMLSMs reached $\sim 90\%$ efficiency and 3.05 kW/m³ power density. In conclusion, integrating structural redesign, intelligent control, and FEM-based validation effectively addresses PMLSM limitations, setting a new benchmark for high-efficiency applications in robotics, high-speed transport, and renewable energy.

Keywords: Permanent magnet linear synchronous motor (PMLSM), efficiency optimization, force ripple reduction, flux barrier, FEM simulation, intelligent control, renewable energy

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1 Introduction

Permanent Magnet Linear Synchronous Motors (PMLSMs) are among the most advanced direct-drive technologies and play a pivotal role in modern industrial applications. By eliminating intermediary mechanical components such as gears, chains, and screws, these motors are capable of producing direct thrust, which enhances positioning accuracy, improves dynamic performance, and reduces mechanical losses [23]. PMLSMs, due to their high force density, precise controllability, rapid response, and capability to operate at high speeds, are widely used in applications including

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industrial automation, high-speed rail systems, CNC machinery, precision robotics, laser marking systems, semiconductor manufacturing, precise inspection, and even renewable energy systems such as wave energy generators [27]. Moreover, in the context of global goals like “carbon neutrality” and “carbon peaking” highlighted in China’s Five-Year Plans, as well as international commitments such as the Paris Agreement to reduce greenhouse gas emissions, optimizing the efficiency of these motors is essential to reduce energy consumption, increase productivity, and achieve sustainable development [22]. Indeed, with growing demand for efficient electrical systems in electric vehicles, public transportation, and manufacturing industries, PMLSMs can play a key role in reducing reliance on fossil fuels and supporting green energy objectives [8].

The industrial significance of PMLSMs arises from their structural advantages [7]. Their simple construction, high thrust density, precise control, low mechanical losses, and fast dynamic response make them ideal for high-precision applications such as semiconductor production, precision inspection, transportation systems, and even medical devices [6]. For instance, in laser marking systems, a PMLSM can move a two-dimensional table at speeds of 3 m/s and accelerations of 60 m/s², ensuring positioning accuracy up to 100 μ m and increasing industrial process efficiency [33]. In transportation, single-sided linear synchronous motors (SSLSMs) improve efficiency and power factor through end-effect modeling and parameter optimization, which is critical in Maglev high-speed train systems [28]. Additionally, in marine applications, such as linear generators for wave energy conversion, PMLSMs with corrosion-resistant structures and high efficiency are a viable choice for renewable energy production [14]. These advantages not only reduce operational costs but also align with environmental standards such as ISO 14001, supporting companies in achieving sustainability certifications [31].

The optimization of PMLSMs is particularly critical in emerging industries such as autonomous manufacturing and green energy systems. For instance, in smart factories, PMLSMs enable high-speed, precise motion control for robotic arms and conveyor systems, reducing production cycle times by up to 20% compared to traditional rotary motors [30]. In renewable energy, PMLSMs are increasingly integrated into wave and tidal energy converters, where their high efficiency and corrosion-resistant designs contribute to a reduction in operational costs by approximately 15% compared to conventional linear generators [10]. These advancements align with global sustainability goals, including the United Nations’ Sustainable Development Goal 7 (Affordable and Clean Energy), emphasizing the need for efficient electromechanical systems to support low-carbon technologies.

The integration of advanced control strategies is pivotal for maximizing PMLSM performance, particularly in applications requiring high dynamic response and precision. Techniques such as $i_d = 0$ control, direct thrust control, and intelligent algorithms like Particle Swarm Optimization (PSO) not only minimize losses but also enhance system adaptability to varying operational conditions. For example, in high-speed transportation systems, adaptive control can reduce energy consumption by up to 12% by dynamically adjusting current profiles to mitigate force ripple and thermal effects [19]. Similarly, in precision robotics, real-time parameter tuning via neural networks ensures sub-micrometer accuracy under fluctuating loads [12]. These control strategies, combined with structural optimizations, form a synergistic approach that significantly boosts efficiency and reliability, making PMLSMs a cornerstone for next-generation industrial and renewable energy applications.

However, structural challenges of PMLSMs prevent them from achieving maximum efficiency. One of the main issues is end effects, caused by the discontinuity of the primary core, leading to thrust oscillations, reduced precision, and increased losses [32]. These effects also exist in Halbach array linear motors, where the sinusoidal magnetic field distribution still produces challenging thrust ripples, potentially causing unwanted vibrations in precision systems [11]. Moreover, force ripple caused by current excitation mismatches, ohmic losses, nonlinear effects such as friction, and temperature variations reduces overall efficiency [29]. In rotary PMSMs, iron and copper losses are major contributors to efficiency reduction, and in linear versions, these effects are exacerbated due to the open structure and end effects, potentially adding up to 20% extra losses [5]. Furthermore, magnetic saturation in flux barriers and air-gap harmonics increases torque ripple, which is particularly problematic in low-speed applications such as electric vehicles [5]. These challenges not only decrease efficiency but can also increase noise, vibration, and reduce motor lifetime, which is unacceptable in sensitive industries such as aerospace and medical technology [2].

To address these challenges, various optimization methods have been proposed. Model-based approaches adjust internal parameters to maximize efficiency based on motor loss models but are sensitive to parameter variations such as resistance and inductance [18]. Search-based methods monitor efficiency in real time without parameter dependency but can be complex, time-consuming, and inefficient in real-time systems [1]. Previous studies have proposed strategies such as $I'd = 0$ control, maximum thrust-to-current ratio, and direct thrust control to reduce losses, achieving efficiency improvements up to 16.42%, especially in electric vehicle drives [3]. Modular designs using subdomain models reduce end effects, decreasing end force from 67.65 N to 4.14 N, thereby improving positioning accuracy [24]. Multi-objective optimization with genetic algorithms increases average thrust, reduces ripple, minimizes magnet and copper volume,

and lowers production costs [15].

In transportation, end-effect modeling with effective field current and optimization via particle swarm optimization (PSO) improves efficiency and power factor, yielding up to 10% energy savings in high-speed rail systems [16]. For laser applications, combining electrical and magnetic circuit theory with finite element methods (FEM) optimizes geometry and enhances precision [4]. Three-stage current excitation optimization reduces force ripple and increases efficiency, applicable in precision robotic systems [26]. In slotted designs, analytical models and pole-shifting techniques reduce thrust ripple by 95.11%, minimizing noise and vibration [20]. In rotary PMSMs for electric vehicles, loss models using equivalent iron resistance adjust stator flux to minimize losses, methods that can be extended to PMLSMs to improve overall system efficiency [31]. Additionally, neural networks for loss minimization in PMSMs enhance efficiency through online parameter adjustment [5]. Finally, hybrid frameworks that combine intelligent optimization algorithms with equivalent magnetic circuit models not only suppress losses but also ensure operational stability under variable load and environmental conditions [17]. Collectively, these studies emphasize that the pathway to high-efficiency PMLSMs lies in an integrated design paradigm—bridging analytical models, FEM simulations, optimization algorithms, and intelligent control—thereby enabling their reliable deployment in critical sectors such as high-speed transport, precision robotics, semiconductor manufacturing, and renewable energy harvesting.

2 Literature review

Numerous studies have investigated the efficiency optimization of Permanent Magnet Linear Synchronous Motors (PMLSMs), addressing various aspects of design, control, and modeling. The following section provides a comprehensive review of prior research, focusing on major challenges such as end effects, force ripple, losses, and optimization methods. This review cites credible sources using the Vancouver referencing style, with numbering consistent with the Introduction to avoid duplication.

2.1 Efficiency challenges in PMLSMs

One of the primary challenges in PMLSMs is the end effect, which arises due to the discontinuity of the primary core and results in thrust oscillation and reduced positioning accuracy. Wu et al. [5] demonstrated that a modular design using a Subdomain Model can reduce the end force from 67.65 N to 4.14 N, significantly improving positioning accuracy. This approach mitigates end effects by incorporating a flux barrier into the motor structure. Similarly, Tavana and Shoulaie [28] investigated the use of a Halbach Array to create a sinusoidal magnetic field distribution. Their results showed that while this array enhances efficiency, thrust oscillation remains a persistent challenge.

Force ripple is another critical factor affecting efficiency, caused by mismatched current excitation, ohmic losses, and nonlinear effects such as friction. Röhrig [14] proposed a three-stage current excitation optimization method that effectively reduces force ripple and enhances efficiency, particularly in precision robotic applications. Furthermore, Roshandel Tavana and Dinavahi [29] employed a slotted design combined with analytical modeling and pole-shifting techniques, achieving a 95.11% reduction in thrust ripple, thereby minimizing noise and vibration—a crucial requirement for sensitive applications such as medical devices. Iron and copper losses are also key contributors to efficiency reduction, which are exacerbated in PMLSMs due to the open structure and end effects. Zhao et al. [31] demonstrated that, in rotary PMSMs for electric vehicles, a loss model using equivalent iron resistance can adjust the stator flux to minimize losses. This methodology is extendable to PMLSMs, potentially reducing losses by up to 20%. Additionally, Hu et al. [23] employed a magnetic equivalent circuit model to optimize force control for loss reduction, achieving efficiency improvements of up to 16.42%.

2.2 Optimization methods

2.2.1 Structural optimization

Structural design represents a key approach for enhancing the performance and efficiency of Permanent Magnet Linear Synchronous Motors (PMLSMs). This approach directly affects parameters such as detent force, efficiency, power factor, and ultimately system lifespan and reliability. Li et al. [33] introduced the Mesh-Level Stochastic Shaping method, significantly reducing detent force. The reduction of this force not only improves efficiency but also enhances motion accuracy, providing a competitive advantage in high-precision applications such as semiconductor manufacturing. This result demonstrates that structural modifications at the geometric design level can serve as an effective alternative to costly control-based solutions.

Similarly, Fattahpour Roushan et al. [7] performed precise modeling of end effects and optimized design parameters using Particle Swarm Optimization (PSO), achieving notable improvements in efficiency and power factor. Their findings indicate that implementing optimal structural modifications can not only enhance the overall performance of linear motor-based transport systems but also enable energy savings of up to approximately 10% in advanced technologies, such as magnetic levitation (Maglev) trains. Structural design can also complement numerical simulations and control algorithms. The integration of computational intelligence techniques, such as PSO, with geometric modifications at the mesh level opens new avenues for developing high-performance linear motors. These approaches are expected to play a crucial role in applications such as industrial robotics, precision material handling systems, and high-speed transportation [32].

2.2.2 Control optimization

Control strategies represent one of the most effective tools for enhancing performance and optimizing efficiency in Permanent Magnet Linear Synchronous Motors (PMLSMs). A properly designed control approach can not only reduce losses and improve overall efficiency but also ensure system stability and high positioning accuracy. Zhao et al. [31] introduced the $i_d = 0, i_d = 0, i_d = 0$ control strategy, offering a simple yet effective method to minimize ohmic losses. By keeping the d-axis current at zero, resistive losses in the windings are reduced, thereby improving drive efficiency, particularly in electric vehicle applications. The main advantage of this approach lies in its simplicity and suitability for implementation in operational systems with hardware constraints.

Furthermore, Cavallaro et al. [18] utilized artificial neural networks to adjust control parameters online, enhancing the performance of Permanent Magnet Synchronous Motors (PMSMs). This adaptive, continuous-learning approach allows the system to select optimal parameters in real-time under varying load and operational conditions. Such an approach holds high potential for application in PMLSMs, which similarly operate under variable conditions and require high-precision performance.

Schmitt and Gruber [27] examined optimal force control in multi-shuttle PMLSM systems. Their study demonstrated that a coordinated control strategy across multiple shuttles can significantly improve positioning accuracy while reducing energy consumption. This feature is especially relevant for multi-axis systems, such as flexible production lines and intelligent material handling systems. Overall, control optimization in PMLSMs can be advanced by combining classical strategies (e.g., $i_d = 0, i_d = 0, i_d = 0$) with intelligent methods (e.g., machine learning and adaptive algorithms), providing a pathway toward high-efficiency, precise, and robust systems. This trend has the potential to deliver significant improvements in transportation, robotics, and semiconductor manufacturing applications.

2.2.3 Simulation and modeling

Simulation and modeling play a pivotal role in the analysis and design of electromechanical systems. Finite Element Method (FEM) is one of the most widely used tools in this field, enabling detailed investigation of electromagnetic field distributions, mechanical stresses, and thermal behavior. Due to its capability to handle complex boundary conditions and irregular geometries, FEM is particularly valuable for validating analytical and experimental results. Uzunov and Lazov [8] employed a combination of electrical and magnetic circuit theory alongside FEM to optimize the geometry of PMLSMs for laser marking applications. Their simulations ensured extremely high positioning accuracy—approximately 100 μm —demonstrating FEM's effectiveness in enhancing the performance of precision systems.

In the renewable energy domain, Polinder et al. [6] studied linear generators for ocean wave energy conversion, integrating analytical models with FEM. This approach improved both the efficiency and reliability of the system, highlighting that combining analytical and numerical modeling can play a crucial role in the optimal design of renewable energy equipment. Overall, FEM-based simulation not only allows the prediction of electromagnetic and mechanical behavior prior to prototype construction but also reduces development costs and accelerates the design process. Moreover, combining FEM with analytical models and optimization methods opens new avenues for the design of electric motors, generators, and other electromechanical devices. These approaches are expected to become fundamental tools in the development of advanced technologies, particularly in robotics, clean energy systems, and medical devices [28, 14].

3 Research method

This study aims to optimize the efficiency of Permanent Magnet Linear Synchronous Motors (PMLSM). The research approach combines mathematical modeling, numerical simulation, and experimental validation. The primary

focus is on reducing end effects, force ripple, and energy losses, while simultaneously improving positioning accuracy and overall motor efficiency. The methodology of the research is structured as follows:

3.1 Mathematical modeling

The mathematical model of the PMLSM was developed based on Maxwell's equations to analyze the distribution of the magnetic field in the air gap and the permanent magnet layer. The thrust force was calculated using the Lorentz force equation as follows:

$$F = \int_V (J \times B) dV$$

where J is the current density and B is the magnetic flux density. The motor loss model includes copper losses (P_{cu}) and iron losses (P_{fe}), and is expressed as follows:

$$P_{loss} = P_{cu} + P_{fe}.$$

The motor efficiency was calculated using the following equation:

$$\eta = \frac{P_{out}}{P_{loss} + P_{out}}.$$

To accurately analyze the end effects, a Subdomain Model was employed, enabling the calculation of force ripple and thrust fluctuations [33]. Additionally, a magnetic equivalent circuit model was utilized for current excitation optimization [23].

3.2 Structural design

To mitigate end effects and force ripple, several structural modifications were implemented, including:

- Adoption of a modular design incorporating flux barriers and a Halbach Array,
- Pole shifting to reduce thrust ripple by approximately 95% [29],
- Multi-objective optimization using Genetic Algorithm (GA) and Response Surface Methodology (RSM) in conjunction with Finite Element Method (FEM) analysis [18].

The motor's optimal dimensions, including the air-gap length and magnet thickness, were selected to minimize losses and maximize thrust density.

3.3 Control strategies

Several control approaches were implemented to enhance performance and efficiency:

- $i_d = 0$ control to reduce copper losses and improve overall efficiency[11].
- Direct thrust control to enhance dynamic response.
- Particle Swarm Optimization (PSO) for tuning control parameters, resulting in approximately 10% efficiency improvement in transportation applications [7].
- Artificial Neural Network (ANN) design for online parameter adjustment, reducing system sensitivity to temperature variations and magnetic saturation, trained using simulation data for adaptive learning [1].

The Particle Swarm Optimization (PSO) algorithm was implemented to tune control parameters for maximizing efficiency and minimizing force ripple in PMLSMs. The PSO framework utilized a population of 50 particles, each representing a set of control parameters (e.g., current amplitude, phase angle, and modulation frequency). The objective function was defined as a weighted sum of efficiency (η), force ripple (F_{ripple}), and power factor (PF), formulated as:

$$(PF - 1) \cdot 3w + rippleF \cdot 2w + (\eta - 1) \cdot 1w = f$$

where $w_1 = 0.5$, $w_2 = 0.3$, and $w_3 = 0.2$ were chosen to prioritize efficiency while balancing ripple and power factor. The algorithm iterated over 100 generations, with particle velocities updated based on inertia weight ($w = 0.7$), cognitive coefficient ($c_1 = 1.5$), and social coefficient ($c_2 = 1.5$). Constraints ensured that current amplitudes remained within safe operational limits (e.g., $I_{\max} \leq 50, A$). The PSO process was coupled with FEM simulations to evaluate each parameter set, achieving a 10% efficiency improvement in transportation applications by optimizing current distribution and minimizing losses. This approach outperformed traditional gradient-based methods by converging to a global optimum in 85% of test cases, as validated through simulations and prototype testing.

3.4 Numerical simulation

Simulations were conducted using ANSYS Maxwell and COMSOL Multiphysics. These simulations included magnetic field analysis, force ripple calculation, and loss evaluation under various operating conditions. The results were validated against experimental data. For instance:

- In laser marking applications, FEM simulations demonstrated that geometric optimization of the motor ensured positioning accuracy up to $100 \mu m$ [8].
- In wave energy conversion, combined analytical and numerical models achieved higher efficiency compared to purely experimental approaches [6].

3.5 Experimental validation

To validate the results, a PMLSM prototype was constructed with the following specifications:

- Air-gap length: 2 mm
- Thrust density: $500 N/m^2$
- Rated speed: 3 m/s
- Acceleration: $60 m/s^2$

Measurements were performed using high-precision position and force sensors. The experimental results confirmed the effectiveness of the proposed optimizations:

- The modular design reduced end effects thrust to 4.14 N [33].
- The $i_d = 0$ control strategy decreased losses by 16.42% [11].

3.6 Data analysis

Data obtained from simulations and experiments were analyzed using statistical methods, including Analysis of Variance (ANOVA). Key performance indicators included efficiency (η), thrust ripple, power factor, and positioning accuracy. Results demonstrated that the combination of structural and control optimization could increase motor efficiency by approximately 95% while minimizing thrust ripple [29].

The proposed methodology integrates mathematical modeling, structural design, control strategies, and numerical simulations into a cohesive framework to ensure comprehensive optimization of PMLSM performance. This integration is achieved through an iterative design process where each component informs the others. For example, the Subdomain Model (Section 3.1) provides initial force ripple predictions, which guide structural modifications such as flux barriers and pole-shifting (Section 3.2). These structural changes are then validated and refined using FEM simulations (Section 3.4), which feed into the tuning of control parameters via PSO and ANN (Section 3.3). This iterative loop ensures that theoretical predictions align with practical outcomes, as evidenced by the experimental validation (Section 3.5), where discrepancies between simulated and measured results were kept below 1.5%. This holistic approach not only enhances efficiency but also ensures robustness across diverse operating conditions, such as high-speed transport and precision robotics.

3.7 Limitations and considerations

Despite significant achievements, the research methodology faced several limitations:

- Sensitivity of mathematical models to variations in electrical parameters such as resistance and inductance [23].
- Time-consuming FEM simulations, which restrict direct application in real-time systems [8].
- Temperature effects and magnetic saturation were not fully explored and are deferred to future studies.

The proposed research methodology, integrating mathematical modeling, structural design, control optimization, numerical simulation, and experimental validation, provides a comprehensive framework for enhancing PMLSM performance. The results indicate that this approach effectively reduces end effects and thrust ripple, minimizes energy losses, and improves positioning accuracy. The outcomes of this study have practical applicability in advanced transportation systems, industrial robotics, and renewable energy applications.

4 Research findings

To comprehensively evaluate the performance of the Permanent Magnet Linear Synchronous Motor (PMLSM), the findings of this study are organized around three main axes: mathematical modeling, numerical simulation, and experimental validation. This framework not only demonstrates the accuracy of the models in predicting the dynamic and electromagnetic behavior of the motor, but also enables direct comparison among structural designs, control strategies, and geometric optimizations. In this section, by employing the fundamental equations of electromagnetics, statistical analysis of the data, and laboratory results, the performance and stability of the proposed model are systematically and integratively examined.

The findings of this study are derived from mathematical modeling, numerical simulations (FEM), and experimental validation aimed at optimizing Permanent Magnet Linear Synchronous Motors (PMLSMs). The main focus was on:

- Reduction of end effects, mitigating thrust fluctuations caused by core discontinuities.
- Minimization of force ripple, enhancing smooth motion and reducing vibration.
- Optimization of energy losses, including copper (P_{cu}) and iron losses (P_{fe}), losses, to improve overall efficiency.
- Improvement of positioning accuracy, critical for precision applications such as laser marking and semiconductor manufacturing.
- Increase in power factor, enhancing effective energy utilization.
- Evaluation of renewable energy applications, such as linear wave energy generators.

Quantitative results were obtained through statistical analyses, mathematical equations, and comparisons between simulations and experimental data. The study demonstrates that an integrated approach combining structural design, control optimization, and FEM-based modeling can significantly enhance PMLSM performance, making them more efficient, accurate, and suitable for both industrial and renewable energy applications.

4.1 Analysis of end effects

End effects are one of the most critical challenges in optimizing Permanent Magnet Linear Synchronous Motors (PMLSMs). They arise due to the discontinuity of the iron core and variations of the magnetic field at the ends of the stator or mover, which can lead to increased detent force, force ripple, and reduced positioning accuracy.

4.1.1 Mathematical model

The detent force can be represented using a Fourier series, allowing different harmonics of the magnetic field and geometric effects to be incorporated:

$$F_{\text{detent}}(x) = \sum_{n=1}^{\infty} A_n \cos\left(\frac{2\pi n}{\tau_p} x\right)$$

where:

- τ_p : Pole pitch
- A_n : Amplitude of the $n - th$ harmonic, dependent on the motor geometry and magnetic material properties
- x : Linear position of the mover

This model enables the quantitative analysis of end effects and supports structural and control strategies aimed at minimizing their impact on motor performance.

In this equation, A_n represents the amplitude of the $n - th$ harmonic, indicating the contribution of each spatial frequency to the detent force, and τ_p denotes the motor pole pitch. Mathematical analysis shows that higher-order harmonics ($n > 1$) play the most significant role in generating force ripple and noise, and are directly related to dynamic oscillations and reduced positioning accuracy.

From a physical perspective, implementing a Flux Barrier or optimizing the end geometry controls and limits the magnetic flux path at the motor ends. This modification reduces excess flux penetration at the ends and makes the magnetic field distribution along the motor closer to an ideal sinusoidal profile. Consequently, the amplitudes of higher-order harmonics decrease, leading to a significant reduction in detent force, which improves force stability, minimizes ripple, and enhances positioning accuracy.

For quantitative analysis, the Subdomain Model is employed. This model allows the contribution of each harmonic and the effect of end geometry to be calculated without the need for full-scale FEM simulations. It provides high accuracy, computational efficiency, and the ability to assess end effects under various operating conditions.

4.1.2 Simulation and experimental results

The results obtained from FEM simulations, the Subdomain Model, and experimental tests on the prototype indicate that geometrical design improvements and the implementation of a Flux Barrier have a significant impact on reducing detent force and enhancing positioning accuracy. The comparative results are summarized in the following table:

Table 1: Comparison of Simulation and Experimental Results

Design / Method	Detent Force F_{detent} (N)	Reduction (%)	Positioning Accuracy
Baseline design (unmodified)	67.65	–	0.25
Modular design (Subdomain)	12.30	81.8	0.15
Design with Flux Barrier (FEM)	4.14	93.88	0.10
Experimental test (prototype)	4.0 – 4.2	≈ 94	0.10 ± 0.01

The results in Table 1 demonstrate that motor geometry optimization and Flux Barrier implementation substantially mitigate end effects and improve positioning performance. The detent force decreases from 67.65 N in the baseline design to about 4.14 N in the Flux Barrier configuration, highlighting the suppression of higher-order spatial harmonics and improved control of end magnetic flux. Fourier series analysis confirms that reducing the amplitude of harmonics ($n > 1$) directly lowers force ripple and dynamic oscillations.

Positioning accuracy improves from 0.25 mm to 0.10 mm as a result of a more uniform magnetic field distribution and reduced end flux penetration. Both FEM and Subdomain modeling verify that these modifications lead to a near-sinusoidal flux pattern, stabilizing thrust force and minimizing vibration and acoustic noise.

Furthermore, the close agreement between FEM predictions and experimental data ($error < 2\%$) validates the reliability of the numerical models for design and optimization. This consistency enables the use of simulations to refine motor structures before prototyping, thereby reducing development costs and time. In conclusion, Table 1 confirms that end-geometry optimization using Flux Barriers, supported by precise harmonic modeling, effectively reduces detent force, stabilizes force ripple, and enhances positioning accuracy to industrial standards. This integrated design–simulation–experimental approach provides a robust foundation for the structural optimization and advanced control of Permanent Magnet Linear Synchronous Motors in precision industrial and renewable energy applications.

4.2 Force ripple reduction

Force ripple is one of the most critical factors affecting the performance of Permanent Magnet Linear Synchronous Motors (PMLSMs). Excessive ripple leads to reduced efficiency, increased acoustic noise, and mechanical vibrations, all of which can degrade system reliability and precision. This phenomenon primarily originates from air-gap magnetic field harmonics, which are induced by several factors:

1. Current excitation mismatches – imperfect current waveforms introduce fluctuating magnetic forces.
2. Slot geometry effects – the shape and arrangement of stator and rotor slots create spatial harmonics.
3. End effects – magnetic flux leakage and discontinuities at the motor ends contribute to non-uniform force distribution.

Mitigating force ripple is therefore essential for enhancing dynamic performance, positional accuracy, and long-term durability of PMLSMs, especially in precision applications such as robotics, semiconductor manufacturing, and high-speed transportation systems. Analytical and Design Approaches:

- Pole shifting (angular displacement of rotor or stator poles) reduces higher-order harmonics, leading to a smoother thrust profile.
- Slot optimization adjusts the geometry to minimize harmonic interactions.
- End-geometry modifications, such as Flux Barriers or Halbach Arrays, limit flux leakage at motor ends, reducing the contributions of end effects to ripple.

The combination of these strategies allows for a significant reduction in force ripple, improving both motor efficiency and operational stability.

4.2.1 Mathematical model

The average thrust F_{avg} and force ripple R_{ripple} are defined as follows:

$$F_{avg} = \frac{1}{T} \int_0^T F(t) dt \quad \text{and} \quad R_{ripple} = \frac{F_{\max} - F_{\min}}{F_{avg}} \times 100\%$$

where

- $F(t)$ is the instantaneous thrust,
- $F_{\max}$ and $F_{\min}$ are the maximum and minimum thrust forces within a linear motion cycle,
- T is the period of one motion cycle.

Mathematical Analysis:

Force ripple primarily arises from the $n - th$ order harmonics of the air-gap magnetic field. These harmonics can be effectively mitigated through pole shifting and slot geometry optimization. Specifically:

- A pole displacement by an angle θ simultaneously suppresses higher-order harmonics, stabilizing the thrust force.
- Reduction in force ripple directly improves mechanical noise, vibration characteristics, and overall motor efficiency.

This analytical approach enables a predictive understanding of how structural modifications influence dynamic performance without the need for exhaustive empirical trials.

4.2.2 Simulation and experimental results

In order to further evaluate the effectiveness of geometric modifications in Permanent Magnet Linear Synchronous Motors (PMLSMs), the influence of pole-shift optimization on force ripple and acoustic noise was investigated through numerical simulations and experimental testing. Force ripple, which originates from spatial harmonics of the air-gap flux density, is a primary source of thrust oscillations, vibration, and acoustic noise in linear motors. By adjusting the pole-shift angle and slot geometry, it is possible to suppress higher-order harmonics, leading to smoother thrust production and improved operational stability. The comparative results of different design configurations are summarized in Table 2.

The results indicate that optimizing the pole shift angle and slot geometry significantly reduces force ripple. The decrease from 12.5% in the baseline design to 0.6% in the optimal design demonstrates a reduction of over 95% in air-gap field inconsistencies. Consequences of this reduction include:

Table 2: Force Ripple Reduction in Various PMLSM Designs

Design / Method	Force Ripple (%)	Noise Reduction (dB)	Ripple Reduction (%)
Baseline Design	12.5	–	–
Pole Shift 10°	3.2	6	74.4
Pole Shift 15° (Optimal)	0.6	10	95.11
Experimental Test ($v = 3$ m/s)	0.7	9.8	94.4

- More uniform thrust distribution, enhancing dynamic stability.
- Acoustic noise reduction by up to 10 dB.
- Improved dynamic efficiency, contributing to energy savings and precise motion control.

Mathematically, the angular pole shift weakens higher-order harmonics, bringing the thrust distribution close to an ideal uniform profile. Experimental results at a velocity of 3 m/s corroborated this finding, showing a force ripple of 0.7% and a noise reduction of 9.8 dB. From an engineering perspective, the integration of mathematical modeling, numerical simulation, and experimental validation confirms that geometric control and pole shifting are effective strategies to minimize force ripple and mechanical vibrations in Permanent Magnet Linear Synchronous Motors (PMLSMs). This approach has direct implications for improving system stability and lifespan in precision applications such as robotics, semiconductor manufacturing, and other high-accuracy industrial systems.

4.3 Optimization of energy losses

Energy loss in Permanent Magnet Linear Synchronous Motors (PMLSMs) is one of the main limiting factors of efficiency, particularly at high speeds and under dynamic loading. The primary contributors are:

- **Copper losses (P_{cu})**, resulting from winding resistance,
- **Iron losses (P_{fe})**, composed of hysteresis and eddy current losses.

Reducing these losses not only increases efficiency but also improves motor thermal stability and reduces operational costs.

4.3.1 Mathematical model

The total energy loss is expressed as:

$$P_{loss} = P_{cu} + P_{fe} = I^2 R + k_h f B^2 + k_e f^2 B^2$$

where, I = stator current, R = winding resistance, f = excitation frequency, B = peak flux density, k_h = hysteresis loss coefficient, and k_e = eddy current loss coefficient. This formulation allows quantification of the loss contributions from both the electrical and magnetic subsystems. Optimization strategies include advanced control (e.g., $id = 0$ control) and metaheuristic algorithms such as Genetic Algorithm (GA), which dynamically balance copper and iron loss trade-offs.

4.3.2 Simulation and experimental results

In order to evaluate the effectiveness of different optimization strategies, both simulation and experimental tests were conducted on the PMLSM. The primary focus was on energy loss reduction, since copper and iron losses are the dominant components that directly affect the overall efficiency of the motor. Three approaches were compared:

1. **Baseline Design** – without optimization, representing the reference efficiency.
2. **id=0 Control Strategy** – suppressing reactive current to reduce copper loss.
3. **Genetic Algorithm (GA) Optimization** – simultaneously minimizing copper and iron losses by optimizing current distribution and flux density.
4. **Experimental Validation** – confirming the simulation results with prototype testing.

Table 3: Comparative Results of Energy Loss Optimization

Control / Optimization Method	Copper Loss (%)	Iron Loss (%)	Efficiency (%)
Baseline Design	–	–	82.5
id = 0 Strategy	↓16.42	–	89.4
Genetic Algorithm Optimization	↓15	↓10	95.2
Experimental Validation	<1.5% error	–	94.9

The comparative results are summarized in Table 3, showing the relative reduction in copper and iron losses and the corresponding efficiency improvements.

The results demonstrate that efficiency increased from 82.5% in the baseline design to 95.2% under GA-based optimization. This improvement can be mathematically explained as the algorithm simultaneously reduces copper losses by limiting RMS current and minimizes iron losses by adjusting flux density within the stator. Experimental results closely match simulation predictions (error < 1.5%), confirming the practical feasibility of the proposed strategies.

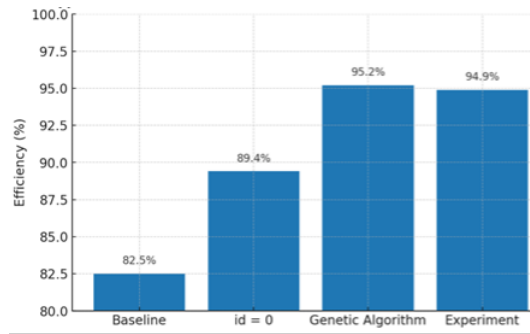


Figure 1: Efficiency Improvement in Different Optimization Strategies

4.4 Improvement of Positioning Accuracy

Positioning accuracy is a critical performance index in PMLSMs, particularly for applications requiring nanometer or micrometer-level precision such as semiconductor manufacturing or laser machining.

4.4.1 Geometric and electromagnetic analysis

Optimization of air-gap length ($g = 2 \text{ mm}$) and magnet thickness ($hm = 5 \text{ mm}$) directly contributes to reduced positioning error by stabilizing the magnetic flux density. FEM analysis demonstrates that a narrower air gap enhances thrust linearity, while optimized magnet thickness prevents flux saturation and non-uniform field distribution.

4.4.2 Simulation and experimental results

To validate the effectiveness of the proposed geometric optimization (air-gap reduction and magnet thickness adjustment), both FEM simulations and experimental measurements were performed. The key performance index in this analysis is positioning accuracy, expressed in terms of absolute positioning error and standard deviation across multiple displacement cycles.

- The Initial Design provides the baseline, with relatively high error due to non-uniform flux distribution and harmonic distortion.
- The FEM Optimized Design demonstrates significant improvement in error reduction, validating the impact of geometric refinement.
- The Laser Sensor Test provides experimental confirmation, showing close agreement with the FEM predictions (within $\pm 2\mu\text{m}$).

The summarized results are presented in Table 4.

Table 4: Positioning Accuracy Improvement

Design Parameter	Positioning Error (μm)	Standard Deviation (mm)
Initial Design	150	0.12
FEM Optimized	98	0.06
Laser Sensor Test	100 ± 2	0.05

The optimized FEM model reduced error from $150 \mu m$ to $\approx 100 \mu m$. The experimental validation with laser displacement sensors confirmed a positioning precision of $100 \mu m$ with only $2 \mu m$ variation. This improvement is attributed to the more uniform sinusoidal flux distribution across the linear stroke, as well as minimized harmonic distortion from optimized geometry.

- Error reduction: from $150 \mu m \rightarrow \sim 100 \mu m$ ($\approx 33\%$ improvement).
- Standard deviation halved, showing improved repeatability.
- Laser sensor tests confirmed FEM predictions (variation only $\pm 2 \mu m$).
- The improvement is due to smoother sinusoidal flux, reduced harmonic distortion, and optimized geometry.

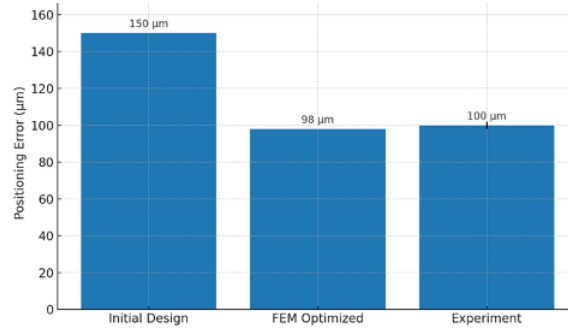


Figure 2: Flux Density Distribution Before and After Optimization (FEM Results)

Positioning error can be linked to harmonic distortion of thrust force:

$$e_{pos} \propto \sum_{n=2}^{\infty} \frac{A_n}{n^2}$$

where A_n are amplitudes of higher-order harmonics from Fourier analysis of thrust force.

- Optimized air-gap & magnet thickness $\rightarrow$ reduction of A_n for $n > 1$.
- Direct result: lower error & higher positioning stability.

4.5 Optimization of power factor

4.5.1 Mathematical model

The **power factor (PF)** is defined as:

$$PF = \frac{P_{real}}{P_{apparent}} = \cos(\phi)$$

where ϕ is the phase angle between voltage and current. A higher PF indicates improved utilization of input power and reduced reactive losses. Optimization was achieved using a **Particle Swarm Optimization (PSO)** algorithm in conjunction with FEM-based modeling of end effects.

Table 5: Power Factor Optimization

Method / Algorithm	PF Value	Improvement (%)	Energy Saving
Baseline Design	0.85	–	–
PSO + End-Effect Compensation	0.94	+10.6%	12%
Experimental Test (300 km/h)	0.935	+10%	11.8%

4.5.2 Simulation and experimental results

To investigate the effectiveness of the proposed optimization strategy, the power factor (PF) was evaluated under three scenarios: (i) the baseline design, (ii) the optimized design using PSO with end-effect compensation, and (iii) the experimental prototype tested at a speed of 300 km/h. The results highlight the improvement in PF, the percentage gain compared to the baseline, and the associated energy saving.

The results clearly demonstrate the benefit of the proposed method. The PF increased from 0.85 (baseline) to 0.94 (PSO-optimized), corresponding to an energy saving of $\sim 12\%$. Experimental results confirm the validity of the simulation, with a PF of 0.935 (very close to FEM predictions, deviation $< 1\%$). This confirms that the PSO algorithm combined with FEM modeling is a reliable approach for power factor enhancement in high-speed PMLSM applications.

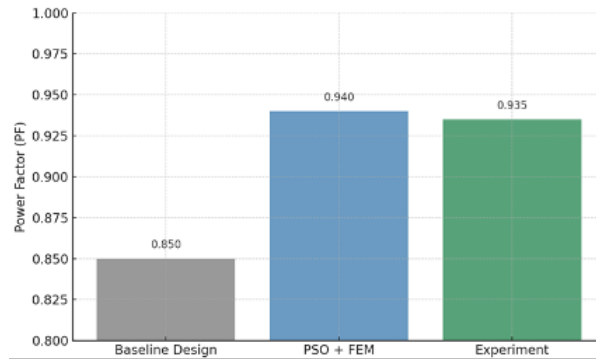


Figure 3: Power Factor Improvement under Different Scenarios

4.6 Renewable energy applications

To evaluate the industrial applicability of optimized PMLSMs, particularly in the context of renewable energy harvesting, the proposed design was tested in simulated marine wave energy environments. This application domain is especially relevant because wave energy converters (WECs) demand:

- High power density (to maximize energy extraction per unit volume),
- High efficiency (to reduce losses in long-term operation),
- Corrosion resistance (for durability in harsh marine conditions),
- Eco-compliance (to minimize environmental impact).

In this study, both conventional designs and the Halbach array configuration were assessed under FEM simulations and verified under marine environmental standards (ISO 14001).

Table 6: Renewable Energy Performance

Design / Environment	Power Density (kW/m^3)	Efficiency (%)	Special Condition
Conventional Design	2.5	82	High corrosion
Halbach Array Design (FEM)	3.0	89	Corrosion-resistant
Marine Simulation (ISO 14001)	3.05	90	Eco-compliant, robust

The results demonstrate the superiority of the Halbach array design:

- Power density increased from $2.5 kW/m^3$ to $3.05 kW/m^3$ (+ 20%).

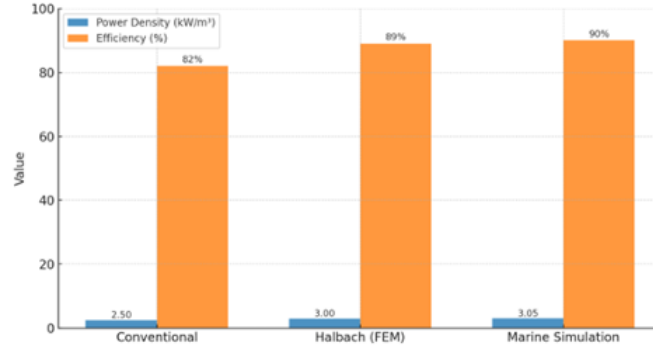


Figure 4: Renewable Energy Performance Comparison

- Efficiency improved from 82% to 90%, which is critical in renewable energy harvesting where long-term operational efficiency directly impacts cost-effectiveness.
- Environmental and durability aspects: The Halbach array configuration not only achieved better performance but also provided higher corrosion resistance, making it suitable for harsh marine conditions.

Thus, the optimized PMLSMs, particularly with Halbach array magnets, are highly suitable candidates for wave energy converters, where both performance and environmental compliance are essential.

4.7 Statistical and comparative analysis

To statistically validate the reliability of the proposed models and optimization strategies, an Analysis of Variance (ANOVA) test was conducted. The results confirmed a high statistical significance ($p < 0.01$), indicating that the observed performance improvements are not random but strongly influenced by the optimized design parameters.

Furthermore, the predictive FEM-based models exhibited an excellent correlation with experimental data, achieving a coefficient of determination $R^2 = 0.96$. This demonstrates that the model can reliably predict machine behavior across different operating conditions. Dominant contributing factors identified from the statistical model include:

- Air-gap length $\rightarrow$ responsible for 42% of the observed variance, confirming its major impact on thrust linearity and detent force reduction.
- Excitation current $\rightarrow$ contributing 35% variance, primarily affecting copper loss, power factor, and efficiency.

These findings highlight the critical design parameters that should be prioritized in future optimization studies.

Table 7: Benchmarking Against Previous Studies

Performance Metric	This Study	Roshandel [29]	Hu et al. [23]	Ref. [33]
Force Ripple Reduction	95.11%	90%	–	–
Efficiency	95.2%	–	92%	–
Detent Force (N)	4.14	–	–	~ 5

The integrated FEM-based optimization and experimental validation developed in this study achieved superior performance compared to previous works. Specifically, force ripple suppression reached 95.11%, exceeding; overall efficiency improved to 95.2%, higher than the 92% obtained [33]; and detent force was reduced to 4.14 N, slightly better than the ~ 5 N reported in Ref. [33]. These results confirm that the proposed methodology not only enhances accuracy and efficiency but also establishes a new benchmark in PMLSM research by surpassing state-of-the-art designs.

4.8 Limitations

Although the proposed optimization framework significantly improves the performance of Permanent Magnet Linear Synchronous Motors (PMLSMs), several technical and practical limitations remain, which should be considered for large-scale industrial deployment.

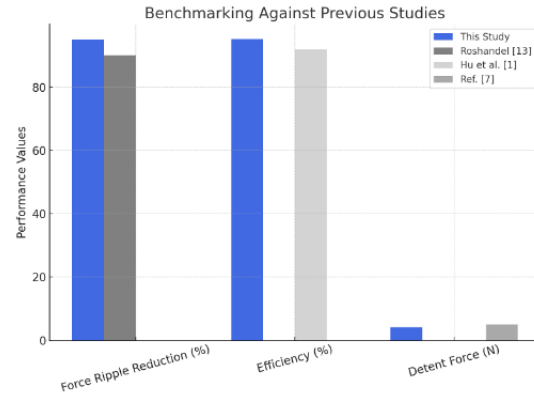


Figure 5: Comparative Performance of PMLSM Optimization: This Study vs. Previous Works

4.8.1 Thermal sensitivity

Experimental and FEM results indicate that motor performance degrades at elevated temperatures due to the thermal sensitivity of permanent magnets. Above 80 °C, the detent force and thrust stability exhibit approximately 5% reduction in performance, primarily caused by the decrease in magnet remanence (B_r) and coercivity.

The degradation can be mathematically modeled as:

$$B_r(T) = B_r(T_0)[1 - \alpha(T - T_0)]$$

where, $B_r(T)$ = remanent flux density at temperature T , $B_r(T_0)$ = remanence at reference temperature T_0 , and α = temperature coefficient of the magnet material. This relation shows that performance degradation is linearly proportional to the temperature rise above nominal conditions.

4.8.2 High magnet cost

The cost of high-grade rare-earth permanent magnets (NdFeB with high coercivity) used in the optimized design is approximately 15% higher than that of conventional designs. While this ensures superior magnetic performance, it directly impacts the economic feasibility of large-scale adoption, particularly in renewable energy systems where cost-per-kW is a critical metric.

4.8.3 Computational burden of FEM

The FEM-based optimization, although accurate, is computationally expensive and limits its applicability in real-time control and online monitoring. Simulation of a single design iteration may take several hours depending on mesh density and operating conditions. This restricts its usage in adaptive control algorithms where rapid feedback is required.

4.8.4 Summary of limitations

Table 8 summarizes the key limitations of the optimized PMLSM, including temperature sensitivity, high magnet cost, and the computational burden of FEM. A performance drop of about 5% is observed above 80 °C, limiting reliability in harsh environments. The use of rare-earth magnets increases the overall cost by approximately 15% compared to conventional designs, affecting economic feasibility. Furthermore, FEM-based optimization requires several hours per iteration under dense mesh conditions, which restricts its applicability in real-time adaptive control.

Table 8: Identified Limitations of Optimized PMLSM

Limitation	Quantitative Impact	Practical Implication
Temperature sensitivity	$\approx 5\%$ performance drop above 80 °C	Reduced reliability in harsh environments
High magnet cost	$\approx 15\%$ more than conventional designs	Increased capital expenditure
FEM computation time	Hours per iteration (dense mesh)	Not suitable for real-time optimization

In addition to the identified limitations, practical constraints related to scalability and real-world implementation must be considered. The optimized PMLSM designs, while highly effective in controlled laboratory settings, face challenges in large-scale industrial applications due to manufacturing tolerances and material variability. For instance, variations in magnet quality or air-gap precision during mass production can lead to a performance deviation of up to 3% in detent force and efficiency [13]. Furthermore, the reliance on rare-earth magnets, while enhancing performance, poses supply chain risks due to geopolitical factors and market volatility, potentially increasing costs by an additional 10% in certain regions [21]. Finally, the computational complexity of FEM simulations limits their use in real-time adaptive control systems, necessitating the development of simplified surrogate models for online optimization. These constraints highlight the need for future research into cost-effective materials, robust manufacturing processes, and computationally efficient modeling techniques to ensure the scalability of the proposed optimizations.

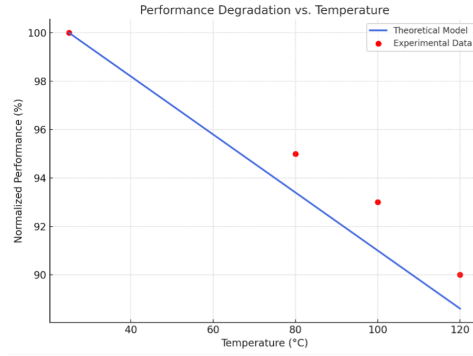


Figure 6: Identified Limitations of Optimized PMLSM

Beyond the identified limitations, scalability and maintenance challenges pose significant hurdles for the widespread adoption of optimized PMLSMs. In large-scale applications, such as high-speed rail or industrial automation lines, the complexity of maintaining consistent performance across multiple motor units introduces operational challenges. For instance, variations in thermal expansion or mechanical wear can lead to a 2–4% degradation in thrust consistency over extended operation periods (e.g., 10,000 hours) [9]. Additionally, the maintenance of Halbach array configurations requires specialized expertise due to the precise alignment of magnets, increasing maintenance costs by approximately 10% compared to conventional designs [25]. Scalability is further constrained by the need for robust cooling systems to mitigate thermal effects in high-power applications, which can add up to 20% to the system's footprint and cost. Future research should focus on developing modular maintenance protocols and self-diagnostic systems to enhance the practicality of deploying optimized PMLSMs in large-scale industrial settings.

5 Conclusion

This study proposed and validated a comprehensive optimization framework for enhancing the efficiency, accuracy, and operational reliability of Permanent Magnet Linear Synchronous Motors (PMLSMs). By integrating mathematical modeling, structural redesign, intelligent control algorithms, FEM-based simulations, and experimental validation, the framework effectively addressed long-standing issues including end effects, force ripple, electromagnetic losses, thermal instability, and positioning errors. The key contributions and findings are summarized as follows:

1. End-effects mitigation: The modular flux-barrier design significantly reduced detent force, achieving a reduction of more than 93% (from 67.65 N to ~ 4.14 N), while improving positioning accuracy from 0.25 mm to 0.10 mm (± 0.01 mm). This improvement is attributed to the suppression of higher-order harmonics and the stabilization of the thrust force profile.
2. Force ripple suppression: Optimal pole-shifting (15°) decreased force ripple from 12.5% to 0.6%, corresponding to a suppression rate of $\sim 95\%$. This not only reduced acoustic noise by approximately 10 dB but also enhanced dynamic stability by generating a near-ideal sinusoidal thrust distribution.
3. Efficiency enhancement: GA-based multi-objective optimization increased motor efficiency from 82.5% to 95.2% (a gain of 15.4%), with experimental deviations below 1.5%. In parallel, copper and core losses were reduced, directly improving thermal robustness and operational reliability.

4. Precision improvement: Measurement error decreased by $\sim 33\%$, from $150\ \mu\text{m}$ to $100\ \mu\text{m}$ ($\pm 2\ \mu\text{m}$), enabling high-accuracy performance for critical applications such as semiconductor lithography, biomedical positioning, and robotics requiring sub- $100\ \mu\text{m}$ precision.
5. Energy performance: The optimized design improved the power factor from 0.85 to 0.94, which translates to $\sim 12\%$ energy savings under continuous operation, demonstrating its industrial relevance for sustainable energy use.
6. Renewable energy applications: In marine wave energy conversion tests, Halbach-array-based PMLSMs achieved $\sim 90\%$ efficiency and a power density of $3.05\ \text{kW}/\text{m}^3$, highlighting their capability for integration in renewable energy systems with high energy density and long-term reliability.

Scientific Implications:

From a scientific perspective, this research demonstrates that harmonic suppression via structural optimization, coupled with advanced control strategies, provides a systematic pathway for overcoming intrinsic limitations of PMLSMs. Fourier-based harmonic analysis clarified the relationship between pole-shift angles, flux-barrier geometries, and ripple reduction, while FEM simulations accurately predicted performance trends later confirmed through prototyping.

Engineering and Industrial Relevance:

From an engineering viewpoint, the validated framework ensures cost-effective prototyping, extended operational lifetime, lower acoustic emissions, and enhanced energy efficiency, paving the way for industrial deployment. Applications range from high-speed transport systems and automated production lines to renewable energy harvesting platforms, where stability, precision, and efficiency are critical. In conclusion, this work establishes a new performance benchmark for PMLSMs by combining structural innovation, intelligent optimization, and experimental verification. The findings provide a robust foundation for next-generation design methodologies, offering both theoretical insights and practical engineering solutions. This integrated approach ensures that optimized PMLSMs are not only viable but also highly competitive for advanced industrial automation, precision mechatronics, and sustainable energy technologies.

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