Development and Design of Magnetic Structures for Improving Reliability Linear Motors

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Abstract: The design of magnetic structures for Permanent Magnet Synchronous Linear Motors (PMSLMs) plays a crucial role in various industrial and technological applications. Through the modernization approach in determining the shapes of structures for magnets and choosing appropriate dimensions. Nonetheless, there is significant room for improvement in their performance, especially in terms of reducing cogging forces and enhancing back electromotive force (EMF) through reducing the harmonic contents of induced back EMF.
This study introduces a model that focuses on optimizing a flat single-sided PMSLM to reduce cogging forces. This model utilizes a blend of analytical and numerical techniques, including FLUX2D/3D optimization to mitigate cogging forces. Numerous design iterations were performed to identify the ideal model, leading to a substantial decrease in maximum cogging pressures. This research integrates several benefits and novel methodologies for the design of efficient linear motors, with ramifications for policy formulation in the domain of Permanent Magnet Synchronous Linear Motors (PMSLMs). Notwithstanding the current limitations, these offered models signify viable solutions for industrial and commercial applications, facilitating the progression of this innovative technology.

Keywords: Permanent magnet linear motor, cogging force, finite.

1. Introduction

Permanent magnet synchronous motors (PMSMs) are widely utilized in many sectors due to their remarkable efficiency and high power density. In addition to the continuous progress in business and artificial intelligence, scholars are currently concentrating on the challenges of determining strategies for safety and comfort. [1], [2]. Permanent magnet linear motors exhibit excellent efficiency by generating a magnetic field with permanent magnets, hence obviating the necessity for an external power source. Accurate prediction of the magnetic field in a specific motor design may require detailed analysis Table:1 Here is a summary of the attributes of linear motors and a comparison of each type with others. . In linear motor applications, precise movement control is crucial. By improving the magnetic field distribution, the motor's efficiency, compactness, and suitability for industrial and transportation purposes can be enhanced[3]–[5].

Table 1. Types of Linear Motors and Comparative Analysis of their Characteristics

Attribute	Fr Iron Core	Air Core	Slotless
LM Cost	Below-average	Elevated	fewest
LM Attractive Force	Maximum	Naught	Reasonable
Cogging of Characteristics	Maximum	Naught	Reasonable
LM Force / Size	Optimal	Reasonable	Decent
Characteristics Thermal	Best	Worst	Decent
Forcer Weight of LM	Weightiest	Ultralight	Reasonable
Forcer Strength of LM	Optimal	Worst	Decent

There is a strong emphasis on substantially increasing the power density of electric motor PMSLMs and introducing innovative design techniques to optimize their performance. [6]. NdFeB magnets are widely regarded as the superior choice for Permanent Magnet Synchronous Motors (PMSMs) owing to their elevated energy density and magnetic strength. Nonetheless, their susceptibility to corrosion and elevated expense may restrict their adoption in some contexts. A contemporary high-energy NdFeB magnet is employed to optimize power density, hence minimizing the motor's volume and enhancing torque density.[7]. However, they often suffer from cogging torque, which leads to undesirable torque ripple, vibration, and noise, negatively impacting motor performance. Therefore, accurately calculating and mitigating cogging torque is crucial during the motor design phase[8], [9]. In summary, cogging force is a recognized and extensively examined phenomenon in linear Permanent Magnet Linear Motors (PMLMs), prompting several researchers to offer diverse methods to diminish or alleviate its impact, as cogging force presents a significant difficulty in the design of linear motors.[10]–[12].In this research[13], the focus was on permanent magnet linear machines, specifically those with 8 poles and 9 slots. The Finite Element Method (FEM) was employed to create a model for these machines. The model underwent rigorous validation under two distinct conditions: no load and nominal load. When operating under no-load conditions, the cogging force measured 1.1N.In[14] , the geometric parameters of the PMLSM, such as tooth width and PM arc, have been determined in such a way that costs and cogging force are reduced. However, a constant PM width along the depth of the machine is used, showing the Figure 1 depiction of a single-sided traditional Permanent Magnet Linear Synchronous.

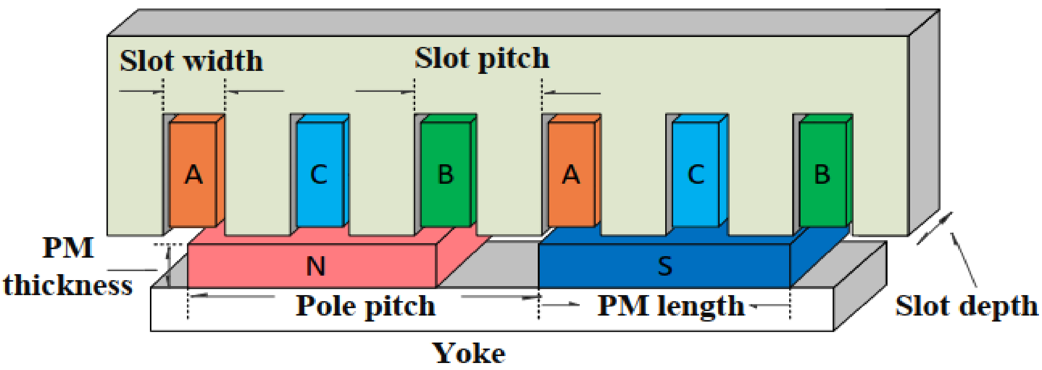


Fig. 1. Depiction of a single-sided traditional Permanent Magnet Linear Synchronous Motor (PMLSM) equipped with a pair of Permanent Magnets (PMs)[15]

In [16] A finite element analysis was performed with planar cross sections, and the resultant data was used to estimate a solution for the three-dimensional model. The investigation demonstrated that the incorporation of a curved track significantly enhanced the cogging force of a single Linear Synchronous Motor (LSM). Nonetheless, the presence of many LSMs demonstrated an interaction effect that diminished the overall rise in cogging force. Subsequently, a geometric optimization was conducted to ascertain the ideal relative placements of the LSMs along the curved tracks, leading to a reduction in the overall cogging force. IN [17], An enhanced control system has been proposed for a small flux-switching permanent magnet motor (FSPM) to improve its performance. This involves determining parameters such as air gap flux density, torque, winding turns, pole number, magnet geometry, and current density in the FSPM. Electromagnetic analysis of the motor was conducted using software (ANSYS-Maxwell) to optimize its performance. In this paper[18], The authors concentrate on enhancing the positional precision of a tiny permanent magnet linear motor intended for MEMS applications by using a novel technique that involves the injection of odd harmonic currents. This method successfully reduces electromagnetic force ripple, resulting from non-sinusoidal air-gap magnetic field distribution, which can considerably hinder motor performance. The micro linear motor functions by supplying sinusoidal currents with a 90° phase difference to two-phase micro windings, generating a Lorentz force that propels the motor in one direction, while reversing the current direction enables reciprocating motion. inside[19], Two techniques have been employed in a flux-switching linear tubular machine to reduce cogging force. The first technique consists of dividing the stator into two modules; the gap between them was filled with iron and its width was adjusted to reduce the cogging force. In the second technique, additional U-shaped teeth were placed at both ends of the stator; the width of the slot in the additional cores was varied to reduce the cogging force. 25% lower cogging force is achieved compared to the first method. In[20], This study aims to reduce torque ripple in electric vehicle (EV) motors, ultimately leading to reduced vibration and noise. Through careful analysis, it is determined that the V-type rotor shape is the most effective in minimizing torque ripple. By optimizing the rotor barrier shape, torque ripple is reduced by 7%. Additionally, the application of wedge skew to the stator shoe leads to a further 9.6% reduction in torque ripple. Overall, these improvements result in a significant 36% reduction in torque ripple when compared to the basic model.

The research investigated the utilization of Semi-closed slot construction for primary components, specifically focusing on altering the width of the pole shoes to achieve the lowest possible thrust ripple. To enhance the optimization of thrust ripple characteristics in Permanent Magnet Linear Synchronous Motors (PMLSM), additional enhancements were explored, including modifications to the shape of the permanent magnets to form arc-shaped magnetic poles. This design alteration serves to promote a more sinusoidal distribution of air gap flux density, consequently leading to a reduction in ripple amplitude[15]. In this study, a comprehensive 2-D analytical model using the subdomain technique was developed for PS-FRPMMs. This model facilitates the accurate and rapid investigation of design parameters' effects on machine performance. Two case studies were conducted, one with 12 stator teeth and 10 poles and another with 18 stator teeth and 13 rotor poles. The study examined design parameters, such as rotor slot width, slot opening width, and PM segment ratio in the two-segment magnetization pattern, in relation to metrics such as instantaneous torque, torque ripple, unbalanced magnetic force (UMF), and electromotive force (EMF). Comparative analysis with 2-D finite element methods (FEM) and 3-D FEM, with and without saturation effects, revealed strong agreement[21], [22]

In [23],presented a new modular linear flux-reversal PM (M-LFRPM) motor in which additional magnets are used on the surface of the stator teeth to improve the back-EMF waveform and decrease the cogging. Form the modelling point of view, different modeling approaches have been presented In[24] This study investigates the impact of flux gap insertion in modular Permanent Magnet Linear Synchronous Motors (PMLSMs) with varying slot and pole configurations. In PMLSMs with more slots than poles, widening flux gaps adversely affect electromagnetic performance, leading to reduced parameters such as winding factor, open-circuit flux linkage, back-EMF, self- and mutual inductances, and average thrust force. It's noteworthy that the enhancements observed in modular PMLSMs with fewer slots than poles are not as significant as those in rotating motors. It's noteworthy that the enhancements observed in modular PMLSMs with fewer slots than poles are not as significant as those in rotating motors. This discrepancy is attributed to the presence of the end effect in linear motors, which remains challenging to mitigate through flux gap insertion. The study introduces a novel design for a double-sided Permanent Magnet Linear Synchronous Motor (DS-PMLSM) with staggered primaries, aimed at reducing detent forces and improving thrust characteristics. The innovative configuration involves staggering two primaries and rearranging windings to suppress end effects without sacrificing average thrust. Theoretical analyses and finite element simulations validate the reduction in detent forces and the overall effectiveness of this design[25]. Finite element simulations are conducted to compare three motor configurations: conventional PMLSM, V-shaped magnetic pole PMLSM, and V-shaped tooth-slot PMLSM. The results show that the V-shaped tooth-slot structure improves thrust characteristics and reduces thrust ripple caused by detent forces[26]. The article introduces a significant concept known as the equivalent permeance model, which plays a central role in calculating the thrust force. This model takes into consideration various factors, including cogging force, permanent magnet thrust, and winding reluctance force, as part of an in-depth analysis and optimization process for a groundbreaking Flux-Switching Transverse-Flux Permanent Magnet Tube Linear Motor (FSTFPMTLM). Furthermore, this model is then skillfully utilized to meticulously assess the overall performance of the motor and explore the influence of diverse parameters, with a particular focus on those associated with the air gap. The study's outcomes compellingly demonstrate that precision adjustments to these parameters hold the key to effectively reducing cogging forces while simultaneously enhancing the motor's thrust output[27]. This research presents a novel design for a permanent magnet linear motor with improvements in magnetic power utilization, achieving high force density at a low cost. optimal geometric parameters are selected using the layered orthogonal optimization method. Subsequently, the electromagnetics performance of the motor is analyzed using the equivalent magnetic network model (MNM). Finally, a method for reducing the imbalance in the three-phase flux linkages is introduced by adding auxiliary teeth to the primary component. This new motor design enables high force density and excellent cost efficiency, making it suitable for linear propulsion applications across various fields[28].In[29] This study focused on the development and analysis of a novel linear oscillating actuator (LOA) design, which employed rectangular-shaped core materials and permanent magnets (PMs)., various parameters were systematically adjusted to achieve optimization, with the ultimate goal of maximizing the electromagnetic (EM) force generated by the actuator. the EM force density of the novel design exceeded that of conventional LOAs by a substantial margin, specifically by 23.8 per cent.

In [30]This study introduces a novel Permanent Magnet Linear Synchronous Motor (PMLSM) designed as an innovative alternative for Electromagnetic Launch Systems. The proposed PMLSM features a distinctive stator structure with consequent poles, and a mover with dual iron cores encapsulating a single permanent magnet. Analytical calculations and structural optimizations were conducted to enhance the motor's thrust and minimize detent force. The reduction in the use of permanent magnets (PMs) results in cost savings. Most scientific research in this field has tended to overlook the complexities of structural design and the associated costs[31]. This study focuses on investigating a novel modular single-sided flat permanent magnet synchronous motor (PMSM) to reduce cogging force, which represents a challenge in design. Through the modernization approach in determining the shapes of structures for magnets with choosing appropriate dimensions. Subsequently, we conduct a comparative analysis of the results with models presented in prior studies. especially in terms of reducing cogging forces and enhancing back electromotive force (EMF) by reducing the harmonic contents of induced back EMF.

2. Module Development:

Creating a linear electrical machine involves applying electromagnetic theories and principles. the B-H curves for the appropriate ferromagnetic materials were used to account for the saturation. As shown in 2The design process includes determining the dimensions of the magnetic circuit and electrical circuit. Additionally choosing designing an appropriate motor for a specific application involves a trade-off among three factors. The surface area of the air gap between the mover and stator (A), the magnetic loading attributed to the permanent magnets (B), and the specific electrical loading caused by the current flowing through the stator windings (Q). The thrust force (F) generated by a permanent-magnet motor can be described as a function of these three crucial factors which can be mathematically expressed in Equation 1.

$$\mathrm{F} = \mathrm{BQA} \tag{1}$$

Although. Maxwell's equations and Maxwell stress theory are more extensive theories that encompass a broader range of electromagnetism and can be used for analyzing various electromagnetic systems, including linear motors[32], [33]. The magnetic loading is determined as the root-mean-square (rms) of the magnetic flux density distribution created by the magnets at the top of the stator coils, situated along the boundary of the air-gap. It is important to note that some magnetic flux escapes from the coils due to flux leakage within the slots, which slightly reduces the effective magnetic loading. Conversely, the specific electrical loading depends on factors such as the current density in the coils, the volume of windings per unit length of the motor, and the winding factor associated with the chosen winding configuration.

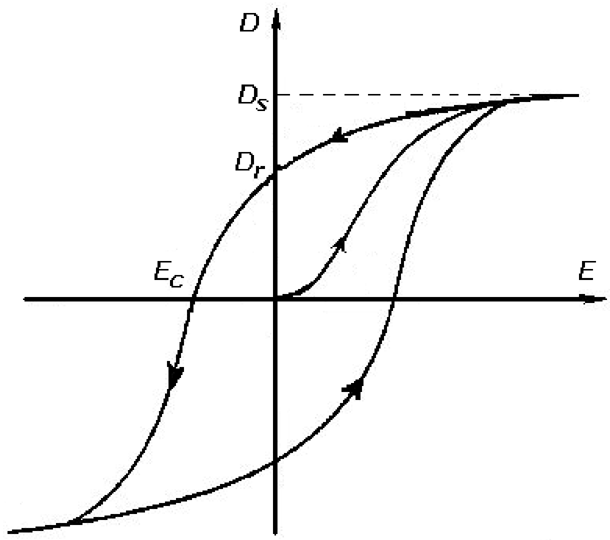


FIG 2 B-H mmfs for the appropriate ferromagnetic materials[1]

Typically, mechanical constraints limit the surface area of the air gap. Therefore, to boost thrust force, it becomes imperative to maximize both magnetic loading and specific electrical loading. This underscores the critical importance of slot proportions in motor design. Larger slots can accommodate a greater cross-sectional area for conductors, resulting in higher specific electrical loading for the same conductor current density[34]. Conversely, as slot width decreases, the effective air gap narrows, leading to an increase in magnetic loading. Furthermore, wider teeth can withstand higher magnetic loading without saturation, especially when employing larger magnets on the mover or reducing the air gap size. This work presents a stepwise exploration of various designs, including rectangular-type, one-sided staircase, two-sided staircase, and hierarchical magnetic designs for linear motors[29], [35]. All these designs are aimed at enhancing the performance of linear motors and offer potential solutions to address challenges for force cogging and harmonic contents of induced back-EMF through a graduated approach to magnetic field design, as illustrated in Figures 3 ,4 and 5. These figures depict an

8-pole magnet array distribution in the bottom region and the stator in the top region, separated by an air gap.

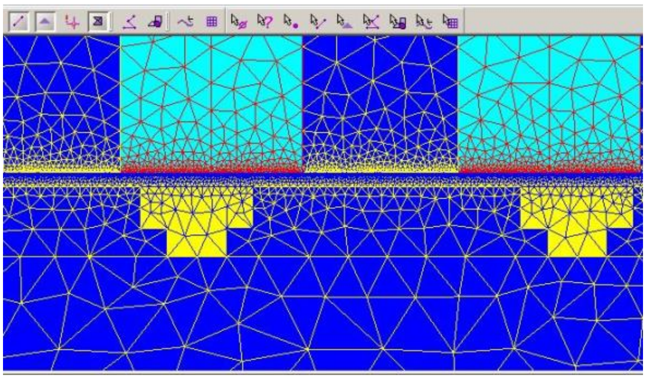


Fig. 3. depicting the construction process

However, The stator core contains slots where coils are wound, represented by red, blue, and green rectangles. The proposed model combines several technological advantages related to dimensional adjustments and magnet design.

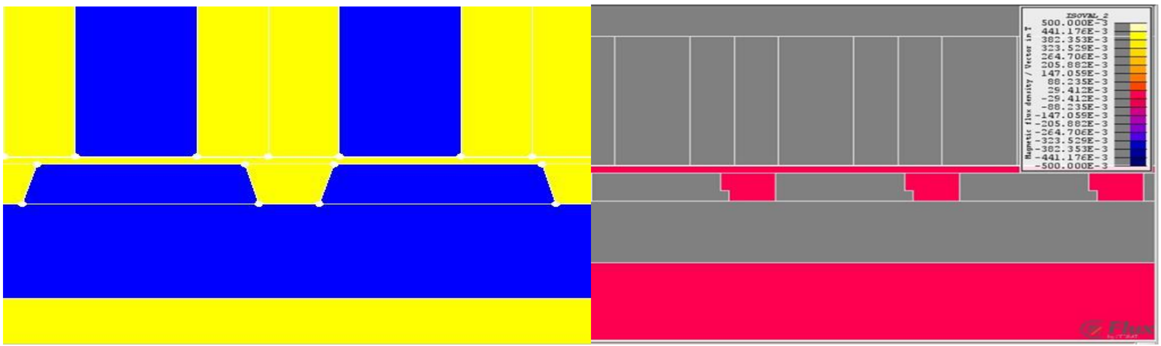


Fig. 4. illustrating the design of multiple models

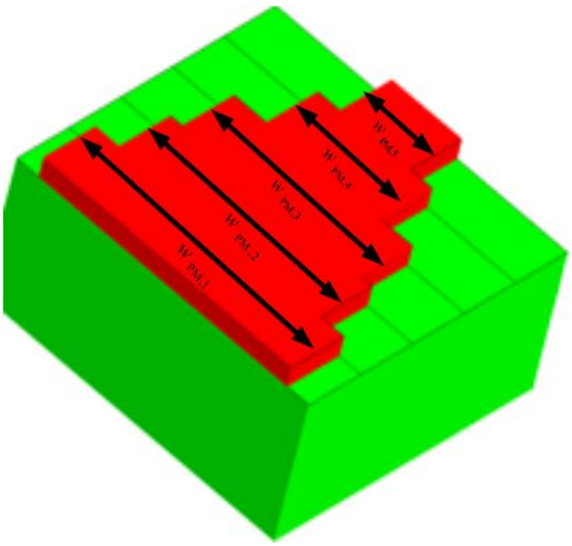


Fig. 5. Segmented PMs with different relative magnet widths

In the Figure 5. The technique of varying the width of permanent magnets along the depth of a motor can enhance its performance through several mechanisms. By adjusting the magnet width, the magnetic field distribution can be optimized, leading to reduced energy losses and unwanted heat generation, thereby improving overall efficiency. The process of PM segmentation involves dividing permanent magnets into distinct sections or segments. This research assesses the influence of various segmentation strategies on the performance attributes of the motor. This model incorporates an 8/9 pole/slot configuration with a rectangular magnet as the primary component. Table illustrating the dimension of models .A model was constructed with two distinct lengths, the first measuring 216mm and the second 240mm. This variation in length served as a critical aspect of our scientific investigation. Several advanced techniques were employed to optimize the design through dimensional variations, including adjustments to the width, length, and spacing of the permanent magnets and focus on the air gap's length to determine the appropriate dimensions . By finely tuning the magnet dimensions, the magnetic field distribution can be optimized, resulting in reduced energy losses and minimized unwanted heat generation, consequently enhancing overall efficiency. To analyze the impact of various parameters shown in table on machine performance and conduct virtual tests, the Finite Element Method (FEM) was employed. Factors integral to electrical machine design, including the magnetic circuit, electric circuit, windings, and the robustness of machine components, were duly considered. An appropriate mesh size was determined through meticulous mesh analysis.

Table 2. PMLSMs two model parameters

Description	Symbol	Model
number of concentrated winding layers	LAYER	2
width of the air gap	AIRGAP	1.5
permanent flux density	BR	1.23
height of the magnets mm	H_MAGNET	5
height of the magnet back	H_MAGNET_BACK	12
slot height	H_SLOT	25
eight of the stator back	H_STATOR_BACK	12
width of the magnets spacing	LENGTH	239.4mm
width of the magnets spacing	MAGNET_DISTANCE	5
relative permeability	MU_R	1.05
number of poles	POLES	8
number of the slots	SLOTS	9
width of the magnets spacing	SLOT_PITCH	5
width of the magnets	W_MAGNET	24.925
slot width	W_SLOT	14
tooth width	W_TOOTH	12.6

3. Analysis and Discussion of Results

the technique of optimizing the design by modifying the dimensions, including the width, length, and spacing of the permanent magnets, has played an effective role in mitigating the total harmonic distortion (THD) and cogging forces. Figure 6 elucidates the critical significance of the magnetic field direction in relation to light sensitivity, as evidenced by the ISO values depicting magnetic flux distribution across distinct segments of the machine. The color variations effectively delineate fluctuations in magnetic flux levels, with the remarkable uniformity in flux distribution across the entire machine bearing testament to its non-oversaturated state. It is noteworthy that the maximum flux level prominently resides within the range of 1.3T to 1.6T.

Figure 7 offers a comprehensive visualization of the flux lines within the optimal motor components. Remarkably, these flux lines establish closed loops connecting the permanent magnets (PMs), stationary components, and the translator. Furthermore, observable leakage flux lines traverse through the optimal motor components, providing valuable insights into the magnetic field dynamics.

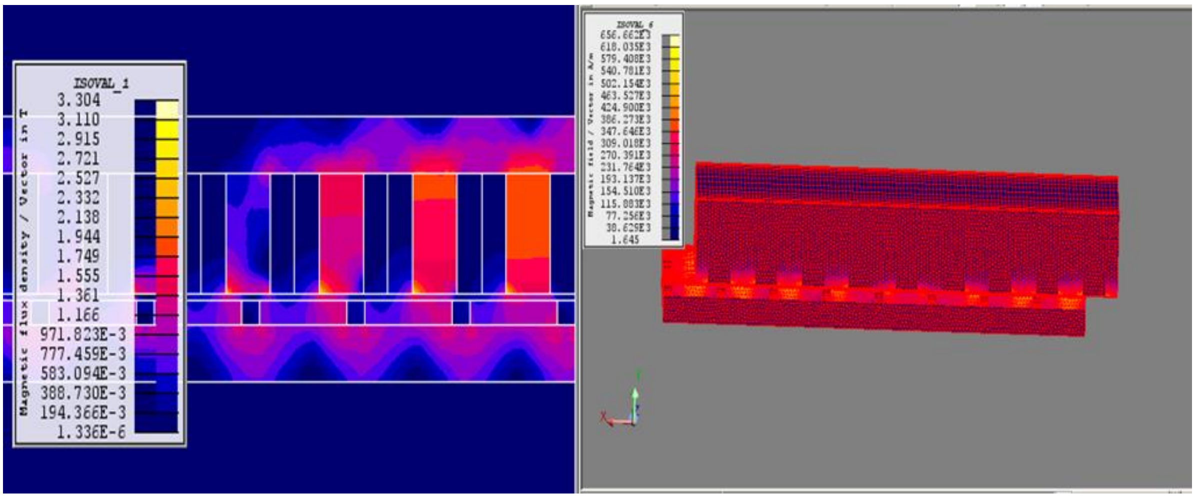


Fig. 6. Illustrates ISO Magnetic Flux Magnitudes Across Various Machine Sections 2D model and3D

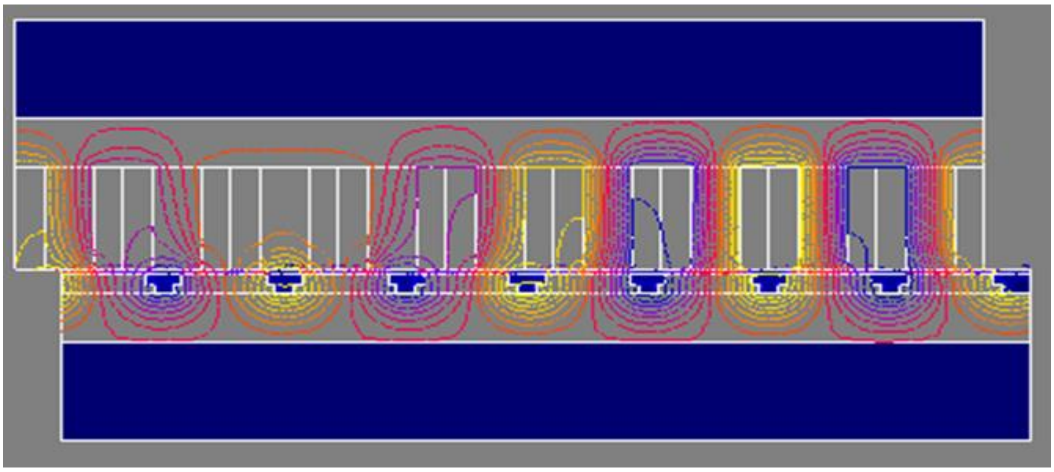
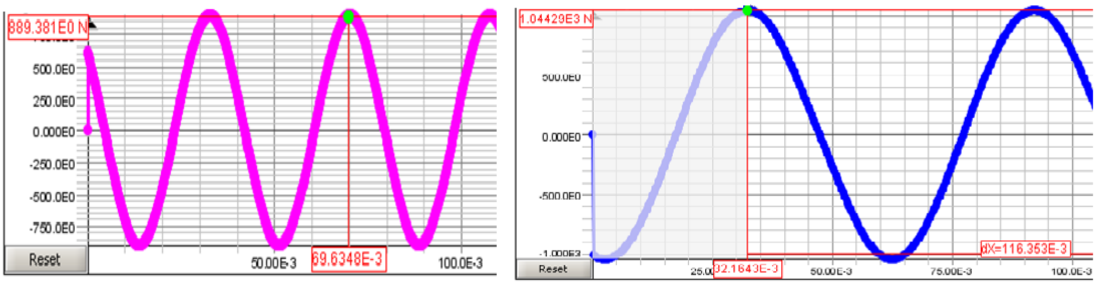


Fig. 7. Magnetic analysis of One of the models,, depicting flux lines

A pivotal criterion in this assessment is the determination of the mean thrust value, which serves as a fundamental benchmark for quantifying the average force exerted by the motor. Upon thorough examination of this analysis, it is revealed that an average thrust of 889N and 1004N for Two lengths respectively has been ascertained shown in Figure 8. Accompanied by a minimal variation in thrust, measuring a mere 1.08%, a parameter commonly referred to as thrust ripple. It is imperative to acknowledge that the fluctuations in force observed under unloaded conditions may differ from those encountered during loaded conditions.



A: Length motor 216mm B: Length motor 216mm

Fig. 8. thrust of the motor at load

This simulation empowers us to meticulously compute the impact of cogging forces, as showcased in Figure 9 The recorded data unequivocally illustrates the machine's remarkable ability to effectively ameliorate the cogging forces. Moreover, a comparative analysis of the cogging forces before and after optimization further substantiates the significant enhancements achieved

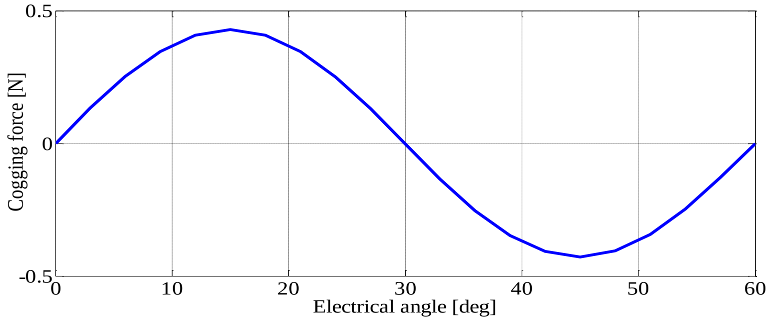


Fig. 9. Cogging Force Analysis of Proposed Model Structure

The analysis entailed the utilization of the Finite Element Method (FEM) for calculating the Back-EMF, which serves as a self-regulating mechanism to mitigate excessive current draw. However, it is imperative to manage this aspect effectively to ensure the motor's optimal performance. Figure 10, depicting the Fast Fourier Transform (FFT), which illustrates the Back-EMF.

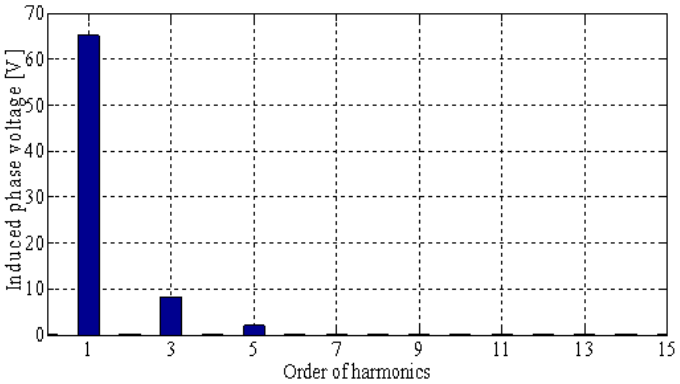


Fig. 10 Fast Fourier Transform (FFT) Analysis of Back EMF at No Load Revealing Insignificant Higher Harmonics

4. Comparative Analysis

Upon a thorough examination of these design modifications and meticulous analysis of our outcomes, it is evident that this model has realized a substantial enhancement of approximately 20% when compared to conventional engine designs. This remarkable improvement was attained through meticulous adjustments in various parameters, including magnet dimensions, air gap configuration, coil quantity, and slot dimensions. The notable degree of enhancement in performance prompted us to undertake a comprehensive comparative evaluation, juxtaposing our findings with existing research studies in the field. Table 3 illustrates the main structure parameters of these models.

Table 3. The main structure parameters of these models

Explanation	model [15]	model[26]	model[13]	Current study
Linear speed	100 m/s	1.6 m/s	1m/s	1 m/s
Thickness of the mover back-iron	--------		0.028	0.028
Height of PMs	--------	0.0041	0.004m	0.004m
Air-gap length	0.008m	0.0009m	0.0014m	0.0015m

Height of the slots	--------		0.025m	0.025m
Total length of the motor	3m	0.150m	0.216m	0.240m
Remanent flux density of the PM material	1.15T	1.05T	1.05T	1.05T
No of pole / No of slots	20/60	22 /24	8/9	8/9
Slot width to slot pitch ratio	0.4	0.32	0.5	0.5
Pole pitch	0.15	0.016	0.027	0.068
Percentage values relative to the reduction in cogging force	0.29%	0.32%	0.25%	0.90%
Pole-arc coefficient	0.613	0.87	0.58	0.53

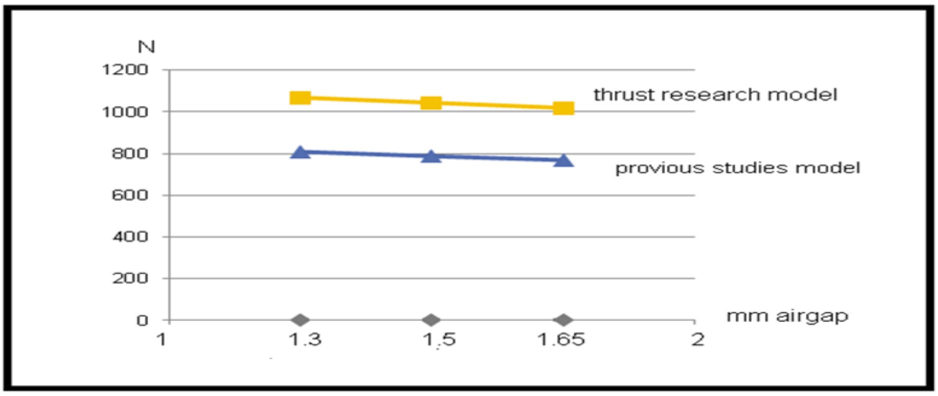


Fig. 11. Comparison between the current study and the research [13] for the same selected dimensions of the air gap

the research[13]and [15] is similar to the current study. A wider range of variables was explored, including gap length, magnet dimensions, slot dimensions, and the spacing between magnets. This comprehensive exploration of variables resulted in improved motor performance. Figure 11 shows a comparison of the effects of the air gap in two models with identical dimensions, except for the motor length, between the proposed structure and the literature review.

The perpendicular and tangential components of the open-circuit magnetic flux density at the centerline of the air gap region are illustrated in Figs. 12,13. As it is obvious, the results obtained from the proposed analytical method are very similar to that of obtained by the FEM. Figs. 10 illustrate the obtained results, mover positions of the first studied motor, i.e. $x_0 = 0$ and $x_0 = L/3$. Similar results for the second studied motor are shown in Fig. 13 at different mover positions, i.e. $x_0 = 0$ and $x_0 = L/5$.

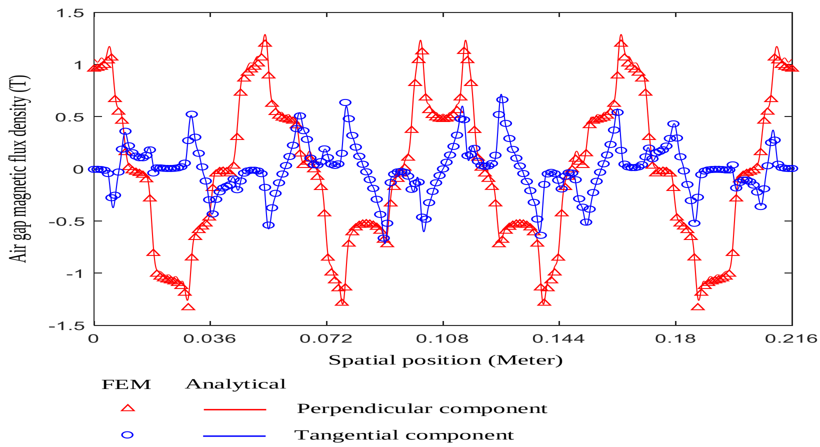


Fig.12. Perpendicular and tangential components of air gap magnetic flux density obtained for the first linear motor ($x_0 = 0$)

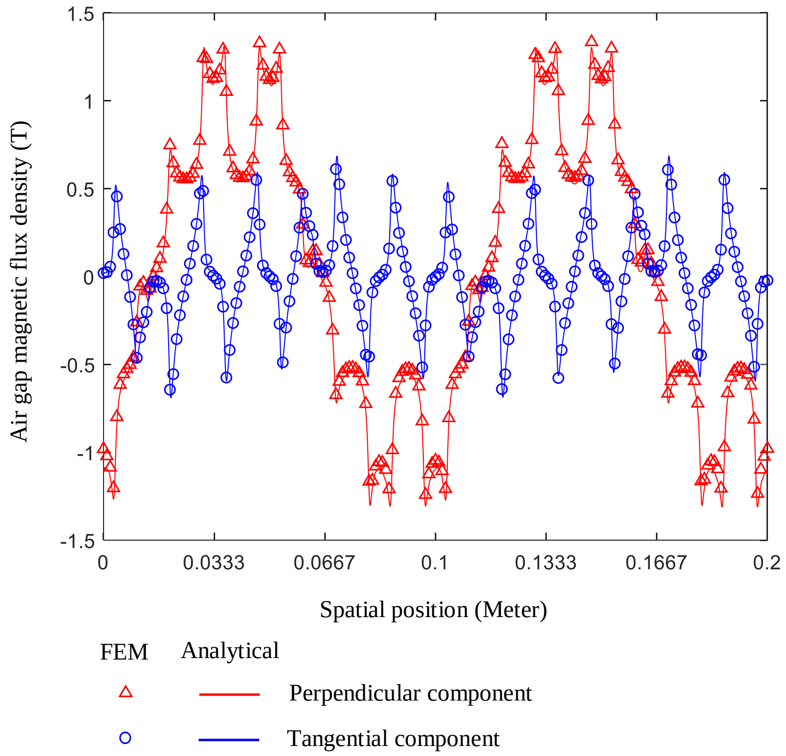


Fig. 13. Perpendicular and tangential components of air gap magnetic flux density obtained for the second linear motor ($x_0 = L/5$)

However, The proposed model combines several advantages of the compared researchers and offers a solution to address the challenges of cogging force and Back EMF. Other methods tend to be costly and also have a tendency to introduce a higher degree of complexity to the structure.

5. Conclusion

Recent research has been dedicated to the development of linear permanent magnetic motors with a focus on design and performance enhancement. However, within the realm of Permanent Magnet Synchronous Linear Motors (PMSLMs), the issue of cogging forces has garnered significant attention from researchers. Our research has been meticulously aimed at addressing the challenge posed by cogging forces. To effectively tackle this issue, we employed a multifaceted approach that involved designing and analyzing various models using numerical simulations. Numerical simulations were conducted using the Flux® 2D program and modern methodologies. Furthermore, a 2-D analytical method was implemented to obtain results for both electromagnetic field (EMF) harmonics and cogging forces in the PMSLM. The outcomes of our study demonstrate a substantial enhancement in motor performance and stability. Moreover, our research has achieved a noteworthy reduction in production costs while significantly improving performance. The adoption of these innovative models effectively addresses the challenges associated with PMSLMs, enhancing their versatility and suitability for a wide range of applications, To get the greatest results, we can integrate the magnet fragmentation approach with our previous work to continue developing it in the future.

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