Article

Electromagnetic Design and Analysis of Permanent Magnet Linear Synchronous Motor

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Abstract: Since permanent magnet linear synchronous motors are widely used in fatigue testing, in this paper, the thrust of a permanent magnet linear synchronous motor (PMLSM) is amplified more than 10 times by the method of resonance. Firstly, the air gap magnetic field is analyzed by the equivalent magnetization current method (EMC), the electromagnetic thrust is calculated, and the expression is given by the Maxwell tensor method. The vibration analysis of the whole machine is used to obtain the conditions under which the motor resonates. The dynamic and static characteristics of the motor are analyzed through finite element simulation, the results of the motor design are judged to be reasonable, and the theoretical calculation results are compared with the simulation results to verify the accuracy of the theoretical calculation. The accuracy of the simulation results is verified by static force experiments. Finally, the rated thrust of the motor was enlarged more than 10 times by resonance experiments.

Keywords: permanent magnet linear synchronous motor; electromagnetic design; magnetic field analysis; resonance; finite element analysis

1. Introductions

In recent years, with the development of permanent magnet materials, the development and application of linear motors is very rapid. Compared with rotating motors, linear motors have the advantages of simple structure, high precision, high speed, and long life, and are widely used in industrial, civil, military, and other linear motion occasions. The structure of linear motors is diverse, among which permanent magnet linear synchronous motors are widely used due to their high thrust and high efficiency [1–5]. Whether there is an iron core in the permanent magnet synchronous linear motor has a great impact on the dynamic and static characteristics of the motor, compared with the iron-free linear motor, the iron core linear motor has a large thrust and high rigidity, suitable for high load, and the heat dissipation effect is good, the cost is low.

The research on linear motors at home and abroad focuses on magnetic field analysis, thrust and thrust fluctuation optimization, temperature field simulation, etc. The literature [6] analyzes the magnetic field distribution of a permanent magnet linear synchronous motor with a double air gap structure. The literature [7] uses a new method of spatial harmonic fields to analyze magnetic fields instead of the equivalent magnetization current method. The literature [7–9] uses the equivalent magnetization current method and the equivalent magnetization strength method to analyze the magnetic field of the motor. The magnetic field is calculated using the subdomain method, which takes into account the end effect of the motor and calculates the thrust in [10,11]. The electromagnetic thrust is calculated using the Maxwell tensor method in [12,13]. In The literature [14] a 3D finite element modeling of a unilateral non-ferrous core hybrid magnetized PMLSM and the analysis and calculation of the magnetic flux density and thrust characteristics of the no-load air gap are...
calculated. The literature [15] committed to the study of a high-thrust PMLSM, analyzing the effect of motor size on motor thrust and normal force and verifying it through finite elements. A new optimization method is proposed to analyze thrust and compare it with experimental results in [16]. Literature [17] designed a fault-tolerant permanent magnet linear synchronous motor and designed electromagnetic parameters and analyzed motor performance. The literature [18] performs electromagnetic design of bilateral permanent magnet linear synchronous motors and compared with the single-sided linear motor, the linear motor with the bilateral structure is verified to have better performance. A new type of high-temperature superconducting flux modulated linear motor is proposed in [19], compared with the traditional linear motor, the motor has a larger thrust and smaller thrust fluctuations, and finally, the motor structure parameters are optimized by finite element analysis and genetic algorithms. The transverse flux linear oscillation motor with a moving stator is taken as the research object, and the vibration characteristics of the motor are analyzed and calculated in [20]. The electromagnetic and vibration characteristics of transverse flux linear oscillatory motors with different magnetization methods are compared and analyzed in [21].

To obtain the large thrust of the motor, this paper proposes a resonant method to amplify the thrust, therefore this paper takes the electromagnetic thrust as the design goal of the unilateral PMLSM electromagnetic design. Through the theoretical analysis of magnetic field and thrust and the comparison of finite element results and performance, the rationality of the motor design is verified, as well as static force experiments to verify the accuracy of simulation results. Through the vibration analysis of the whole machine, it is concluded that the output thrust can be amplified when the input frequency is consistent with the vibration frequency of the whole machine. Finally, the output thrust of the motor is amplified more than 10 times by resonance experiments. This article is divided into 6 sections in total. The structure and parameters of PMLSM are given in Section 2. In Section 3, magnetic field analysis of the motor is performed using the equivalent magnetization current method and thrust analysis calculations are performed using the Maxwell tensor method. In Section 4, finite element analysis of motor no-load and load results is performed by electromagnetic field simulation. In Section 5, the static force experiment is performed on the motor, and the rationality of the motor design is further verified by calculating the thrust constant of the motor. Finally, the full text is summarized in Section 6.

2. PMLSM Structure and Parameters

According to the actual motor according to a certain proportion of the motor structure design, the motor model is shown in Figure 1. The motor is composed of a primary and secondary, and the primary is composed of a mover core and windings, which is the moving element part, the windings are wound around the mover’s teeth, the potential star diagram of the tank, and the winding order are shown in Figure 2. The secondary stage is composed of a stator core and a permanent magnet, which is the stator part, permanent magnets are arranged at a certain distance on the stator core, the permanent magnet is magnetized in the direction of radial magnetization and adjacent permanent magnets have opposite polarity, the slot poles selected by PMLSM are 12 slots and 10 poles. The primary core material is DW465_50, the secondary core material is steel_1010, the permanent magnet material is NdFe35, and the coil winding material is copper, the parameters of PMLSM are shown in Table 1.

![Figure 1. PMLSM structure.](image-url)
\[
\mathcal{M}(x) = 4B_\delta \sin(2n-1)\pi x \left( -1 \right)^{i+1} \cos(2n-1)\pi x = 0
\]

\(\mathcal{A} + \partial_y \mathcal{A} \)

**Figure 1.** PMLSM structure.

(a) (b)

**Figure 2.** Winding arrangement order: (a) Electrical potential star chart of slot; (b) Winding arrangement order.

**Table 1.** PMLSM parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot width</td>
<td>(b_s)</td>
<td>12</td>
<td>mm</td>
</tr>
<tr>
<td>Slot depth</td>
<td>(h_s)</td>
<td>40</td>
<td>mm</td>
</tr>
<tr>
<td>Tooth width</td>
<td>(b_t)</td>
<td>8</td>
<td>mm</td>
</tr>
<tr>
<td>The length of the mover core</td>
<td>(L)</td>
<td>252</td>
<td>mm</td>
</tr>
<tr>
<td>The thickness of the mover yoke</td>
<td>(h_2)</td>
<td>20</td>
<td>mm</td>
</tr>
<tr>
<td>Permanent magnet width</td>
<td>(\tau_m)</td>
<td>21</td>
<td>mm</td>
</tr>
<tr>
<td>Permanent magnet height</td>
<td>(h_m)</td>
<td>4.4</td>
<td>mm</td>
</tr>
<tr>
<td>Air gap height</td>
<td>(g)</td>
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<td>mm</td>
</tr>
<tr>
<td>Stator core length</td>
<td>(L_1)</td>
<td>500</td>
<td>mm</td>
</tr>
<tr>
<td>Stator iron yoke thickness</td>
<td>(h_1)</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>Polar pitch</td>
<td>(\tau)</td>
<td>24</td>
<td>mm</td>
</tr>
<tr>
<td>Number of coil turns</td>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Number of permanent magnets</td>
<td></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Number of slots</td>
<td></td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

3. PMLSM Theoretical Analysis

3.1. Magnetic Field Analysis

In this paper, the equivalent magnetization current method is used to analyze and calculate the magnetic field of the motor. The PMLSM magnetic field analysis model is shown in Figure 3 and proposes the following assumptions [22]:

\(\begin{align*}
\mathcal{A} & + \partial_y \mathcal{A} \\
\mathcal{A} & = \mathcal{M}(x) \\
\mathcal{M}(x) & = 4B_\delta \sin(2n-1)\pi x \left( -1 \right)^{i+1} \cos(2n-1)\pi x = 0
\end{align*}\)

\(\mathcal{A} + \partial_y \mathcal{A} \)

**Figure 3.** PMLSM magnetic field analysis model: (a) Permanent magnet magnetic field analysis model; (b) Magnetic field analysis model of armature windings.

(1) The magnetic field changes in the z-axis direction, ignoring the transverse edge effect;
(2) The permeability of primary and secondary cores is infinite;
(3) The demagnetization curve of the permanent magnet basically coincides with the recovery line;
(4) The demagnetization curve of the permanent magnet material is straight, and the permanent magnet is magnetized relatively uniformly.

The model of the magnet magnetization intensity is shown in Figure 4:

\(\begin{align*}
\mathcal{M}(x) & = 4B_\delta \sin(2n-1)\pi x \left( -1 \right)^{i+1} \cos(2n-1)\pi x = 0
\end{align*}\)
According to the above assumptions, the magnetization intensity is expanded into each harmonic according to the Fourier series:

\[ M(x) = \frac{4B_r}{\pi \mu_0} \sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{2n-1} \sin \left( \frac{(2n-1)\pi \tau}{2\tau} \right) \cos \left( \frac{(2n-1)\pi x}{\tau} \right) \]  

(1)

where \( \mu_0 \) is the vacuum permeability, \( B_r \) is the permanent magnet residual magnet, \( \tau \) is the polar distance, and \( \tau_m \) is the permanent magnet width.

The equivalent magnetization current density of the permanent magnet is:

\[ J_m(x) = -\frac{4B_r}{\tau \mu_0} \sum_{n=1}^{\infty} (-1)^{n+1} \sin \left( \frac{(2n-1)\pi \tau_m}{\tau} \right) \sin \left( \frac{(2n-1)\pi x}{\tau} \right) \]  

(2)

When permanent magnets act alone, the following magnetic field equations can be established according to Maxwell’s equations:

In the air gap area:

\[ \frac{\partial^2 A_{m1}}{\partial x^2} + \frac{\partial^2 A_{m1}}{\partial y^2} = 0 \]  

(3)

In the permanent magnet area:

\[ \frac{\partial^2 A_{m2}}{\partial x^2} + \frac{\partial^2 A_{m2}}{\partial y^2} = -\mu_0 J_m \]  

(4)

The separation variable method is used to obtain a general solution:

\[ \begin{align*}
A_{m1} &= [A_1 \text{sh}k_ny + B_1 \text{ch}k_ny] \cdot [M_1 \cos k_nx + N_1 \sin k_nx] \\
A_{m2} &= [A_2 \text{ch}k_ny + B_2 \text{sh}k_ny] \cdot [M_2 \cos k_nx + N_2 \sin k_nx] \\
&= \frac{4B_r}{\pi^2 \tau} \sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{(2n-1)^2} \sin \left( \frac{(2n-1)\pi \tau_m}{2\tau} \right) \sin \left( \frac{(2n-1)\pi x}{2\tau} \right) 
\end{align*} \]  

(5)

Equation (6) can be obtained according to the boundary condition:

\[ \begin{align*}
B_1 &= F_n \text{sh}k_nh_m \\
A_1 &= -F_n \frac{\text{ch}k_nH}{\text{sh}k_nH} \text{sh}k_nh_m \\
A_2 &= F_n \left[ \text{sh}k_nh_m - \frac{\text{ch}k_nH}{\text{sh}k_nH} \text{sh}k_nh_m \right] \\
&= \frac{F_n}{\text{sh}k_nH} \text{sh}k_n(H - h_m) 
\end{align*} \]  

(6)

In the above equation: \( k_n = \frac{(2n-1)\pi}{\tau} \), \( F_n = \frac{4B_r}{\pi^2 \tau} \sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{(2n-1)^2} \sin \left( \frac{(2n-1)\pi \tau_m}{2\tau} \right) \).

The vector magnetic potential and magnetic induction intensity of the air gap magnetic field region can be obtained, respectively:

\[ \begin{align*}
A_{m1} &= F_n \frac{\text{sh}k_n(H-h_m)}{\text{sh}k_nH} \cdot \sin k_nx \cdot \text{ch}k_ny - F_n \sin k_nx \\
B_{m1x} &= -\frac{\partial A_1}{\partial y} = F_nk_n \frac{\text{sh}k_n(H-h_m)}{\text{sh}k_nH} \cdot \sin k_nx \cdot \text{sh}k_ny \\
B_{m1y} &= -\frac{\partial A_1}{\partial x} = -F_nk_n \frac{\text{sh}k_n(H-h_m)}{\text{sh}k_nH} \cdot \cos k_nx \cdot \text{ch}k_ny + F_nk_n \cos k_nx 
\end{align*} \]  

(7)

The vector magnetic potential and magnetic induction intensity of the permanent magnet region are, respectively:
\[
\begin{align*}
A_{m2} &= -F_n \sin k_n \cdot \sin k_n x \cdot \sin k_n y (H - y) \\
B_{m2x} &= -\frac{\partial A_{m2}}{\partial x} = F_n \sin k_n \cdot \sin k_n x \cdot \sin k_n y (H - y) \\
B_{m2y} &= -\frac{\partial A_{m2}}{\partial y} = F_n \sin k_n \cdot \sin k_n x \cdot \sin k_n y (H - y)
\end{align*}
\]  

(8)

The equivalent magnetization current of the armature winding is:

\[
I_s(x) = \frac{2}{\pi} \sum_{n=1}^{\infty} \left[ \cos \frac{n\pi(3+k)}{6} - \cos \frac{n\pi(3-k)}{6} \right].
\]

(9)

In the above equation: \(I_a, I_b, I_c\) is the current density of the windings, the expression is as follows:

\[
\begin{align*}
I_a &= \frac{N_i I}{b_{ch}} \\
I_b &= \frac{N_i I}{b_{ch}} \\
I_c &= \frac{N_i I}{b_{ch}}
\end{align*}
\]

(10)

In the above equation: \(N_i\) is the number of coil turns; \(I\) is the amplitude of the current; \(\omega\) is the motor angular frequency; \(\phi\) is the phase angle.

For armature windings acting alone, the following magnetic field equations can be established according to Maxwell’s equations:

In the air gap area:

\[
\frac{\partial^2 A_{s1}}{\partial x^2} + \frac{\partial^2 A_{s1}}{\partial y^2} = 0
\]

(12)

In the armature winding area:

\[
\frac{\partial^2 A_{s2}}{\partial x^2} + \frac{\partial^2 A_{s2}}{\partial y^2} = -\mu_0 I_b
\]

(13)

By using the method of separating variables, a general solution can be obtained:

\[
\begin{align*}
A_{s1} &= [a_1 \sin k_n y + b_1 \sin k_n x] \cdot [n_1 \cos p_n x + n_1 \sin p_n x] \\
A_{s2} &= [a_2 \sin k_n y + b_2 \sin k_n x] \cdot [m_2 \cos p_n x + m_2 \sin p_n x] \\
&+ \frac{18\tau_n^2 \mu_0}{n^2 \pi^2} \sum_{n=1}^{\infty} \left[ \cos \frac{n\pi(3-k)}{6} - \cos \frac{n\pi(3+k)}{6} \right] \\
&\times \left\{ I_a \cos \left[ \frac{n\pi}{3\tau_n} (x + \tau_s) \right] + I_b \cos \left[ \frac{n\pi}{3\tau_n} x \right] + I_c \cos \left[ \frac{n\pi}{3\tau_n} (x - \tau_s) \right] \right\}
\end{align*}
\]

(14)

Equation (15) can be obtained according to the boundary condition as:

\[
\begin{align*}
a_1 &= G_n \sin k_n \cdot e^{(p_n H)^2} \\
a_2 &= -G_n \sin k_n \cdot e^{(p_n H)^2} \\
b_2 &= G_n \sin k_n \cdot e^{(p_n H)^2}
\end{align*}
\]

(15)

In the above equation: \(p_n = \frac{n\pi}{3\tau_n}, G_n = \frac{18\tau_n^2 \mu_0}{n^2 \pi^2} \sum_{n=1}^{\infty} \left[ \cos \frac{n\pi(3-k)}{6} - \cos \frac{n\pi(3-k)}{6} \right], k = \frac{b}{\tau_n}\).

The vector magnetic potential and magnetic flux density in the air gap region are, respectively, as follows:

\[
\begin{align*}
A_{s1} &= \frac{G_n \sin k_n}{\sin k_n} \cdot e^{(p_n H)^2} \sin k_n y \cdot \left\{ I_a \sin \left[ p_n x + \tau_s \right] + I_b \sin \left[ p_n x \right] + I_c \sin \left[ p_n (x - \tau_s) \right] \right\} \\
B_{s1x} &= \frac{G_n \sin k_n}{\sin k_n} \cdot e^{(p_n H)^2} \cdot \sin k_n y \cdot \left\{ I_a \sin \left[ p_n x + \tau_s \right] + I_b \sin \left[ p_n x \right] + I_c \sin \left[ p_n (x - \tau_s) \right] \right\} \\
B_{s1y} &= -\frac{G_n \sin k_n}{\sin k_n} \cdot e^{(p_n H)^2} \sin k_n y \cdot \left\{ I_a \cos \left[ p_n x + \tau_s \right] + I_b \cos \left[ p_n x \right] + I_c \cos \left[ p_n (x - \tau_s) \right] \right\}
\end{align*}
\]

(16)
The vector magnetic potentials and magnetic flux densities of the armature winding region are as follows:

$$
A_{s2} = -G_n \left[ \frac{sh_{p_n}H_n(p_nh_y)^2}{sh_{p_n}(h_y+H)} \right] \cdot \left[ \frac{ch_{p_n}(h_s + H - y) - 1}{ch_{p_n}(h_s + H - y)} \right] \\
+ \left\{ J_a \sin[p_n(x + \tau_a)] + J_b \sin(p_n x) + J_c \sin[p_n(x - \tau_a)] \right\} \\
B_{s2x} = G_n \left[ \frac{sh_{p_n}H_n(p_nh_y)^2}{sh_{p_n}(h_y+H)} \right] \cdot \left[ \frac{sh_{p_n}(h_s + H - y) - 1}{sh_{p_n}(h_s + H - y)} \right] \\
+ \left\{ J_a \sin[p_n(x + \tau_a)] + J_b \sin(p_n x) + J_c \sin[p_n(x - \tau_a)] \right\} \\
B_{s2y} = G_n \left[ \frac{sh_{p_n}H_n(p_nh_y)^2}{sh_{p_n}(h_y+H)} \right] \cdot \left[ \frac{sh_{p_n}(h_s + H - y) - 1}{sh_{p_n}(h_s + H - y)} \right] \\
+ \left\{ J_a \cos[p_n(x + \tau_a)] + J_b \cos(p_n x) + J_c \cos[p_n(x - \tau_a)] \right\}
$$

(17)

3.2. Electromagnetic Thrust Calculation

Based on the analysis of the magnetic field, the Maxwell tensor method is used to analyze and calculate the horizontal electromagnetic thrust of PMLSM. The method is to equate the volumetric electromagnetic force received by any region of the stressed object to the tension on the surface outside the area of the object, and then obtain the sum of the electromagnetic forces by integrating the equal density of the magnetic field tension tensor. The integral path for calculating the electromagnetic thrust by this method only contains a primary iron core, and the integral path selected in this paper is A-B-C-D, the PMLSM integration path is shown in Figure 5. Using Maxwell’s method to calculate the electromagnetic force in the two-dimensional magnetic field, the total electromagnetic thrust of the surface can be obtained as follows:

$$
F = \frac{D}{\mu_0} \oint_s \left[ \vec{B} \left( \vec{B} \cdot \hat{n} \right) - \frac{1}{2} \vec{B}^2 \hat{n} \right] ds
$$

(18)

$D$ is the length of the motor in the $z$-axis direction, $\mu_0 = 4\pi \times 10^{-7}$ the $\hat{n}$ and $\vec{B}$ expressions are as follows:

$$
\begin{align*}
\hat{n} &= n_x \hat{a}_x + n_y \hat{a}_y \\
\vec{B} &= B_x \hat{a}_x + B_y \hat{a}_y
\end{align*}
$$

(19)

$\hat{a}_x$ and $\hat{a}_y$ are unit vectors in the $x$ and $y$ directions, respectively. $n_x$ and $n_y$ are projections of the normal vectors of the surface in the $x$ and $y$ directions, respectively.

The horizontal and normal electromagnetic force magnitude of the motor can be found as follows:

$$
\begin{align*}
F_x &= \frac{D}{\mu_0} \oint_s \left[ B_x^2 - B_y^2 \right] n_x + 2B_x B_y n_y \right] ds \\
F_y &= \frac{D}{\mu_0} \oint_s \left[ B_y^2 - B_x^2 \right] n_y + 2B_x B_y n_x \right] ds
\end{align*}
$$

(20)

where $B_x$ and $B_y$ are tangential and normal magnetic flux density, respectively, and $s$ is the integral path, this article focuses on the horizontal electromagnetic thrust.

![Figure 5. PMLSM integration path.](image-url)
3.3. Vibration Analysis

The linear motor mechanical loading model is shown in Figure 6.

![Figure 6. Linear motor mechanical loading model.](image-url)

Replace the mass of the mover part with mass block \( m \), replace the elastic element and related components and dampers with springs with a stiffness \( k \) and damping \( c \), respectively, and use \( F(t) \) to represent the electromagnetic force generated by the motor. This dynamic model can be regarded as a single-degree-of-freedom forced vibration system according to vibration theory, so the alternating load test applied to the specimen by this actuator is fully in line with its vibration theory method. The external excitation of the motor is as follows:

\[
F(t) = A_0 \cos \omega t = kA \cos \omega
\]  \hspace{1cm} (21)

where \( A_0 \) is the incentive amplitude, \( A \) is an order with displacement, and \( \omega \) is the frequency of excitation. For this mechanical loading model, according to the vibration analysis theory, the equation of motion of the second-order system is:

\[
m \ddot{x}(t) + c \dot{x}(t) + kx(t) = F(t)
\]  \hspace{1cm} (22)

\[
k = \omega_n^2 r m = 2\xi \omega_n
\]  \hspace{1cm} (23)

\( \omega_n \) is the natural frequency of the system, and \( \xi \) is the viscous damping factor. Bring the above expression into the above formula:

\[
\ddot{x}(t) + 2\xi \omega_n \dot{x}(t) + \omega_n^2 x(t) = A\omega_n^2 \cos \omega t
\]  \hspace{1cm} (24)

Solving Equation (25) can be obtained:

\[
x(t) = X \cos(\omega t - \phi)
\]  \hspace{1cm} (25)

\[
X = \frac{A}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right] + \left(2\xi \frac{\omega}{\omega_n}\right)^2}}
\]  \hspace{1cm} (26)

\[
\phi = \tan^{-1} \frac{2\xi \frac{\omega}{\omega_n}}{1 - \left(\frac{\omega}{\omega_n}\right)^2}
\]  \hspace{1cm} (27)

The derivative of Equation (28) is zero, and its pole position can be derived, that is, the peak point position of the amplitude of the response force with respect to the driving frequency \( \omega \):

\[
\omega = \omega_n \sqrt{1 - 2\xi^2}
\]  \hspace{1cm} (28)

Let \( \beta \) be the magnification factor, the value of which is:

\[
\beta = \frac{1}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right] + \left(2\xi \frac{\omega}{\omega_n}\right)^2}}
\]  \hspace{1cm} (29)

When driving frequency \( \omega \) is associated with the natural frequency of the system \( \omega_n \), the output thrust of the linear motor actuator will be infinitely amplified.
4. Finite Element Analysis

4.1. Analysis of No-Load Simulation Results

No-load is the state in which the coil windings of the motor are not current. The PMLSM flux waveform diagram and the back EMF waveform diagram are shown in Figure 7. It can be seen from the Figure that the sinusoidal rate of the flux waveform is relatively good, reflecting the high performance of the motor, and also confirms that the air gap magnetic flux density is also sinusoidal distribution, and the amplitude of the flux is 0.34 Wb. The back EMF waveform is relatively poorly sinusoidal, and there are mutations in the peaks and troughs, this is not only closely related to the magnetic flux density of the no-load air gap but also has a certain impact on the thrust fluctuations of the motor. In addition, the amplitude of the back EMF is 47 V.

Due to the structural characteristics such as the disconnection and slotting of the primary core, horizontal detent force and normal detent force are generated during operation, and the detent force produces thrust fluctuations during operation, which greatly reduces the performance of the motor. In this paper, the detent force is reduced by optimizing the primary length to suppress the longitudinal end effect. PMLSM horizontal detent force and normal detent force are shown in Figure 8, the horizontal detent force amplitude fluctuates between $-74$ N and $105$ N, the detent force fluctuation amplitude is $179$ N, and the average normal detent force is $6.6$ KN.

Figure 9 is the result of solving the air gap normal magnetic flux density by the equivalent magnetization current method and finite element method. It can be seen from the figure that both waveforms are positively linear and have a period of twice the polarity of 48 mm. As a result of the finite element solution, the wave has a depression at the cogging groove due to the effect of the cogging effect. As a result of the EMC solution, the waveform is smoother and has the characteristics of a flat top wave. From the figure, it can be obtained that the maximum value of EMC to solve the air gap magnetic density is $1T$, and the finite element method to solve the maximum value of the air gap magnetic density is $1.11T$, and the solution results of the two are basically the same. EMC simplifies the motor model to two dimensions and idealizes some boundary conditions, this method of solving the magnetic flux density of the air gap is relatively simple and is the basis for other solution methods. Furthermore, the finite element analysis solution takes into account the cogging effect, so the solution result is relatively more accurate.

Figure 10 shows the Fourier analysis of the air gap magnetic flux density, the result includes the first 10 harmonic components, the air gap magnetic density fundamental wave amplitude is $0.9647T$, accounting for 86.5% of the maximum air gap magnetic flux density, indicates that the fundamental wave is consistent with the total waveform. Among them, the third and fifth harmonious components are relatively large. Through the above analysis, it can be concluded that the air gap magnetic density waveform is good, all of which are sinusoidal distributions, which not only verifies the accuracy of theoretical calculations but also verifies the design results of the motor are reasonable. In addition, the air gap magnetic density fundamental wave amplitude is relatively large, which can provide a large enough thrust to the motor to meet the design goal of the motor’s electromagnetic thrust.

![Figure 7. PMLSM flux and back-EMF waveform diagram: (a) Motor flux waveform diagram; (b) Motor back EMF waveform diagram.](image-url)
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![Figure 7. PMLSM flux and back-EMF waveform diagram](image)

**Figure 7.** PMLSM flux and back-EMF waveform diagram. (a) Motor flux waveform diagram; (b) Motor back EMF waveform diagram.

![Figure 8. PMLSM horizontal detent force and normal detent force](image)

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Figure 9. No-load air gap magnetic flux density distribution curve: (a) No-load method calculates the solution results for magnetic flux density theory; (b) The result of the no-load method is to solve the finite element of magnetic flux density.
Figure 10 shows the Fourier analysis of the air gap magnetic flux density, the result includes the first 10 harmonic components, the air gap magnetic density fundamental wave amplitude is 0.9647 T, accounting for 86.5% of the maximum air gap magnetic flux density, indicates that the fundamental wave is consistent with the total waveform. Among them, the third and fifth harmonious components are relatively large. Through the above analysis, it can be concluded that the air gap magnetic density waveform is good, all of which are sinusoidal distributions, which not only verifies the accuracy of theoretical calculations but also verifies the design results of the motor are reasonable. In addition, the air gap magnetic density fundamental wave amplitude is relatively large, which can provide a large enough thrust to the motor to meet the design goal of the motor’s electromagnetic thrust.

![Figure 10. Air gap magnetic density Fourier analysis.](image)

4.2. Analysis of Load Simulation Results

The magnetic field line and magnetic flux density distribution cloud diagram of PMLSM running 0.01 s at a speed of 0.96 m/s are shown in Figure 11. This can be seen in the magnetic field line distribution cloud map, most magnetic field lines travel through a loop of permanent magnets, air gaps, and amateur windings, a small number of magnetic field lines are the components of the permanent magnet in the horizontal direction. Furthermore, it can be seen from the magnetic flux density distribution cloud diagram that the maximum magnetic flux density of the tooth part is 2.3 T, and the maximum magnetic flux density of the primary yoke is 1.6 T, there is some magnetic saturation.

Figure 12 is the result of solving the horizontal electromagnetic thrust of the motor by finite element analysis (FEA) and Maxwell tensor method, respectively. It can be seen from the figure that the average electromagnetic thrust of Maxwell’s tensor solution is 987 N, and the average electromagnetic thrust of the finite element solution is 948 N, the results of the two are basically the same, and the accuracy of the theoretical analysis was verified.
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Figure 11. PMLSM magnetic field lines and magnetic flux density distribution cloud map: (a) Magnetic field line distribution; (b) Magnetic flux density distribution.
Figure 12 is the result of solving the horizontal electromagnetic thrust of the motor by finite element analysis (FEA) and Maxwell tensor method, respectively. It can be seen from the figure that the average electromagnetic thrust of Maxwell’s tensor solution is 987 N, and the average electromagnetic thrust of the finite element solution is 948 N, the results of the two are basically the same, and the accuracy of the theoretical analysis was verified.

Figure 12. Maxwell stress tensor method and finite element method solution for the horizontal electromagnetic thrust of the motor: (a) Finite element solves for the horizontal electromagnetic thrust of the motor; (b) Maxwell stress tensor method solves for the horizontal electromagnetic thrust of the motor.

5. Experimental Analysis

5.1. Thrust Constant Test

The PMLSM experimental platform is shown in Figure 13, which is composed of a whole machine part and a servo drive, of which the whole machine part is composed of a motor body, a pressure sensor, and a force measuring ring.
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![Figure 13. PMLSM experimental platform: (a) Motor overall and force measuring device; (b) drive.](image)

In this paper, the static force loading test of the unilateral PMLSM is carried out, and the performance of the motor is checked by testing the thrust constant of the motor, and the expression of the thrust constant is as follows:

\[ C_F = \frac{F}{I} \]  

(29)

Simulation and experimental output thrust and thrust constants under different currents are shown in Table 2, in the case of the motor-rated thrust constant of 93 N/A, the simulated thrust constant can be calculated as 97.29 N/A, the error is 4.6%, and the experimental thrust constant is 96.53 N/A, the error is 3.79%, and the error is less than 5%, which verifies that the motor performance is good. The data of motor simulation and experimental output thrust are fitted by the least-squares method as shown in Figure 14, and it can be seen from the figure that the simulation and experimental output thrust curves meet the linear regression equation, and the motor design results are more reasonable. However, as the current increases, the motor is affected by the amateur reaction and temperature, causing the thrust constant decreases gradually.

<table>
<thead>
<tr>
<th>Current RMS A</th>
<th>Simulate Output Thrust N</th>
<th>Simulate Thrust Constant N/A</th>
<th>Experimental Output Thrust N</th>
<th>Experimental Thrust Constant N/A</th>
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</thead>
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<tr>
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<td>99</td>
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<td>948</td>
<td>94.8</td>
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<td>96.6</td>
</tr>
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</table>
In this paper, the resonance amplification experiment of PMLSM is carried out to achieve thrust amplification at the condition of the motor movement speed is 5mm/s, the amplitude of the current is 15 A, the voltage is 230 V, and the running time is 1s at each frequency. First of all, by finding the frequency range when the system is in approximate resonance to determine the resonance point of the system, the input waveform of the actuator is set to a sine wave, the input frequency is within the range of 1–200 Hz, and the frequency corresponding to the output thrust is the resonance point of the system. The fitting curve is shown in Figure 15, the frequency range when the system reaches resonance is about 128 Hz to 132 Hz. By comparing the thrust output at these frequencies, it can be concluded that the resonant frequency of the linear motor actuator is 130 Hz, and the actuator output load is 11.5 KN. The output of the maximum continuous thrust of 950 N relative to the linear motor is approximately 12.1 times the output thrust in the resonant state. Usually, the natural frequency of the component is several thousand Hz, which is much bigger than the system’s natural frequency, so the motor will not be destroyed.

Figure 14. Simulation and experimental output thrust curves.

5.2. Resonance Experiments

Figure 15. Thrust-frequency fitting curve.
6. Conclusions

In this paper, the electromagnetic design of the unilateral PMLSM is carried out and the structural parameters are given. Furthermore, the magnetic field and electromagnetic thrust of the motor are theoretically analyzed, and mathematical expressions are given by EMC and Maxwell tensor method. Through the vibration analysis of the whole machine, the conditions for the resonance of the motor are obtained. In the case of no-load, the magnetic chain and back EMF are positive linear, the detent force is reasonable, the air gap magnetic flux density waveforms positive linearity, and the theory is consistent with the simulation solution results. In the case of load, most of the magnetic field lines form a closed loop, but there is a certain magnetic saturation in the core part, and the theoretical analysis of electromagnetic thrust is consistent with the simulation results. Through the PMLSM static force test, the thrust constant under the experiment is basically consistent with the simulation solution results, and the errors of both are less than 5%. Through the above analysis, it can be concluded that the motor design results are more reasonable. Finally, through resonance experiments, the thrust was amplified by 12.1 times under the condition that the rated thrust of the motor was 950 N.

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