Design and implementation of a single-side flat synchronous linear motor model

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Abstract. In recent decades, the demand for a linear motor has increased in various applications, due to its ability to develop a linear motion directly. One of the significant problems facing the operation of the linear motor is the presence of force ripple caused by the irregular magnetic field of the permanent magnets. Accordingly, a developed single-side permanent magnet synchronous flat linear motor (PMSLM) model has been designed based on minimizing its force ripple produced. A Maxwell ANSYS simulation is performed to study and enhance the dynamic characteristics and performance of the model and then verifying it with experimental measurements. Multi-objective optimization had been achieved through reducing the size of permanent magnets and reaction rail at specific rates with maintaining the required thrust and reducing the cogging force. The results of the improved model design showed that the maximum value of the force ripple is reduced by about 81.13% compared with the primary model at a smaller ripple coefficient of 0.22%. The comparison between the experimental measurements and numerical analysis showed a good agreement and accuracy of the analytical results.

1. Introduction

More than a hundred years ago, industry rotary motors with a traditional mechanism are still dominated to get linear motion [1]. Thus, the need for linear motors (LMs) is required to compensate those rotary ones for generating the linear motion directly. Furthermore, the LM has several attractive features such as simple structure, easy maintenance, and high acceleration/deceleration [2]. Though, in slotted permanent magnet (PM) linear motors, there is an undesirable phenomenon, known as detent (or cogging) force [3], produced due to slotting and finite length of the moving parts. This force is generated as a result of mutual attraction between the magnets and iron core of the motor with respect to the position of the translator relative to the magnets [4].

Thus, different methodologies had been applied in the literature to enhance motor performance and achieve the best results by reducing the force ripple, such as structural optimization or control method [5]. Optimizing structures include the tantamount to adjust the size of some critical structures, such as PMs modification [6], stator shape, and size in addition to the PM or stator skewing angle [7] likewise the employment of the fraction number of slots per pole [8]. Furthermore, the adjustments of the air gap and slot opening length are applicable methods [5]. Among control methods, the most popular one
was applied by involving a feed-forward current compensation method [9]. Although these techniques had reduced the cogging forces effectively, some methods either increased fabrication difficulties. Therefore, this paper suggests an optimization method to estimate the optimum dimensions of the single-sided 12/10, flat type permanent magnet synchronous linear motor PMSLM based on regular steps with the aid of the Maxwell ANSYS simulation. The optimum dimensions required are the magnet length, magnet width, magnet height, air gap length, motor length at z-direction and the motor ends’ width.

2. 2-D Analysis and optimization method
2.1. Structure and operating principle

The PMSLM is mainly composed of a moving platform and a stator base. Three-phase windings are mounted on the mover’s core with tablet cover assembled on the moving platform. The moving platform translates along with a pair of linear guides represented by four linear rolling bearings while the stator base is located along the moving path with mounted permanent magnets.

Generally, the production of the thrust in the PMSLM is influenced by electrical and magnetic sources. Electrical source normally depends on current feeding the motor coils. According to the Lorentz law [10], if a conductor carrying a current of $I$ is placed in a magnetic field with flux density $B$, an induced electromotive force $F$ on a section with a length of $L$ will be generated. The space-time distribution of the magneto-motive force ($F$ or MMF) of a symmetrical three-phase winding with distributed parameters fed with a balanced system of currents can be expressed as [3]:

$$F(x, t) = \frac{1}{2} \sum_{v=1}^{v_{\text{max}}} F_{\text{mv}} \left\{ \sin \left( \omega t - \frac{v \pi}{3} x \right) + (v - 1) \frac{2\pi}{3} \right\} + \left\{ \sin \left( \omega t + \frac{v \pi}{3} x \right) - (v + 1) \frac{2\pi}{3} \right\}$$

(1)

Where $F_{\text{mv}}$ is the magnitude of the $v^{th}$ harmonic of the armature MMF and $v$ is the harmonic number. The generated electromagnetic power ($P_{\text{elm}}$) and thrust force ($F_{\text{th}}$) could be obtained as follows [11]:

$$P_{\text{elm}} = \frac{m_{1} |v_{1}| (R_{1} \cos \delta + X_{s} \sin \delta) - E_{f} R_{1}}{(X_{s} + R_{1})^2} \times \left[ V_{1} (X_{s} \cos \delta - R_{1} \sin \delta) (X_{s} - X_{q}) + E_{f} (X_{s} - X_{q}) + R_{1}^2 \right]$$

$$= E_{f} X_{s} (X_{s} - X_{q})$$

(2)

Where,

$$E_{f} = 2\pi f N_{1} k_{w} \Phi_{f}$$

(3)

$$F_{\text{dx}} = \frac{P_{\text{elm}}}{v_{s}}$$

(4)

$$v_{s} = 2\pi f$$

(5)

Where, $v_{s}$ is the synchronous velocity, depends only on the frequency $f$ and pole pitch $\tau$. To verify the results of design calculation, maximum thrust force be determined for the single-sided PMSLM model. The motor has rated values of the input power of 402.7W, the linear velocity of 1m/s, the thrust force of 350N at $m_{\text{load}} = 17$ kg, and the current of 4.3A. The dimensions listed in Table 1 show the stator and the mover specification for the designed PMSLM model, which is used as an initial model for the optimization process.

Table 1. Basic specification of the PMSLM designed model

| Parameters          | Symbols | Quantities |
|---------------------|---------|------------|
| Conductor           | $0.5 \text{ mma}^2, 105^\circ\text{C Insulation temperature}$ |
| Air gap             | $g_{1}$ | 1 mm |
| Motor active        | $g_{1}$ | 288 mm |
length
Motor active width

| Material       | $b_{11}$ | $h_{11}$ | $h_{14}$ | $b_{14}$ | $t_1$ | Slots |
|----------------|---------|---------|---------|---------|------|-------|
| 1010 steel     | 14mm    | 17.2mm  | 3mm     | 4.4mm   | 24mm | 12     |
| NFEb Class N42SH |        |         |         |         |      |       |

2.2. 2-D Numerical field analysis

The 2-D finite element method FEM is an effective method for numerical calculation of electromagnetic field distribution. The commercial FE package based on Maxwell ANSYS has been used for this purpose depending on Maxwell equations [11]. The nonlinear material properties and structural details are taken into consideration. Maxwell ANSYS solution is divided into a load and no-load transient magnetic solution stages where its time period for every load step is 0.0016sec with 0.0001 nonlinear residual and backward Euler time integration solving methods. Whereas, the single solved curve during $2\tau$ is composed of 36 steps.

Meshes generation with the triangular element shape, the element sizes adjusted by the user to adequate the analysis, depending on the physics of the model structure. The model is designed with three meshing regions; each one contains 1200 elements with 5.76mm maximum element length. The triangular element shape of modeling 2-D geometries is well suited for automatic mesh generation as shown in Fig. 1 (a). Figure 1(b) shows the results of the field distribution. As noted, the flux lines move in a transverse direction performing closed loops as it should. The maximum flux density $B_{\text{max}}$ equals 3.5T and $\text{MMF}$ of 426A.T.

![Figure 1](image1.png)

(a) The optimum model meshing
(b) Magnetic field density as a vector

**Figure 1.** FEA of semi-closed core of the LM at position = 4.8 mm, time = 0.0048 sec (1m/s)

2.3. Optimal design

The optimization had accomplished based on the designed model demonstrated in Table. 1. Maxwell ANSYS optimization has based on two cases in order to predict best dimensions that lead to lowest cogging force at no load case. The first iteration of Table 2(a) has affirmed that the maximum cogging force has decreased by 73.9% while the second one has achieved with another set of constant values as it's displayed where the cogging force results have decreased by 77.43%. As a result, the second iteration offers the best percentage value of cogging force reduction in the first case of optimization. Otherwise, ends width of the motor translator affect on the variation of the cogging forces, therefore, the second case should be applied according to Table 2(b) depending on the best results obtained from
the first case represented by the second iteration. The results of 2.625mm the translator end length led to a reduction in cogging force by 81.13%.

Although the area of the translator end section has decreased, it is still suitable for the linkage flux passing and did not cause flow dispersion out of the core metal. As well as taking several possibilities separately for high reaction rail (\(h_{c1}\)) and showing that the best value is the designed value itself. Table 3 illustrates the final results of optimization and Figs. (2 and 3) show the thrust force (at load case) and cogging force (at no-load case) before after the improvement. Figure 4 shows The Flowchart of the optimization procedure.

Table 2. (a) First and (b) Second case of optimization procedure (All dimensions in mm)

| Parameters | Iterations |  |  |  |  |  |  |  |  |  |  |  |
|------------|------------|---|---|---|---|---|---|---|---|---|---|---|
|            | \(g_1\)    | \(h_M\) | \(\omega_P\) & \(L'_1\) | \(e_m\) | \(e_m\) | \(\omega_P\) | \(e_m\) | \(\omega_P\) | \(e_m\) | \(\omega_P\) | \(e_m\) |
| First      | 1          | 5  | 24.32 - 95                 |          |          |          |          |          |          |          |          |
|            |            |    | 18.66 - 95                 |          |          |          |          |          |          |          |          |
|            |            |    | 12.32 - 95                 |          |          |          |          |          |          |          |          |
|            |            |    | 24.32 - 85                 |          |          |          |          |          |          |          |          |
|            |            |    | 18.66 - 85                 |          |          |          |          |          |          |          |          |
|            |            |    | 12.32 - 85                 |          |          |          |          |          |          |          |          |
|            |            |    | 24.32 - 75                 |          |          |          |          |          |          |          |          |
|            |            |    | 18.66 - 75                 |          |          |          |          |          |          |          |          |
|            |            |    | 12.32 - 75                 |          |          |          |          |          |          |          |          |
| Second     | 1.5        | 3  | 24.32 - 75                 |          |          |          |          |          |          |          |          |
|            |            |    | 18.66 - 75                 |          |          |          |          |          |          |          |          |
|            |            |    | 12.32 - 75                 |          |          |          |          |          |          |          |          |

Table 3. Basic specification of the PMSLM optimized model (All dimensions in mm)

| Parameters | \(g_1\)  | \(L'_1\) | \(L_M\) | \(h_M\) | \(\omega_P\) | \(h_{c1}\) |
|------------|----------|----------|---------|---------|--------------|------------|
| Quantities | 1.5      | 75       | 75      | 3       | 2.625        | 12.32      | 8         |

Figure 2. Primary model output thrust

Figure 3. Optimized model output thrust

The size of the translator is smaller and therefore the motor needs less thrust force proportional to the weight difference with preserving the thrust force requires for carrying the desired load, as proposed in Figs. 2 and 3. The rms value of the optimum thrust force is found to be equal to
320.4833N at the mean value of the rms motor currents $I_a = 3.555A$ at $m_{load} = 17kg$ and optimum $m_{translator} \approx 4.75kg$ with the same velocity at a frequency, $f = 17.36Hz$.

![Flowchart of the optimization procedure](image)

**Figure 4.** Flowchart of the optimization procedure
Figure 5. (a) Iron losses of the optimized laminated core, (b) Output thrust in this case, and (c) 3-phase currents

In another case where the core loss component is taken into consideration, it will be equal to 36.9W as illustrated in Fig. 5(a), where these analyses have achieved at low speed with the laminated core and the output thrust force in Fig. 5(b) is found to be 290.059N at a mean value of rms motor currents of $I_a = 3.547$A in Fig. 5(c) where the core loss affects the machine flux linkages and its reduction causes decreasing the thrust.

3. PMSLM model implementation and discussion

The manufacturing of the proposed motor is a long process comprising different stages. Starting with core sheets shown in Fig. 6 provided according to the designed model, and manufacturing it using CNC wire-cut KNUTH smart DEM. This process will produce 115 pieces with 0.65mm sheet thickness as shown in Fig. 7.

Figure 6. Electrical single sheet after manufacturing the NX

Figure 7. A single sheet was drawn by

115 pieces of the core laminations have been cut and arranged by using three iron guides as shown in Fig. 5, then they were pressed by the machine vice to weld all sheets together as one block using MIG welding.
F-Class fiber insulator has been used with 25\(\mu\)m thickness with 0.95mm diameter (copper) winding coil has been selected to accomplish a single layer concentrated winding, while for the stator, the permanent magnets have been mounted on the reaction rail surface. Fig. 8(b) shows the completely wounded translator. Both the insulation resistance test and the series test had been carried out on the translator. Finally, all the parts were assembled along with trying to adjust the air gap as possible so as to form a PMSLM model prototype shown in Fig. 9.

Figure 10(a) shows the device screen and the result of phase A with 0.705m/s at 12.25Hz, note that B and C phases have the same results with 120° shifting. Likewise, Fig. 10(b) illustrates the FE analysis of the back \textit{emf} at the no-load case at the same speed. As noticed, the value of the experimental back \textit{emf} is 21.8% larger than the FE analytical value since the Maxwell ANSYS neglects the ends of the motor coils at 2-D analysis and this is responsible for back \textit{emf} increment in the experimental model case.
Fig. 11 shows the comparison between the three cases of cogging forces that have been tested. The analysis had accomplished using FEM solving the cogging force of the optimized design as shown in Fig. 11 (a), while the experimental test has accomplished using a force meter with pull and push sensors as shown in Fig. 11(b). The case (b) presents a slightly lower value of the cogging force because of the error resulting from the air gap length. The translator frame in the prototype was made of steel and aluminum, it was deformed severely related to the great normal force, and thus the air gap comes to be uneven.
Thrust force constants, force ripple coefficient and the efficiency percentage results are illustrated in Table 4. The greater value of the force constant \( (k_F = \frac{F_{dl}}{I_a}) \) leads to least thrust ripple \( k_r \) and highest efficiency which represent the best model. Variant results were observed in the model's \( k_{F,RMS} \) values. This disparity is located due to a few reasons whereas two of them are convergent, unlike the rest. The convergence of the first two models' values is related to the error between the analytical and numerical equations while the increment of the third model is due to applying the optimization method in order to enhance the performance which is the goal of this paper. On the other hand, loss consideration in the fourth model causes the \( k_{F,RMS} \) value to decrease. However, the ripple coefficient is equal to 0.223 which is considered an acceptable value to the practical designs in comparison with the rest models that offer high efficiency or better ripple coefficient but remain a virtual design. Finally, the improved (optimum) model has been built and tested experimentally which has low efficiency as expected, since practical models differ from the theory, related to the existence of electrical and mechanical losses.

**Table 4.** Force constant values, ripple coefficient and efficiency

| Models                   | \( k_{F,Max} \) (N/A) | \( k_{F,Min} \) (N/A) | \( k_{F,RMS} \) (N/A) | \( I_a \) (A) | \( k_r \) | Efficiency % |
|--------------------------|-----------------------|-----------------------|-----------------------|--------------|----------|--------------|
| Analytical model         | ……                    | ……                    | 81.395                | 4.3          | ……      | 86.91        |
| Simulated model          | 129.65                | 59.814                | 81.096                | 4.32         | 0.93     | 86.92        |
| Optimal model            | 108.257               | 88.963                | 90.15                 | 3.555        | 0.22     | 83.57        |
| Optimal model with losses| 98.279                | 76.082                | 81.775                | 3.547        | 0.281    | 75.64        |
| Experimental model       | ……                    | ……                    | 63.636                | 3.3          | ……      | 60           |

**4. Conclusions**

In this paper, an improved design of a three-phase flat PM excitation SLM with a single-side type of 10/12 pole-slot combination has been designed and modeled using 2D and 3D FEA simulation whereas ANSYS package has been employed. The following conclusions are drawn:

- The design achieves optimum motor performance with minimum thrust ripple coefficient of 0.22 and thrust force of 320.4833N at rms load current of 3.555A where \( k_{F,RMS} \) of 90.15.
- The optimized motor gives a thrust ripple twice less than the original model.
- The core losses of the optimum model causes a thrust ripple coefficient of 0.281 and thrust force of 290.057 N at rms load current of 3.547A where \( k_{F,RMS} \) of 81.775.
- The experimental back \( emf \) is greater than the FEA value by 6.79%, while the experimental cogging force is smaller than the FEA value by 7.41%.
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