Optimization Design to Reduce Detent Force and Standardize Back-EMF for Permanent Magnet Synchronous Linear Motor

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Abstract

The permanent magnet synchronous linear motor (PMSLM) has increasingly been used in a wide range of commercial and industrial applications, while Low force ripple of the PMSLM is an essential requirement. This paper presents three effective design approaches for the force ripple minimization, with particular emphasis on the detent force reduction and Back-EMF standardization, which are the two critical causes producing force ripple in the PMSLM. Related design features are analyzed by FEA method, and the flat PMSLM with 1000N thrust force is developed.

1 Introduction

The permanent magnet synchronous linear motor (PMSLM) has increasingly been used as an alternative solution to rotary motors in a wide variety of applications due mainly to their excellent dynamic characteristics and accurate positioning capability [1]-[6]. However, the PMSLM generally suffers from force ripple, which may be extremely high, especially when high-strength permanent magnets are employed. On the other hand, the force smoothness is crucial in most motion control applications, such as CNC machine tool, industrial automation, and high-end machinery. Therefore, the minimization of the force ripple in the PMSLM is quite important and remains the key target of design considerations. Generally, the causes of these undesirable ripples may be categorized as those contributed from the motor and from the associated control strategy. Although certain suitable control strategy can reduce the force ripple at the expense of increased control complexity, it is desirable to reduce the force ripple by feasible design of the PMSLM.

On the motor design aspects, the force ripple sources can be generally classified as follows: the detent force, and the distortion of Back-EMF. More specifically, the detente force is mainly caused by attraction between the permanent magnet (PM) and the iron core, which can be divided into two components: the slot-effect component and the end-effect component. The slot-effect detente force, which is analogous to the cogging torque in the rotary motors, is generated by the interaction of permanent magnets with displacement variations in the armature magnetic reluctance, whilst the end-effect detente force is produced by the interaction of permanent magnets with the finite-length armature core. There are two types of Back-EMF harmonics in the PMSLM. One type is under balanced condition, while the other refers to the unbalanced Back-EMF harmonics, which are induced by the end-effect in the PMSLM. According to [7], both types of the Back-EMF distortions may lead to non-neglectable force ripple in the PMSLM.

Therefore, the detent force should be reduced as low as possible, and the Back-EMF should be developed as standard sinusoidal wave without distortion.

There are many techniques have been reported for reducing the detent force and standardizing the Back-EMF. Since the slot-effect component of detent force also exist in the rotary Permanent Magnet (PM) motor, most of the detent-force-minimization and the Back-EMF standardization techniques used in the rotary PM motor can be appropriately employed in the PMSLM. The skewed magnets are widely used for the PMSLM. The feasible design of Skewing can reduce the fluctuation of detent force caused by slot-effect, as well as standardize the Back-EMF[8]. However, because of the end-effect, the detent force can still be significant. Furthermore, and it also results in trust force reduction and a more complex manufacturing process. Therefore, the skewed structure is not employed for the PMSLM design in this paper.

In this paper, three design approaches are used for the optimization design. The first solution is to optimize the magnet shape to obtain the sinusoidal Back-EMF. The second way is to reduce the thrust cogging force by using the optimal slot tooth design. And the third approach is to optimize the end effect to reduce the detent force (thrust force) fluctuation. All of the design analysis has been implemented by using finite element analysis and the actual design also has been completed.

2 PMSLM Model

The original PMSLM model with 10-pole/12-slot fractional structure is shown in Fig.1. The leading design parameters of the motor are given in Table 1. As shown in Fig.2, the mover of the motor is the armature, and the stator is the magnet. In order to suppress the phase unbalance and decrease the detent force caused by end-effect, auxiliary tooth are provided on both end-side of the armature core.

Based on the given specifications of the PMSLM, the two-dimensional (2D) FEA method is used to calculate the performance of the motor. Fig.3 illustrates the results of static force distribution with respect to the mover position, and Fig.4 gives the waveforms of the phase Back-EMF, respectively. It can be seen that the peak value of the detent force in the preliminary PMSLM structure is 145N, and the total harmonic distortion (THD) of Back-EMF is 13.06%, which are too large compared to the requirements.

Rated force	1000N
No. of phases	3
Detent force ripple	<40 N
Rated voltage	380Vac
Rated speed	2m/s
No. of poles	10
No. of slots	12

Table 1. Leading design parameters of the PMLSLM

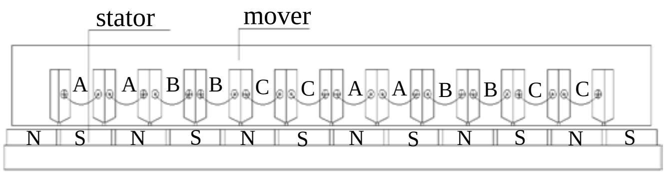


Fig.1 The original PMSLM structure

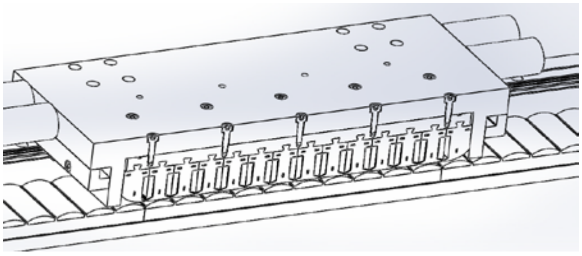


Fig.2 PMSLM 3D design

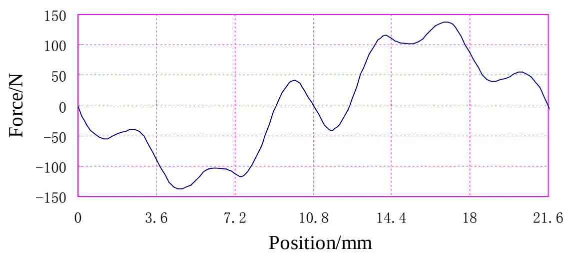


Fig.3 The unloaded static force distribution of the preliminary PMLSM

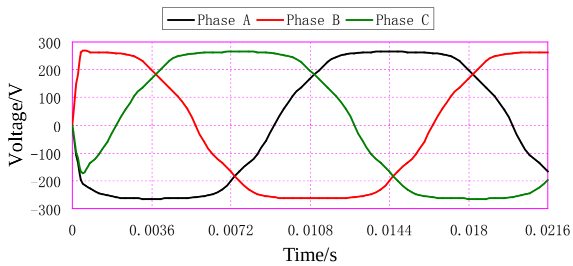
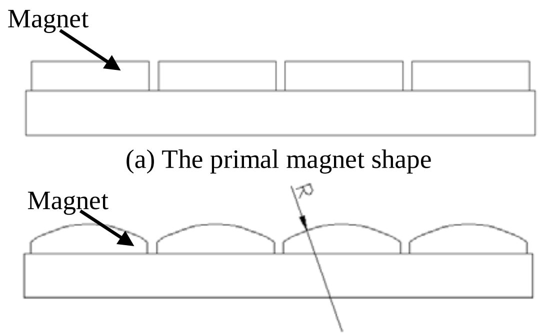


Fig.4 The phase Back EMF(2m/s) of the preliminary PMLSM

3 Magnet Shaping

It is well known that the magnetic flux distribution, which is affected by the edges of the magnet, has a significant influence on the Back-EMF and cogging force. In general, an optimal shaped magnet is conducive to lower THD of the magnetic flux in the PMSLM. Therefore, in this section, the proposed technique focuses on optimizing the shape of the PM, so that the waveform of the magnetic flux in the motor is almost sinusoidal. As a consequence, the Back-EMF is standardized, and the rate of reluctance change with respect to the different stator-mover relative position is reduced, hence, the force ripple is suppressed.

The primal magnet edges in the PMSLM are assumed to be complanate, as shown in fig.5, and the thickness of the magnet is 5mm. Then, the outer surface of each magnet is sinusoidally chamfered, and the outer surface arc of each magnet is varied from 15mm to 21mm.



(a) The primal magnet shape

(b) The sinusoidally chamfered magnet shape

Fig.5 The magnet shape before and after optimization

Fig.6 shows the magnetic field distribution, while Fig.7 and Fig.8 show the phase Back-EMF and force ripple of the PMSLM, respectively, when the magnets are sinusoidally shaped with 18mm outer face arc radius. It can be seen clearly from Table 2 that, the THD of the Back-EMF in the PMSLM with complanate outer surface is 13.06%, whilst significantly reduced to 0.70% by using optimal magnet shape. Since the magnetic field is varied from uniform to sinusoidal, the THD of the Back-EMF is significantly reduced, and also the amplitude of the detent force ripple is decreased, hence, the fluctuation of torque during the rate condition is suppressed.
As shown in table 2, it should be noted that, the Back-EMF is standardized by sinusoidally chamfering, at the cost of a reduction in amplitude, which means the output force also decreases under the giving input current condition. Based on this analysis, the design trade-off between high force density and low THD of the Back-EMF should be considered from the systematic optimization point of view.

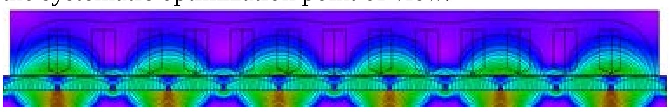


Fig. 6 The unloaded magnetic field distribution of the PMLSM with the magnets sinusoidally shaped by 18mm outer face arc radius

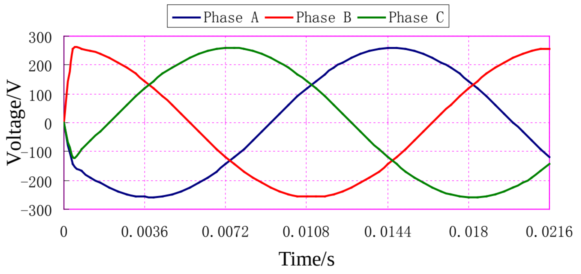


Fig. 7 The phase Back EMF(2m/s) of the PMLSM with the magnets sinusoidally shaped by 18mm outer face arc radius

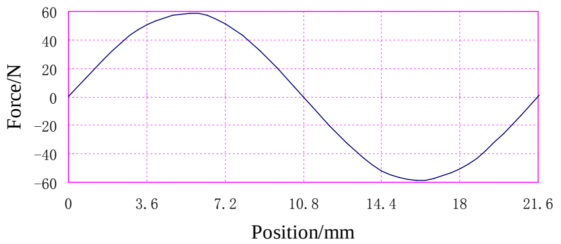


Fig.8 The unloaded static force distribution of the PMLSM with the magnets sinusoidally shaped by 18mm outer face arc radius

Arc	Detent force	THD of back EMF	The elementary peak value of back EMF
0mm	145N	13.06%	301V
15mm	59N	0.77%	255V
16mm	59.6N	0.77%	256V
17mm	60N	0.72%	257V
18mm	61.8N	0.70%	260V
19mm	58.2N	1.32%	262V
20mm	57.7N	1.84%	264N
21mm	57.5N	2.34%	266N

Table 2. The phase Back EMF(2m/s) and maximum detent force of the PMLSLM with different outer surface arc

4 Optimal Slot Opening Design

As mentioned in Section 1, the slot-effect detent force is mainly caused by the interaction of the PM and the iron core, due to the slot opening, it is necessary to implement an analysis that minimizes the detent force ripple generated by the slot opening. In this section, the slot opening influence is analyzed based on the optimal shaped PM model. All the constant parameters used for optimization are shown in the Table 3 and Fig.9, whilst the only optimization variable is the slot opening, which indicates the distance between the two tooth tips. The auxiliary tooth is kept as the original shape, of which the optimization is discussed in the next section.

Parameter	Value
a	1mm, 1.5mm,2mm, 2.5mm, 3mm
b	2.5mm
θ	20°

Table 3 The slot parameters

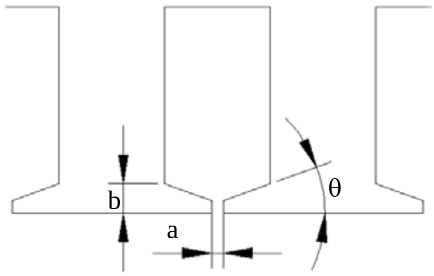


Fig.9 The slot structure

According to Table 4, the detent force ripple is decreased from 61.8N to 47N, while the Back-EMF is almost the same, as the slot opening width varied from 3mm to 1mm. Since the slot-effect detent force (cogging force) is generated by the variation of air-gap permeance due to the slot opening, narrowing the slot opening width can result in a lower air-gap permeance variance ratio, and hence it can reduce the detent force. However, because of the requirement on winding assembling process, the slot opening of armature core should be narrowed to some extent, in case there is insufficient space for the coil winding.

Slot Opening	Detent force	THD of back EMF	The elementary peak value of back EMF
1mm	47N	0.41%	265V
1.5mm	50.2N	0.48%	263V
2mm	52.3N	0.55%	262V
2.5mm	56.1N	0.62%	261V
3mm	61.8N	0.70%	260V

Table 4. The phase Back EMF(2m/s) and maximum detent force of the PMLSLM with different Slot opening

5 Auxiliary Tooth Optimization

The remained detent force is mainly generated by the end-effect after the highlighted optimization of the PM shape and the slot opening of the armature core. To avoid affecting the flux distribution around the end tooth and auxiliary tooth, we provide an improved design of auxiliary tooth to suppress the end-effect.

As shown in Fig.10, the auxiliary tooth is optimized by a circle-arc edge with different radius. Based on section 3 and section 4, the magnet outer arc is 18mm, and the slot opening is 1mm. Table 6 and Fig.11 gives the Back-EMF and cogging force values with different circle-arc of the auxiliary tooth edge.
It is clearly that the detent force ripple varies a lot along with the circle-arc changes, and there exists an optimum value of the circle-arc radius, which is 15mm in this case.

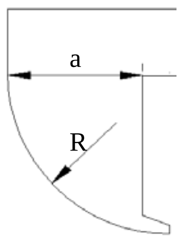


Fig.10 The auxiliary tooth structure

Parameter	Value
a	15
R	0mm,3mm,6mm,9mm,11mm,13mm,15mm

Table 5: The auxiliary tooth parameters

R	Detent force	THD of back EMF	The elementary peak value of back EMF
0mm	47N	0.41%	265V
3mm	42N	0.42%	265V
6mm	105N	0.42%	265V
9mm	122N	0.41%	265V
11mm	107N	0.43%	265V
13mm	74N	0.42%	265V
15mm	33N	0.41%	265V

Table 6: The phase Back EMF(2m/s) and maximum detent force of the PMLSLM with different auxiliary tooth arc radius

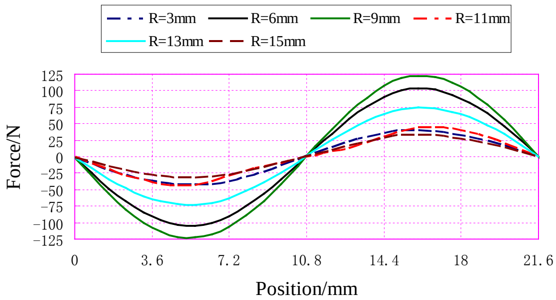


Fig.11 The unloaded static force distribution of the PMLSM with different circle-arc of the auxiliary tooth edge

6 Conclusion

This paper presents the design methods to reduce the detent force and obtain standard sinusoidal Back EMF by adding optimized auxiliary teeth, narrowing the slot opening, and shaping the magnet outer face. The results show that the detent force is significantly reduced and the Back EMF is perfect for control. By using these optimization design approaches, the detent force is reduced from 145N to 33N (about 3.3% of the total thrust force), and he Back EMF is optimized as standard sinusoidal, with the phase voltage THD reduced to 0.41%.

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