Control Based Reduction of Detent Force for Permanent Magnet Linear Synchronous Motor

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Abstract

The detent force of the permanent magnet linear synchronous motor (PMLSM) is caused by the interaction between the permanent magnet and the iron core of the mover without input current. It is a function of the mover position relative to the stator. This paper proposes a control based method to reduce the detent force for the PMLSM. This detent force that can be predicted by finite element method (FEM) is compensated by injecting the instantaneous current using the field oriented control (FOC) method. Both the simulated and experimental results are reported to validate the effectiveness of this proposed method.

1. Introduction

Permanent magnet linear synchronous motor (PMLSM) is the most suitable for high precision and fast dynamic control system. However, the significant drawback of PMLSM is the detent force that will deteriorate the performance of drive system. The detent force is caused by the interaction between the permanent magnet and the iron core of the mover without input current. The optimal constructive design technique can reduced the detent force effectively. However, this technique is complex and cost too much, and usually more than 10 [N] detent force is remained. Furthermore, the PMLSM that is a direct linear motion drive system without any indirect coupling mechanism is sensitive to the force disturbance. Even the remained small detent force will deteriorate the PMLSM performance seriously. Therefore, this paper proposes a control based method to reduce the detent force for PMLSM. Usually, this technique is implemented by involving an estimator, which is complex and sensitive to the estimated parameters [1]. In this paper we propose a simple feed-forward current compensation method based on the detent force function predicted by the finite element method (FEM). Furthermore, an online observer that is only based on the mathematical model of the PMLSM is involved to suppress other unexpected forces. This is easily implemented by the FOC method, and no additional hardware is needed.

First, the structure of the PMLSM is introduced. Second, the detent force characteristics are analyzed by the FEM. Then the feed-forward current compensation method is used to counteract the detent force. Finally the effect of this proposed method is proved by the simulated and experimental results.

2. PMLSM Model Analysis

The PMLSM model in this paper is the moving armature type, the PMLSM structure is shown in Fig. 1. The mover is composed of the laminated iron core that is in a 9-slot/8-pole fractional-slot pitch structure with concentrated winding, which is similar to the structure of the rotary motor core being cut off on the middle point between two adjacent teeth and straightened. The stator is the path with surface mounted permanent magnet. The parameters of the PMLSM are listed in Table I.

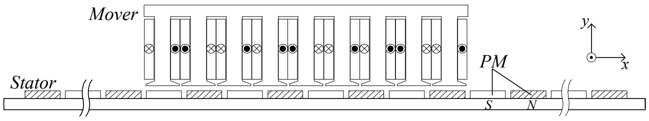


Fig. 1. PMLSM structure.

Based on the specifications the magnetic field, the detent force and the thrust can be calculated by the 2-D FEM. This 9-slot/8-pole fractional-slot pitch structure not only reduces the back EMF harmonics, but also suppresses the detent force [2]. The calculated results of static force distribution with respect to the mover position are shown in Fig. 2. The output thrust is seriously distorted by the detent force. The peak value of the detent force of the PMLSM is 43.4[N]. It is 7.2% to the rated electromagnetic force, which is too large and needs to be reduced.

Table I
SPECIFICATIONS OF PMLSM

Item	Value	Item	Value
Phase number	3	Rated thrust	600 N
Winding number/slot	80 turns	Pole pairs	4
Slot/pole/phase	3/8	Pole pitch	29.25 mm
Mover core height	77 mm	Slot pitch	26 mm
Mover yoke height	23 mm	Slot width	15 mm
stator yoke height	9 mm	PM length	95 mm
Air-gap length	3 mm	PM width	21 mm
Material of PM	Nd-Fe-B	PM height	4 mm

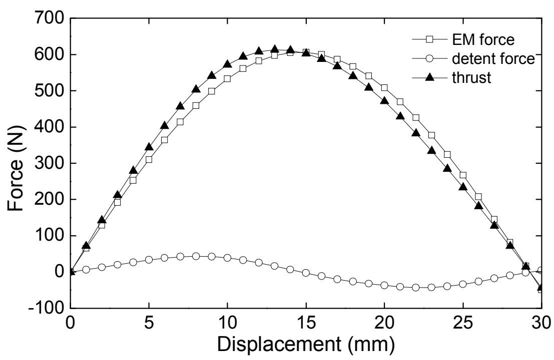


Fig. 2. Static force waveforms according to mover position.

3. Field Oriented Control Method

The force characteristics of PMLSM are obtained by the upper analysis; we then use the FOC method that employs a force compensator and an online observer to compensate the detent force in order to obtain a stable output thrust from the PMLSM drive system.

The voltage equations can be given by [3] as follows:

$$\left.\begin{aligned} u_d &= R_s i_d + p\lambda_d - \pi\upsilon\lambda_q/\tau \\ u_q &= R_s i_q + p\lambda_q + \pi\upsilon\lambda_d/\tau \end{aligned}\right\} \quad (1)$$

where $\lambda_d = L_d i_d + \lambda_{PM}$; $\lambda_q = L_q i_q$; u_d and u_q are the d- and q-axis stator voltages, respectively; R_s , the stator resistance; i_d and i_q , the d- and q-axis stator currents; p , the differential operator; υ , the mover electrical velocity; λ_d and λ_q , the d- and q-axis stator flux linkages; L_d and L_q , the d- and q-axis inductances; τ , the pole pitch; and λ_{PM} , the permanent magnet flux linkage.

The d-axis current i_d is zero for the FOC method and the d- and q-axis reluctances are the same. Therefore, the electric thrust is given as

$$F_e = 3\pi n_p \lambda_{PM} \cdot i_q / 2\tau = k_f \cdot i_q \quad (2)$$

where F_e is the electric thrust; n_p , the pole pairs; and $k_f = 3\pi n_p \lambda_{PM} / 2\tau = 42.85$ [N/A], the thrust coefficient. The thrust F_e is proportional to i_q within the rated current range.

The motion equation of the PMLSM is

$$F_e(x) - F_d(x) = M\frac{d\upsilon_m(t)}{dt} + B\upsilon_m(t) + F_l(t) \quad (3)$$

where M is the total mass of the moving element system; B , the damping coefficient; υ_m , the mover mechanical velocity; F_d , the detent force, and F_l , the external load thrust.

The system control diagram of the PMLSM is shown in Fig. 3. The detent force compensation block, shown in the dashed region, is a position dependent function as Fig. 2.

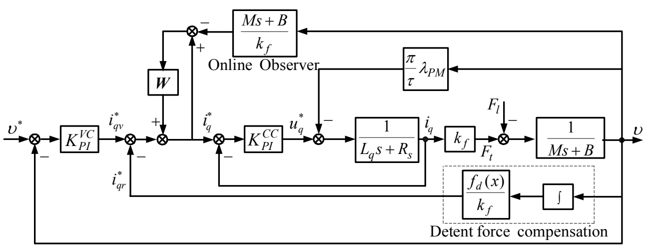


Fig. 3. FOC control diagram of PMLSM.

Therefore, Based on the detent force calculated by 2-D FEM and (2) we can calculate the compensation current i_{qr} as

$$i_{qr}(x) = F_d(x)/k_f \quad (4)$$

The FOC algorithm enables real-time control of force by controlling q-axis current component.

4. Simulated and Experimental Results

The PMLSM system is sensitive to the force disturbance. Even the remained small detent force will deteriorate the PMLSM performance seriously, especially at low speeds with no load. Therefore, we take a simulation by Matlab with a reference velocity command on 0.1 [m/s] without any load in order to investigate the effectiveness of this proposed feed-forward current compensation technique. To validate the simulation, the experiments are carried out using the digital signal processor (DSP) based PMLSM drive system. We take experiment in the same condition as simulation. And the prototype machine of the PMLSM is shown in Fig. 4.

First, the closed-loop control for PMLSM system without current compensation is performed. In this case the compensation current i_{qr} is zero. The velocity controller has the effect on constraining the velocity vibration. However, this effect is limited and the vibration is still obvious. Second, the closed-loop control for PMLSM system with current compensation is performed. The compensated current i_{qr} is a position dependent component as (4).

Fig. 4. Prototype machine of PMLSM.

Fig. 5 shows the simulated and experimental thrust responses of the close-loop control for the PMLSM system with/without current compensation. The average output thrust of the PMLSM is 24.33 [N] that results from the friction force. Compared with the simulation results, the experimental thrust responses contain high order harmonics that are caused by other unexpected disturbance, such as friction force, wind disturbance, asymmetric fixing, and so on.

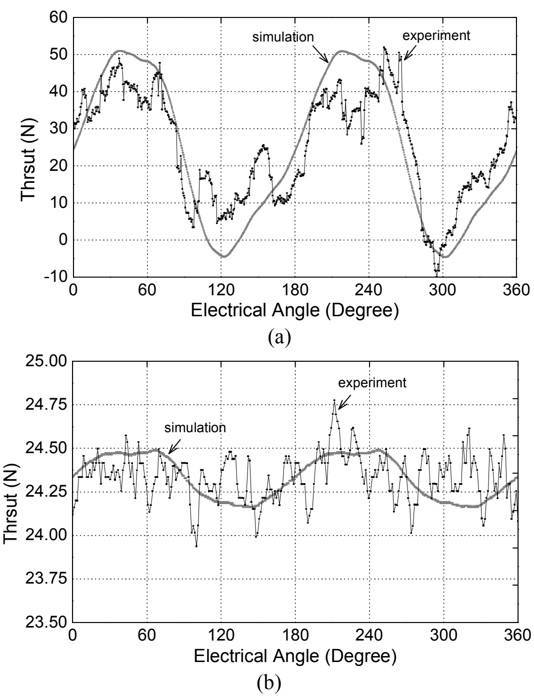
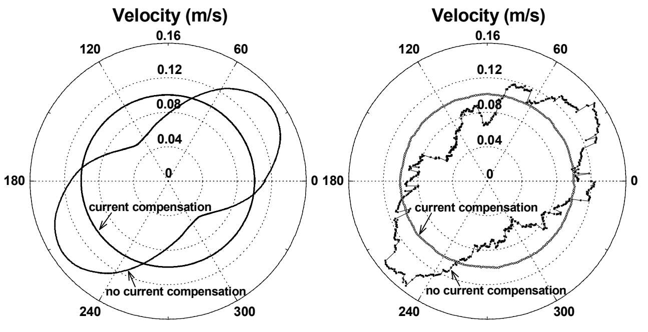


Fig. 5. Comparison of the simulated and experimental thrust responses for PMLSM with/without current compensation. (a) without current compensation and (b) with current compensation.

When the thrust fluctuation component is large shown as Fig. 5(a) we can distinguish that the period of the experimental thrust is same as that of the simulated one. When the thrust fluctuation component is small shown as Fig. 5(b) we can not distinguish the period of the experimental thrust. Since the unexpected disturbance component is also predominant. Whatever, the magnitudes of the results are in good agreement. The maximum value of the thrust ripple with this proposed feed-forward current compensation is significantly reduced compared with the thrust ripple for the PMLSM system without current compensation. The detail results are listed in table II.

The simulated and experimental velocity responses for the PMLSM system with/without current compensation are shown in polar coordinate as Fig. 6. These experimental curves are similar to the simulated ones. The velocity curve of the PMLSM system without current compensation fluctuates twice in one electrical period. It is because that the wavelength of the detent force is one pole pitch τ_p. Whereas, the velocity curve of the PMLSM system with current compensation is round. It means that the fluctuation component is constrained effectively by using the proposed feed-forward current compensation method. According to the simulated and experimental results, we obtain that this proposed feed-forward current compensation method has good effects on the reduction of the thrust ripple and velocity fluctuation.



(a) (b)

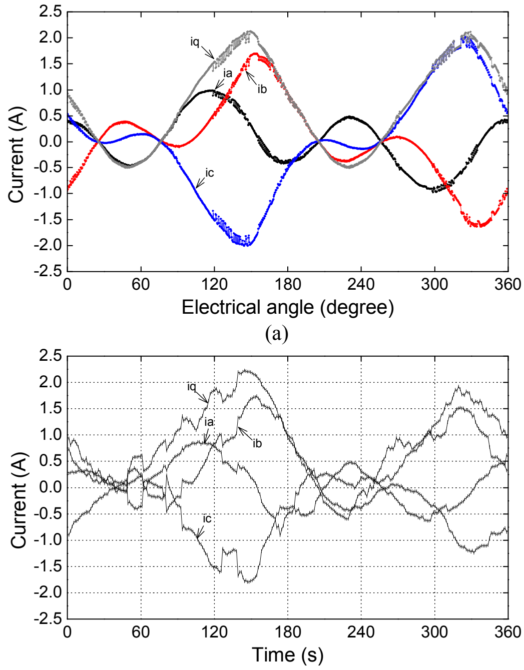
Fig. 6. Simulated and experimental velocity responses for PMLSM with/without current compensation. (a) simulation (b) experiment.

In this paper the coefficient of the Clark-transformation of the FOC is set to 2/3. Therefore, the phase currents directly follow the q-axis current. For general FOC the q-axis current is constant in the steady state and the 3-phase currents are clearly sinusoidal. However, the q-axis current of the feed-forward current compensation FOC method is distorted and not constant any more. The q-axis current also fluctuates twice in one electrical period. The alternative component of the q-axis current is used to compensate the thrust ripple. The corresponding phase currents that follow the q-axis current are also distorted seriously and unbalance shown in Fig. 7. These simulated and experimental results are also in good agreement and the experimental ones contain high order harmonics due to the unexpected disturbance.

The detail simulated and experimental results are listed in Table II. The error means the peak to peak value of the error. The percentage values of the velocity and the thrust ripple are the ratio of the error value to the rated value. The velocity and thrust responses are much better for involving the feed-forward current compensation method.

5. Conclusion

This paper introduced a method to suppress the detent force of PMLSM. First a simple design of PMLSM model with 9-slot/8-pole fractional-slot pitch structure was given to get rid of flux linkage harmonic; the detent force predicted by the 2-D FEM was minimized by involving the feed-forward current compensation method that was implemented by the field oriented control method. The numerical calculation results and experimental results validated the effectiveness of this proposed detent force minimization method.



(a)

(b)

Fig. 7. Simulate and experimental currents of PMLSM with current compensation. (a) simulation and (b) experiment.

Table II.
EXPERIMENTAL RESULTS

Condition		Velocity		Thrust ripple	
		Error	Percentage	Error	Percentage
Simulation	NCC	0.0924	92.4%	55.57	9.28%
	CC	0.0007	0.68%	0.3297	0.05%
Experiment	NCC	0.1030	103.0%	61.94	10.32%
	CC	0.0025	2.46%	0.8393	0.14%

NCC = no current compensation, CC = current compensation, Rated thrust = 600[N], Rated velocity = 0.1[m/s].

Acknowledgment

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Reference

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