Analysis of Detent Force Reduction Method in a Permanent Magnet Linear Synchronous Motor

Seok-Myeong Jang, In-Ki Yoon, Sung-Ho Lee, Do-Hyun Kang and Yeon-Ho Jeong

Abstract - The severe problem in improving the positioning precision of a permanent magnet linear synchronous motor (PMLSM) is the large detent force caused by the permanent magnet arrangement. It is generally an undesired effect that contributes to the torque ripple, vibration and noise of machine. The detent force is arisen from the difference of the position of a permanent magnet end and a tooth position. In this paper, the four methods to reduce detent force were studied and analyzed. The methods are adjusting the width of permanent magnet, varying the shape of armature teeth, relocating the permanent magnet, and adjusting the width of permanent magnet and relocating the permanent magnet at the same time. To analyze the detent force according to four methods, a two-dimensional Finite Element Anlysis [FEA] was used and we compared with the ratio of reduction of the detent force according to the four methods.

Keywords - Permanent Magnet Linear Synchronous Motor, detent force, FEA, detent force reduction method

1. Introduction

In order to produce a linear motion, rotary to linear converter- screw, gear, chain and belt -have been used for rotary machine in the field of factory automation. Therefore, system is complex and not effective. Moreover, decline of the accuracy due to structural limits of the machine and limits of the rated speed have occurred. On the other hand, linear motor produces linear motion directly. Therefore, linear motor does not have to be equipped with a power converter and has the advantage of having no limits of rated speed. So linear motor is being used for various industrial application field. In comparison with linear induction motor, PMLSM has lower control performance and higher cost. But using permanent magnet, PMLSM is more effective, has higher ratio of thrust to mass and power factor relatively. Therefore, it is possible to accelerate PMLSM with high thrust. PMLSM has the high ratio of thrust to current and is easy to be controlled. Recently, PMLSM was studied and used for not only the transport system but also the ropeless elevator and so on. As the permanent magnet, which has a high energy density is developed, we could obtain the permanent magnet cheaply. However, in comparison with a rotary machine, PMLSM has mechanical restraint of a large air gap and finite length relatively. Therefore, in designing, we should consider normal force, fringing effect and mechanical sustenance of a secondary mover. In PMLSM, the severe problem in improving the positioning precision of a permanent magnet linear synchronous motor is the large detent force caused by the permanent magnet arrangement. To improve the position precision of a PMLSM, we should reduce the detent force. It is generally undesired effect that contributes to the torque ripple, vibration and noise of machine[2]. The detent force is arisen from the position of a permanent magnet end and a tooth position. In order to improve performance of the PMLSM, we should study the method to minimize the detent force.

In this paper, the formerly established methods to reduce the detent force were analyzed. The methods are adjusting the length of permanent magnet (PM), varying the shape of armature teeth, relocating the permanent magnet end and adjusting the length of permanent magnet and relocating the permanent magnet at the same time. To analyze the detent force according to four methods, a two-dimensional Finite Element Analysis(FEA) is employed. Using these analysis results, we investigated how much detent force each of methods reduced quantitatively.

2. Detent force in PMLSM

2.1 Detent force reduction of PMLSM

As a moving type, PMLSM can be distinguished between a moving magnet type and a moving armature type. In these two types, a moving magnet type PMLSM was studied and analyzed. Fig 1 shows a conventional PMLSM. In a moving magnet type, it takes advantage of doing not have to be equipped with power supply device. Because the moving part is not heavy, it has merits of

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acceleration and deceleration. On the other hand, in comparison with a moving armature type, a moving magnet type has a defect of supplying electric power device for the whole armature.

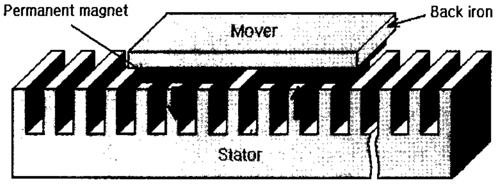
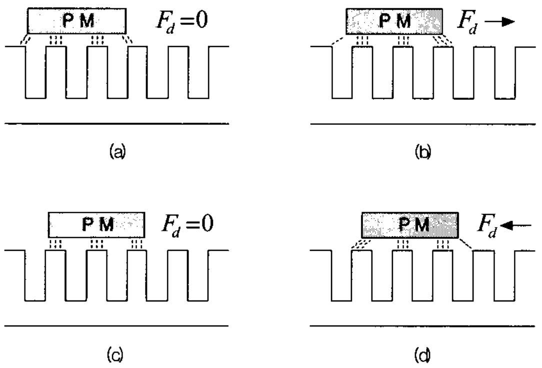


Fig. 1 Configuration of a moving magnet PMLSM

Fig. 2 shows mechanism of the detent force of PMLSM. In the fig 2, we set up (a) as an initial point. When permanent magnet is moved from (a) to (d) at 1/4 slot pitch, magnetic unbalance between permanent magnet ends and tooth positions causes the detent force as shown in fig. 2(b) and (d). Due to the slotted nature of the primary core, the detent force is periodic and repeats itself over every slot pitch. The detent force distorts the characteristics of thrust force. When we operate PMLSM, the detent force causes to make a noise and vibration in addition to a decline of characteristics of control[2]. Therefore, in order to improve the performance of PMLSM, we should minimize the detent force.



(a) (b)

(c) (d)

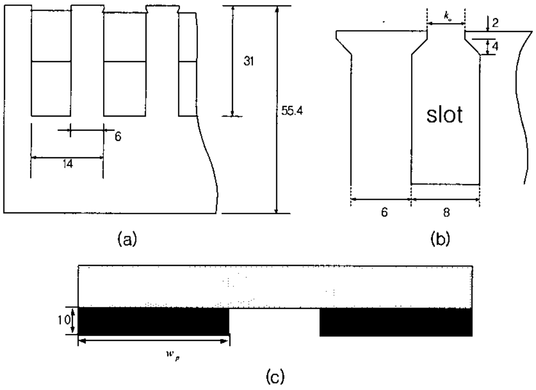
Fig. 2 Mechanism of the detent force due to interaction of PM and teeth

Reduction methods of the detent force in PMLSM are as follows.

- ◉ Method I: Setting standard on the basis of PM length/slot pitch, we can reduce the detent force by adjusting the ratio of PM length to slot pitch such as 3.25, 4.25, 5.25(n+0.25, where n is integer) [1][2].
- ◉ Method II: Semi-closed slots of primary can reduce the detent force [2].
- ◉ Method III: Moving a permanent magnet out of two by $\tau_s/2$, the total detent force can be canceled [3].
- ◉ Method IV: Considering the method I and III at the same time[1][2].

2.2 Example of analysis model

As an analysis model of the detent force, Fig.3 shows configuration and specification of a short primary PMLSM. Fig. 3 shows a primary with open slots and semi-closed slots, where k_0 is open width of the slots and w_p is a length of PM movement direction. Table. 1 shows an example of analysis model according to reduction methods of the detent force. Table. 2 shows a common specification of the secondary and the primary that has open slots and semi-closed slots respectively.



(a) (b)

(c)

Fig. 3 Analysis model of PMLSM
(a) primary with an open slots
(b) primary with semi-closed slots
(c) secondary PM

Table 1 Analysis of PMLSM

Reduction Method	Primary	PM width $< w_p>$
I	Opien slot	73.5mm
II	Semi-opien slo	80mm
III	Opien slo	80mm
IV	Opien slo	]74mm

Table 2 Specification of armature and PM

	Primary		Primary
Rated voltage	220 [V]	Number of turns per phase	414 [turn]
Rated current	5 [A]	Coil resistance	1.79 [Ω]
Pole number	6		PM
Number of turns per pole per phase	3	Class	MQ30 (NdFeB)
Slot pitch	14 [mm]	B_r	1.1[T]
Pole pitch	26 [mm]	Coercive force	-78 [kOe]
Coil diameter	1.35 [mm]	Numver of PM	2

3 Analysis of the characteristic according to methods

3.1 Verification of Finite Element Analysis result using experiment

In order to verify finite element analysis result of the detent force, experiment was performed. Fig. 4 shows specification of PMLSM and static test configuration. The secondary was manufactured, where w_p is 60mm and the primary was used a existing one. Table. 3 shows a measuring instrument.

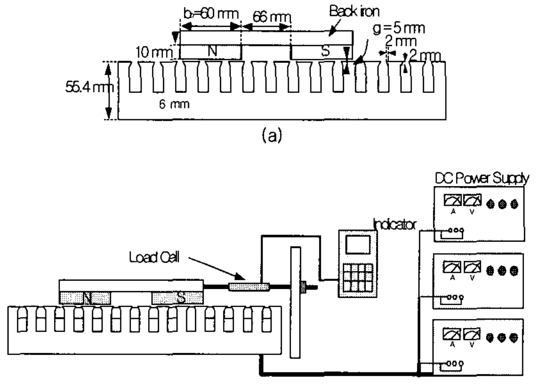


Fig. 4 System configuration of static thrust test of PMLSM (a) Specification of PMLSM (b) Static test configuration

Table 3 Measuring Instrument used static thrust test

Measuring Instrument	Model Name	Remarks
Load Cell	20 - DBBP	
DC Power Supply	EDP 3010	
Indicator	BS - 300A	

Fig. 5 shows a detent force of PMLSM with semi-closed slots and 60mm-PM. As you see in the fig. 5, the result of FEA almost agrees with that of the experiment

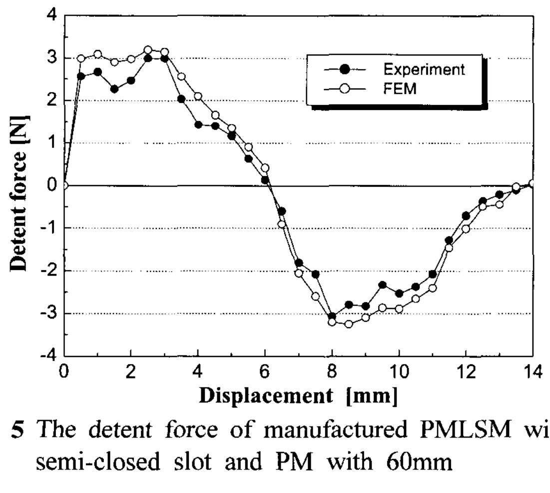


Fig. 5 The detent force of manufactured PMLSM with a semi-closed slot and PM with 60mm

3.2 Analysis of characteristic according to reduction methods of the detent force

3.2.1 Method I

The detent force produced by one edge of a permanent magnet interacting with a steel tooth was assumed to be sinusoidal. Since there are two edges (a leading edge and a trailing edge) of each permanent magnet, it is possible to optimize the permanent magnet length so that the two sinusoidal force wave-forms of each edge cancel out one another[1][2]. We can reduce the detent force by adjusting the ratio of PM length to slot pitch such as 3.25, 4.25, 5.25 (n+0.25, where n is integer). A primary with open slot (slot pitch: 14mm) and a secondary (PM length: 73.5mm) are selected as an analysis model, Where 73.5mm-PM length is in the ratio of 5.25. As a standard of comparison object, PMLSM having 80mm-PM and open slots primary was selected arbitrarily in the analysis. From now on, it having 80mm PM and open slot will be called standard PMLSM(STPMLSM). In the STPMLSM, the detent force reduction is not considered. Fig. 6 shows an analysis result of the detent force between PMLSM with PM length 73.5mm and STPMLSM. As shown in the fig. 6, the detent force was reduced to 98.4% in comparison with STPMLSM.

3.2.2 Method II

Since detent force arises from the interaction between the edge of the stator teeth and that of the permanent magnets, detent force is reduced by using the semi-closed slots instead of open slot. In the primary with semi-open slots, the detent force depends on slot width k_0 because the space harmonics are reduced according as the slot width is decreased.

Fig. 7 shows a analysis result of the detent force between PMLSM with semi-closed slots and STPMSL. As you see in the fig. 7, the detent force was reduced to 55.2% in comparison with STPMLSM.

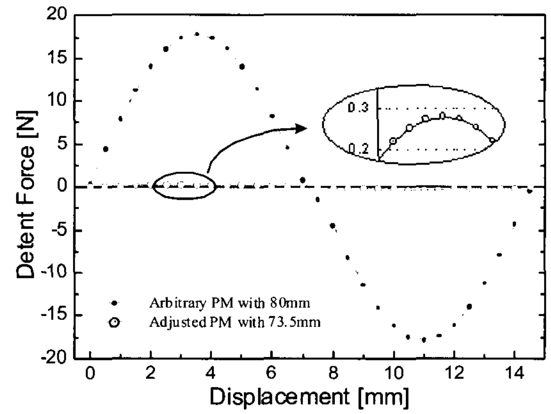


Fig. 6 The detent force according to the method I

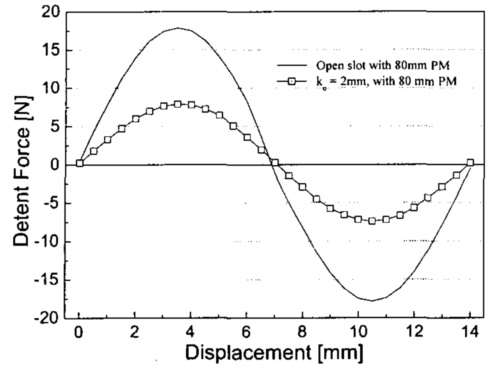


Fig. 7 The detent force according to the method II

3.2.3 Method III

The detent force is the thrust directional component of the interaction between the primary teeth and the permanent magnet. The detent force is influenced by the thrust-directional component of the magnetic unbalance between the magnet end and the tooth. Fig.8 shows a reduction method of the detent force. Let us assume the detent force caused by single magnet is sinusoidal. Therefore, if two magnet ends are located so as the generated detent force is displaced 180 degrees from each other, the total detent force is canceled. In the moving magnet PMLSM, detent force is periodic and repeats itself over every slot pitch, and represented by Fourier series. That is as follows.

$$F_{th} = m \cdot F_h(x) = \sin(n\frac{2\pi}{\tau_s}x) \tag{1}$$

Where $F_h(x)$ is the detent force produced from the PM per pole and m is pole number of the primary. But if one magnet is displaced $\tau_s/2$ when slot pitch is τ_s, the detent force canceled and represented as follows.

$$\begin{aligned} F_{th} &= \frac{m}{2} \cdot \left\{ F_h(x) + F_h(x+\frac{\tau_s}{2}) \right\} \\ &= m \cdot \sum_{n=2,4,6}^{\infty} a_n \sin(n\frac{2\pi}{\tau_s}x) \end{aligned} \tag{2}$$

Fig. 9 shows an analysis result of the detent force between PMLSM using method III and STPMSL. The detent force was reduced to 97.7% in comparison with STPMLSM. PM length is 80mm in the method III.

4. Proposal of effective method of reduction

4.1 Method IV

In these three methods, method I that has ratio of 98.4% to the detent force reduction is the most effective. But in order to reduce more detent force than method I II III, a method IV is suggested and analyzed. The method IV considers the method I,III at the same time. In the method IV, a primary with open slot (slot pitch : 14mm) and 74mm-PM are selected as a analysis model and one magnet is displaced $\tau_s/2$ where slot pitch was τ_s. Fig. 10 shows a analysis result of the detent force between PMLSM using method IV and STPMSL. In the method IV, the detent force was reduced to 98.7% in comparison with STPMLSM. Therefore the detent force could be reduced more effectively using method IV.

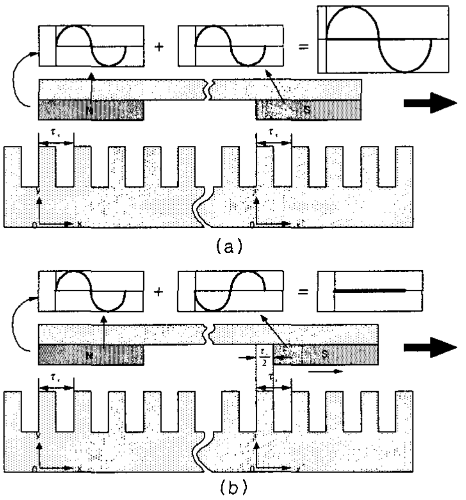


Fig. 8 The detent force according to the method of method III
(a) In the case of having no consideration of the detent force (b) In the case of method III

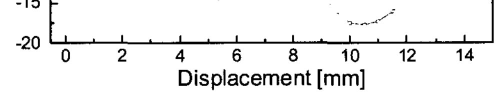


Fig. 9 The detent force according to the method III

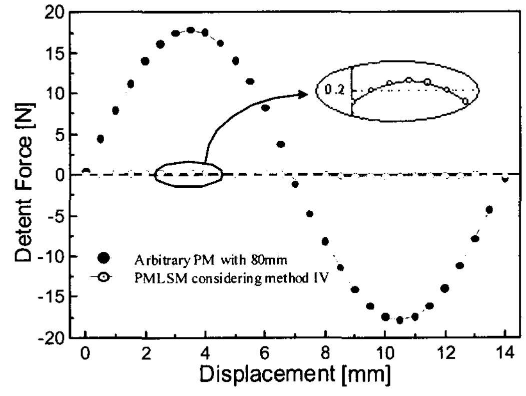


Fig. 10 The detent force according to the method IV

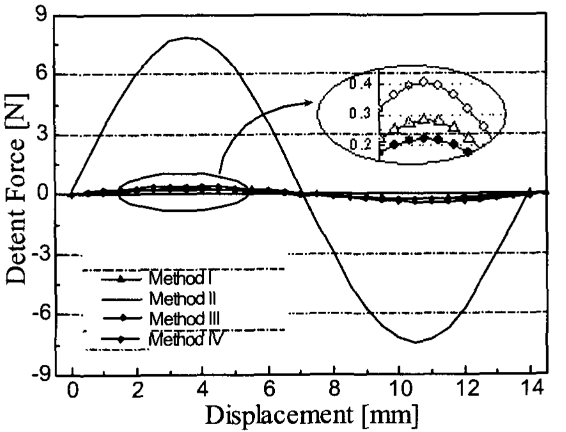


Fig. 11 The detent force according to each methods

4.2 Detent force according to reduction methods

To reduce detent force of PMLSM having a short primary, the formerly established three methods to reduce the detent force and method IV were analyzed. Fig. 11 shows detent forces according to reduction method of PMLSM. Fig. 12 shows thrust waveform of four methods according to load angle. Since there are nine stator teeth per pole, the detent force waveform should repeat itself nine times over the pole-pitch. In the fig. 12, maximum force of method I, IV are smaller than those of method II,III because PM length of method I,IV is 73.5mm. In the method II,III, PM length is 80mm. Therefore, maximum force can be increased using ratios of 6.25 7.25 and so on. Fig. 13 shows ratios of detent force reduction quantitatively. We saw that method IV was the most effective to reduce the detent force of PMLSM.

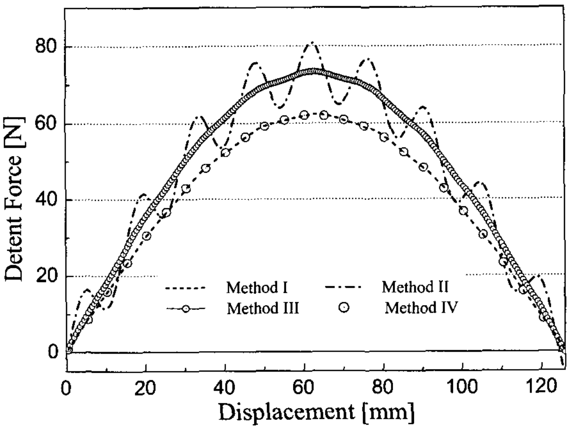


Fig. 12 The detent force according to load angle

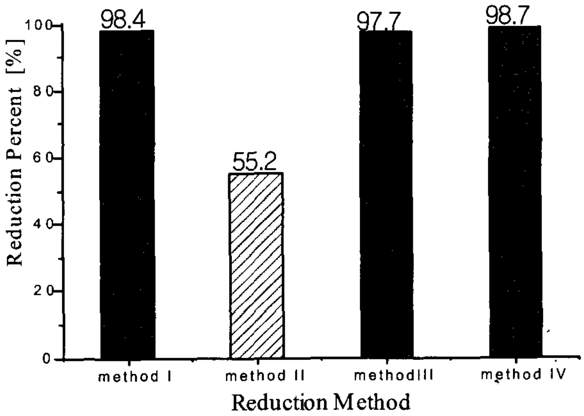


Fig. 13 The ratios of detent force reduction according to method

5. Conclusion

The detent force of PMLSM is arisen from of the position of a permanent magnet end and a tooth position. Due to the slotted nature of the primary core, the detent force is periodic and repeats itself over every slot pitch. The detent force distorts the characteristics of thrust force and causes to make a noise and vibration in addition to a decline of characteristics of control. In this paper, the established three methods to reduce the detent force were analyzed and method IV as a more effective one that considered method I, III at the same time was suggested. The method of adjusting PM width (method I) has reduction ratio of 98.4%, that of primary has semi-closed slots (method II) has reduction ratio of 55.2%, that of relocating the PM (method III) has reduction ratio of 97.7% and that of considering method I,III at the same time (method IV) has reduction ratio of 98.7%.

Reference

[1] In-Soung JungAnalysis of Permanent magnet Linear Synchronous Motor Using Improved Numerical analysis Method Dept of Electrical Engineering. Hanyang University, Seoul 133-791,korea

[2] R.J.Cruise, C.F.Landy 'Reduction of Cogging Forces in Linear Synchronous Motors 'IEEE Trans. on Mangetics, Vol.31, pp. 623-626

[3] T.Yoshimura. H.J.Kim, M.Watada, S.Torii,D.Eb ihara. 'Analysis of the Reduction of Detnet Force in a Permanent Magnet Linear Snchronous Motor' IEEE Trans.Mag. vol.31.pp 3728 3730.1995.

[4] S.A.NASAR, I.BOLDEA 'Linear motion electric machines' 1976

[5] Jacek F. Gieras, Zbignies J.Piech 'LINEAR SYNCHRONOUS MOTORS' 1999, July

[6] In-Soung Jung, Sang-Baeck Yoon, Jang-Ho Shim Dong-Seok Hyun analysis of Forces in a Short Primary Type and a Short Secondary Type Permanent Linear Synchronous Motor IEEE Trans. Energy Conversion, Vol.14, No. 4, December 1999

[7] I.BOLDEA, S.A.NASAR Linear Motion Electro-magnetic Systems 1985

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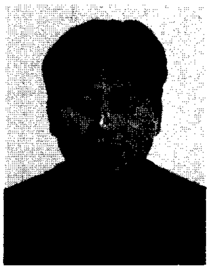

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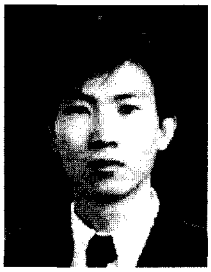

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