Comparison of two types of Permanent Magnet Linear Synchronous Motor with the Minimum Detent Force

Seok-Myeong Jang, Sung-Ho Lee and In-Ki Yoon

Abstract - Comparision on the performances between the Halbach array type permanent magnet linear synchronous motor (HA-PMLSM) and the convensional array type permanent magnet linear synchronous motor (CA-PMLSM) was made with finite element analysis (FEA) and experiment. The HA-PMLSM is seen to be superior to the CA-PMLSM. Optimum ratio of magnet length to slot pitch of the HA-PMLSM which reduces the detent force was determined. Also, Comparison of forces of the HA-PMLSM and the CA-PMLSM with minimum detent force is presented.
Keywords - Halbach Array, Conventional Array, Permanent Magnet Linear Synchronous Motor, Detent Force, FEA

1. Introduction

Permanent magnet linear synchronous motor (PMLSM) are widely used for factory automation, reciprocating serve system, conveyance system, transportation applications and so on [1]. The conventional array of permanent magnets has been used for these applications. In particular, to improve power efficiency, Halbach array type permanent magnets as a mover can be used for the short secondary (short permanent magnet poles) type linear synchronous motor. Halbach array does not require any ferromagnetic yoke and produces stronger magnetic flux density. It is closer to the sinusoids than the conventional array [2].

The detent force resulting in a thrust ripple is due to the interaction between the edge of permanent magnets and the primary slotted core of the PMLSM. Various techniques to reduce the detent force in the conventional array type PMLSM (CA-PMLSM) have been reported [3]-[5].

In this paper we present design criteria to reduce the detent force of the Halbach array type PMLSM (HA-PMLSM). Three steps are taken to apply Halbach array to the short permanent magnet poles type linear synchronous motor. Comparison of the characteristics such as the open-circuit magnetic field, detent force, static thrust, and normal force of the two types, HA-PMLSM and CA-PMLSM, is made by finite element simulation and experiments. We then determine the optimum permanent magnet size of the HA-PMLSM that gives a minimum detent force. Finally, comparison of forces of the HA-PMLSM and the CA-PMLSM with minimum detent force will be presented.

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2. PMLSM with Conventional Array and Halbach Array

2.1 Analysis Model

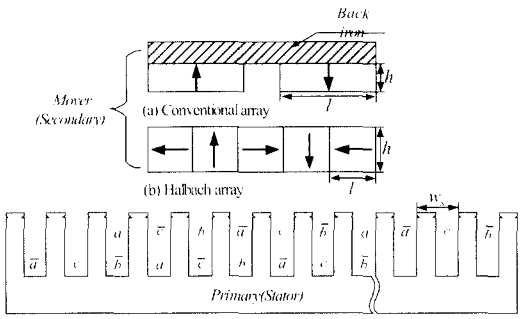


Fig. 1 PMLSM with (a) conventional array of PMs and (b) Halbach array of PMs

Fig. 1 shows models of CA-PMLSM and HA-PMLSM with the same configuration of the primary stator. The primary stator consists of a three-phase, double-layer, distributed and short-pitch winding with open slots. Permanent magnets used for the secondary mover are NdFeB with remnance 1.1 Tesla. The CA-PMLSM consists of a ferromagnetic yoke and permanent magnets magnetized in the nomal direction (perpendicular to the active surface) as shown in Fig. 1(a). The HA-PMLSM shown in Fig. 1(b) employs special arrays of permanent magnets (Halbach arrays) to give high magnetic efficiency. Here five permanent magnets as a set were used for 2-pole.

2.2 Finite Element Analysis of Two Types of PMLSM

2.2.1 Governing Equation:

The governing equation of HA-PMLSM is given by:

$$\nabla \times \nu(\nabla \times \vec{A}) = \vec{J}_0 + \nu_0(\nabla \times \vec{M}) \quad (1)$$

where $\vec{A}$ is the magnetic vector potential, ν denotes the reluctivity, $\vec{J}_0$ is the exciting current density and $\vec{M}$ is the magnetization of permanent magnet.

2.2.2 Thrust and Normal Forces:

The force acting on the machine is calculated by Maxwell stress tensor method. The thrust F_x and the normal force F_y are calculated as follows:

$$F_x = \frac{1}{2\mu_0} \int_s [(B_x^2 - B_y^2)n_x + 2n_y B_x B_y] ds \quad (2)$$

$$F_y = \frac{1}{2\mu_0} \int_s [(B_y^2 - B_x^2)n_y + 2n_x B_x B_y] ds \quad (3)$$

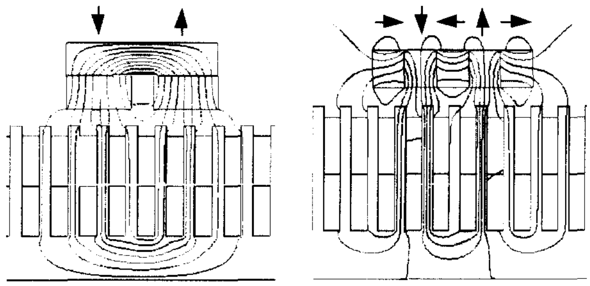
where s is the surface of integration, B is the magnetic flux density, n is the unit normal vector and μ_0 is the free-space permeability.

3. Comparision of HA-PMLSM and CA-PMLSM

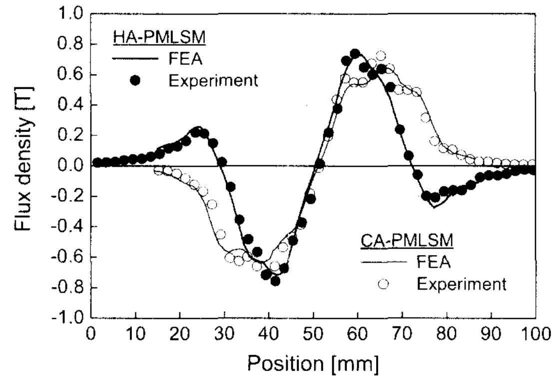
CA-PMLSM and HA-PMLSM have the permanent magnet length to slot pitch ratio, 2.353 and 1.176 respectively. They have the same primary configuration with open-slotted core, slot pitch 8.5 mm and air-gap 3 mm and the same permanent magnet width and height. The primary exciting phase current is 1 A.

Fig. 2 shows open-circuit magnetic fields. The magnetic field on the lower side of the Halbach array is enhanced while the magnetic filed on the upper side is almost cancelled as shown in Fig. 2(b). Therefore, in comparison with conventional array, the Halbach array has the kind of self shielding property on the upper side of the array and does not require any ferromagnetic yoke. Fig. 2(c) shows the air-gap magnetic flux density distribution in the normal direction. Since there are permanent magnets magnetized in the horizontal direction in the HA-PMLSM, it is seen that more magnetic fluxes are produced at the edges of the Halbach array set in comparison with the CA-PMLSM. Fig. 2(d) shows the flux density versus permanent magnet height to slot pitch ratio. It is seen that the flux density of the HA-PMLSM is larger than that of the CA-PMLSM for permanent magnet height/slot pitch ratio above 1.0.

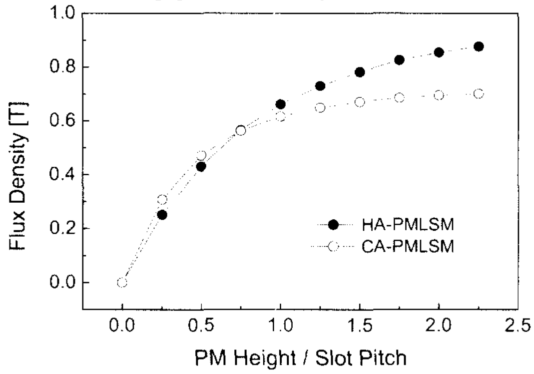
Fig. 3(a) shows detent force versus magnet position. The magnetic flux produced more at the edges of the Halbach array has a positive influence on the detent force. The detent force is periodic and repeats itself over every slot pitch. Fig. 3(b) shows static thrust as a function of load angle. Experimental data in Fig. 2 and Fig. 3 are shown to agree very well with numerical



(a) CA-PMLSM (b) HA-PMLSM



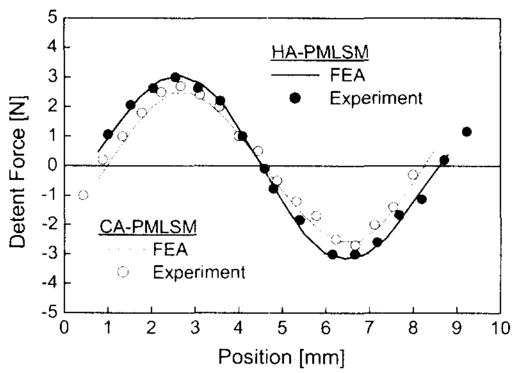
(c) Air-gap flux density distribution



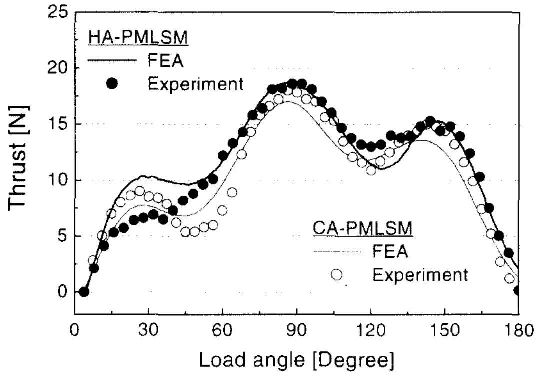
(d) Flux density vs. the ratio of PM height to slot pitch

Fig. 2 Comparison of open-circuit magnetic field

calculations. The detent force and thrust in Fig. 3 are seen similar in their values for both cases. However the thrust to mover weight ratio of HA-PMLSM is larger than that of CA-PMLSM by 1.8 times.



(a) Detent force vs. position



(b) Static thrust vs. load angle

Fig. 3 Comparison of the detent force and static thrust

4. Forces of HA-PMLSM due to the PM size and air-gap length

Fig. 4 represents the whole process to calculate forces due to the PM size and air-gap length of HA-PMLSM.

Fig. 5 represents the maximum detent force and the static thrust/normal forces as a function of air gap and permanent magnet length/slot pitch ratio. The width of the magnet is 50 mm. The detent force increases as the air-gap length decreases. It repeats pulsation and increases periodically in proportion to the magnet size as shown in Fig. 5(a). The detent force takes a minimum value when the ratio of magnet width to slot pitch is 1.22 and the air-gap length is 5 mm. Since the detent force influences thrust, the general trends according to air-gap and magnet length show similarity for both cases, as shown in Fig. 5(a) and (b). The normal force increases in proportion to the magnet size as shown in Fig. 5(c).

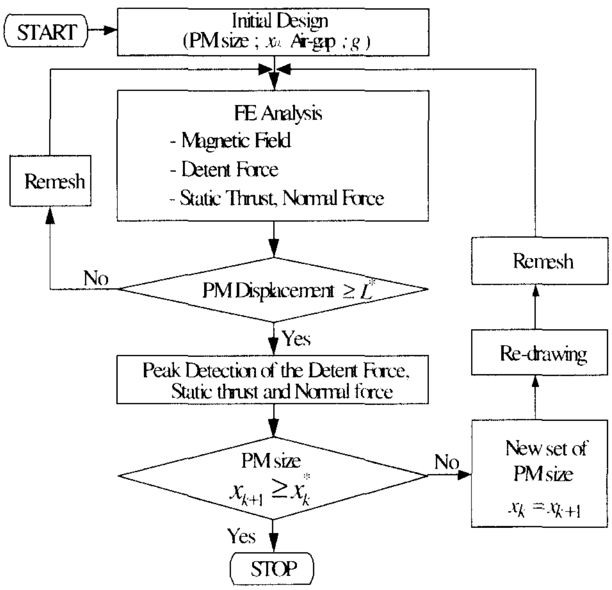
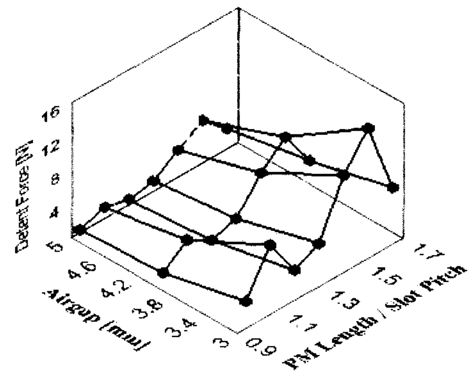
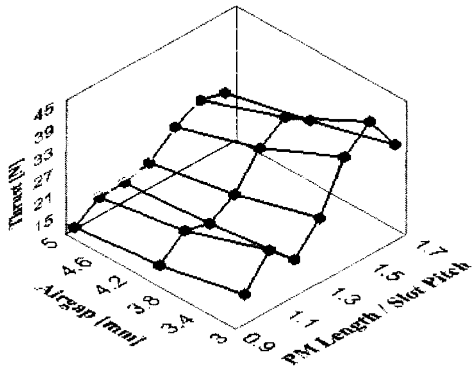


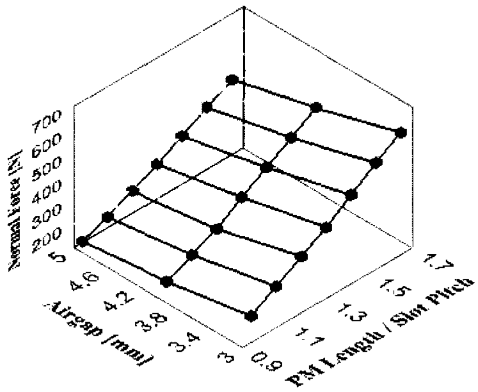
Fig. 4 Flow chart for calculating forces of HA-PMLSM



(a) Detent Force



(b) Static thrust



(c) Normal Force

Fig. 5 Force versus ratio of PM length to slot pitch and air-gap length

5. Comparison of Two Types of PMLSM with Minimum detent force

Various methods can be employed to reduce the detent force, namely, optimization of the magnet length, the use of semi-closed slots or magnetic slot edges and skewing. In our work, optimization of the magnet length is considered for detnet force reduction. The detent force produced by one edge of a magnet interacting with the primary slotted core can be 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 magnet length so that the two sinusoidal optimize the magnet length so that the two sinusoidal force waveforms of each edge cancel out one another [3].

The detent force of CA-PMLSM can be reduced by adjusting the ratio of PM length to slot pitch to 3.25, 4.25, 5.24 (n+0.25, where n is integer) [4].

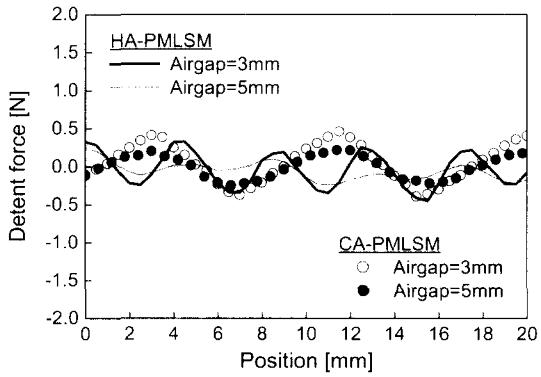
Under the constraint of a required thrust, PM length/slot pitch ratio of HA-PMLSM for the detent force reduction was determined from the FE simulation results shown in Fig. 5.

Size of permanent magnets which minimize the detent force are shown in Table. 1 for both cases. The detent force ripple/weight in Table. 1 refers to the difference between the maximum and the minimum values of detent forces. The magnet height and stack width are same for both cases. The optimized magnet length/slot pitch was 1.22 for HA-PMLSM and 2.25 for CA-PMLSM respectively. As shown in Table.1, the ratio of static thrust to the weight of the secondary mover for HA-PMLSM is larger than that for CA-PMLSM by 1.85 and 1.79 times at the air-gap 3 mm and 5 mm, respectively.

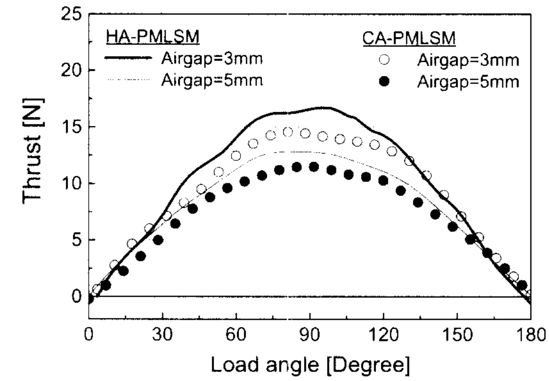
Fig. 6(a) shows minimized detent forces with magnet position. Both types show small fluctuations. Fig. 6(b) shows static thrust as a function of load angle. The maximum thrust for HA-PMLSM is larger than that for CA-PMLSM by about 15 %. Thrust and detent forces are compared in Fig. 7.

Table 1 PM sizes for detent force reduction and Force characteristics

Item \ Type	CA-PMLSM	HA-PMLSM
Height of PM [mm]	10.4	
Width of PM [mm]	50	
PM length / slot pitch	2.25	1.22
Air-gap length = 3 [mm]		
Detent force ripple / Mover weight [N/kg]	2.55	2.62
Thrust / Mover weight [N/kg]	44.35	82.05
Air-gap length = 5 [mm]		
Detent force ripple / Mover weight [N/kg]	1.47	1.63
Thrust / Mover weight [N/kg]	35.31	63.03



(a) Detent Force



(b) Static Thrust

Fig. 6 Forces of HA-PMLSM and CA-PMLSM with minimized the detent force

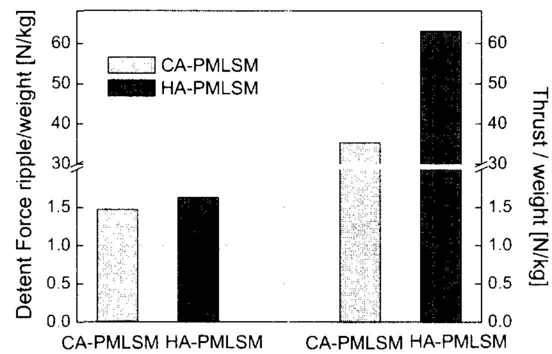


Fig. 7 Comparison of the force performance

6. Conclusion

Comparison between HA-PMLSM and CA-PMLSM was made by FE simulation and experiments. It was seen that the thrust to weight raito of the secondary mover of the HA-PMLSM is larger than that for the CA-PMLSM. The magnet size to minimize the detent force of the HA-PMLSM was determined. Detent force and thrust with minimum detent force are compared for both types. It was confirmed that the power efficiency of HA-PMLSM is higher than that of CA-PMLSM.

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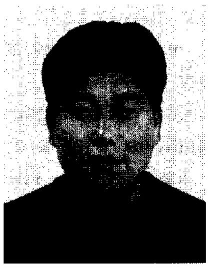

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