

# Proposal of short armature core double-sided transverse flux type linear synchronous motor

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**Abstract** — Linear motors have been a great interest from industries. Especially, linear synchronous motor that uses rare earth permanent magnets in the field side (PMLSM) has contributed to the popularization in industrial fields because of its high efficiency and compact size. However, the thrust force density could not be largely enhanced in conventional PMLSM due to the space competitions between the stator teeth and armature conductors. In recent years, the transverse flux PM-type linear synchronous motor has been researched as alternative because it can inherently offer high thrust density. The authors propose a short armature core double-sided transverse flux type PMLSM. In this paper, the concept and structure of the proposed model are introduced and its characteristics are both theoretically analyzed and numerically computed by field calculation using Finite Element Method (FEM).

**Keywords** — Linear synchronous motor, high thrust density, transverse flux type machinery, double-sided type.

## I. INTRODUCTION

Linear motors are being employed increasingly in industrial fields. Such direct devices offer many advantages over ball-screw drive, which result in a higher dynamic performance and reliability.

There are many types of linear motors including linear synchronous motor, linear induction motor and linear stepping motor etc. Especially, linear synchronous motor that uses permanent magnets (PMLSM) in the field side has contributed to the popularization in industrial fields because of the advent of rare earth permanent magnet [1].

In general, characteristics required to PMLSM in industrial fields are high thrust, high positioning accuracy and simple structure etc.

Especially, how to obtain high thrust density is one of the most significant investigation subject today. The transverse flux type machinery is an ideal alternative.

It has some advantages distinguished from other types of motors. Most importantly, there is no competition between the space requirement of flux carrying core irons and the space occupied by armature windings.

This increases the design flexibility compared with the longitudinal flux type machinery, in which there is a fundamental competition between the stator teeth and armature conductors. The other advantage of the transverse flux type machinery is that it can increase the

thrust density with increase in the pole number or decrease in the pole pitch in designated dimension.

However, conventional transverse flux type machinery has such complex manufacturing requirements that it is impractical for industrial production [2].

For that reason, the authors propose short armature core double-sided transverse flux type PMLSM. In this paper, the concept and structure of the proposed model are introduced and its characteristics are both theoretically analysed by magnetic circuit method and numerically computed by field calculation using FEM.

## II. BASIC STRUCTURE AND THE OPERATIONAL PRINCIPLE OF THE PROPOSED MODEL

Fig. 1 shows fundamental configuration of three-phase unit of the proposed model.

An armature unit consists of two armature core that has square shape, four armature coil in order to generate travelling field and non-magnetic material box.

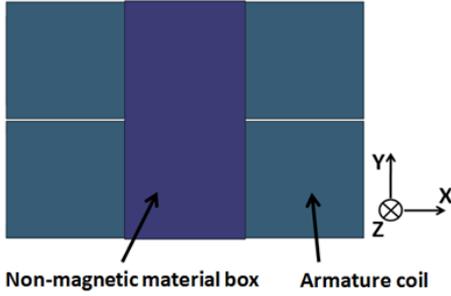
The square-shaped armature core has basically two salient poles and can be simply fabricated by laminated steel, which is a large improvement compared with conventional transverse flux machine that has complex structure. Also, it is simply inserted to non-magnetic material box, which results in simple assembly.

Four armature coils are wound around each salient pole as shown in Fig. 1 (a). Since it is enough to insert armature coils to each salient pole, armature core is not needed to be segmented in order to save space for winding. For that reason, simplification of components and easy production will be achieved.

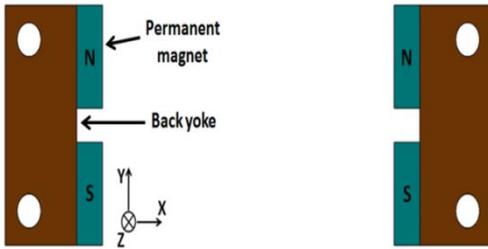
In the field side, an field unit consists of four magnets, two back yokes as shown in Fig. 1 (b). The back yoke can be also simply fabricated by laminated steel, which results in simple structure and manufacturing.

An magnetic circuit has achieved in the proposed model as shown in Fig. 1 (c) by inserting an armature unit to an field unit. The flux leakage can be reduced by placing field magnets on the surface of back yoke and a short air gap length. Also, the magnetic flux linking an armature coil is not reduced largely because the armature coils is closed to the field magnet. This short flux path can make motor more compactly and increase the back

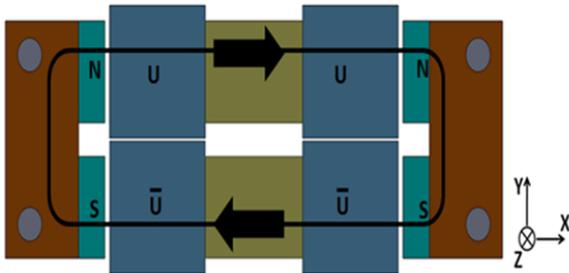
electromotive force, which results in an increase of a thrust density.



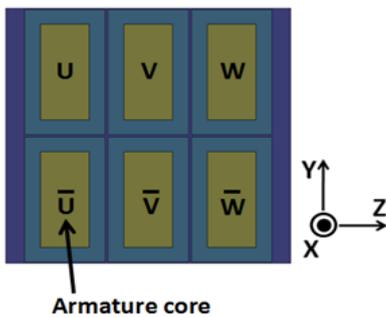
(a) An armature unit



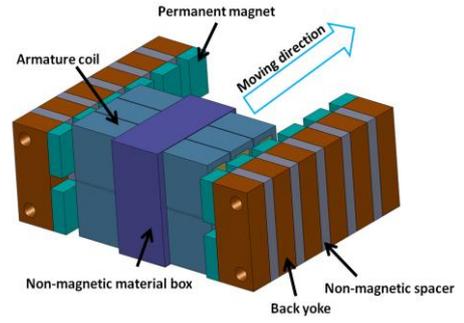
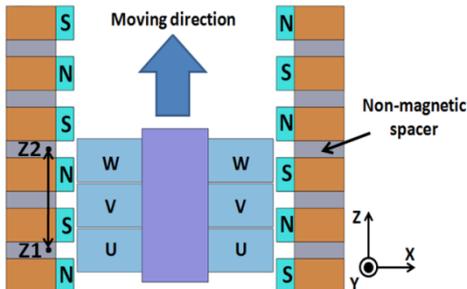
(b) An field unit



(c) An magnetic circuit



Armature core



(d) Configuration to the moving direction

Fig. 1. Fundamental configuration of three-phase units (Significant points in Fig. 1(d) are marked on the graphs in Fig. 6 and Fig. 7.).

Also, strong normal attractive force between the armature side and the field side can be cancelled in principle because of double-sided type structure.

In moving direction, armature cores are arranged to moving direction Z as shown in Fig. 1 (d). Each armature core is apart with 120 degrees spatially.

The back yoke is arranged to the moving direction Z with non-magnetic spacer and each magnet is apart with 180 degrees electrically. This non-magnetic material spacer between cores in the armature and field side can achieve magnetic separation of each core.

By adding AC current which has 120 degree phase difference to each armature core, the proposed motor drives as three-phase AC synchronous machinery. The distance between point Z1 and point Z2 in Fig. 1(d) is a mechanical period in the moving direction.

### III. THEORETICAL AND NUMERICAL EVALUATION OF THE FUNDAMENTAL CHARACTERISTICS IN THE PROPOSED MODEL

The authors have employed magnetic circuit method in order to conduct simple design and estimate fundamental characteristics theoretically [3].

In order to estimate characteristics of the proposed model simply, the authors have considered one magnetic circuit as shown in Fig. 2. Also, they assumed the permeability of armature and field cores are infinitely large.

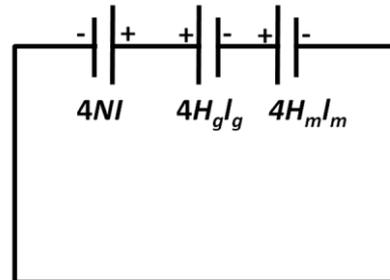


Fig. 2. Equivalent magnetic circuit considering an magnetic circuit.

The authors applied three-dimensional FEM analysis to the proposed model for rational verification of fundamental characteristics. Table I shows the materials used in FEM analysis and Fig. 3 represents the  $B$ - $H$  curves of 50JN230 [4]-[5].

TABLE I  
SPECIFICATION OF MATERIAL USED IN FEM ANALYSIS

Armature core	50JN230 (JFE-steel Corp.)
Field core	50JN230 (JFE-steel Corp.)
Permanent magnet	N50M (Shinetsu Chemical.) (NdFeB, $H_c$ :1092436A/m, $B_r$ :1.32T)
The current density of armature coil [A/mm <sup>2</sup> ]	7
The diameter of armature coil [mm]	0.804×0.804(conductor:0.7×0.7)

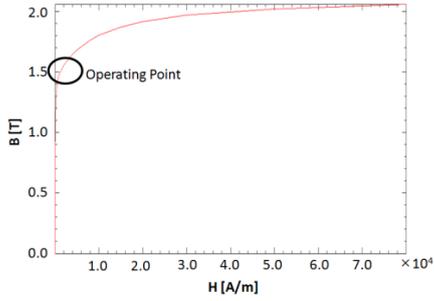


Fig. 3. B-H curve of 50JN230 (JFE Steel Corp.)

### 3.1 The air gap flux density

The air gap flux density  $B_g$  can be written as (1).

$$B_g = \frac{B_r}{\frac{A_g}{A_m} + \frac{\mu_0 g_c}{\mu_m l_m}} \left( 1 - \frac{NI}{H_c l_m} \right) \quad [\text{T}] \quad (1)$$

In (1),  $B_r$  is remanence of magnet and  $\mu_0$  is permeability of the air gap,  $H_c$  is the coercive force of magnet,  $g_d$  is the air gap length considered cater coefficient,  $l_m$  is the length of magnet,  $I$  is armature current  $A_m$ ,  $A_g$  are the dimension of magnet and air gap and  $N$  is the turn number of a winding of an armature pole.

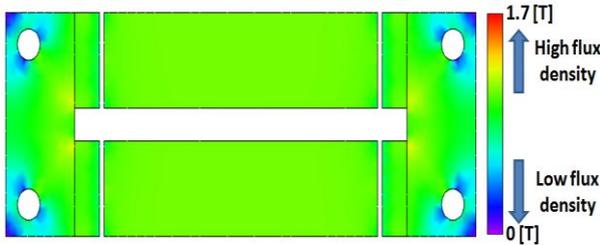


Fig. 4. Flux density distribution of the proposed model.

Fig. 4 shows one of the results of the flux density distribution in the proposed model at no load. In three-

dimensional FEM analysis considered saturation of core, the maximum flux density in the air gap was 1.068T. Also, the flux density is distributed in the overall region. It means that the occupancy ratio of iron core is high in the proposed model, which results in an increase of thrust density because of low wasted space.

Fig. 5 shows the comparison of the air gap flux density by moving an armature unit. The maximum air gap flux density in theoretical calculation was nearly the same with three-dimensional FEM value. Also, its wave form was nearly sinusoidal. From this result, the authors has decided the flux leakage coefficient  $k_l$  as 0.98.

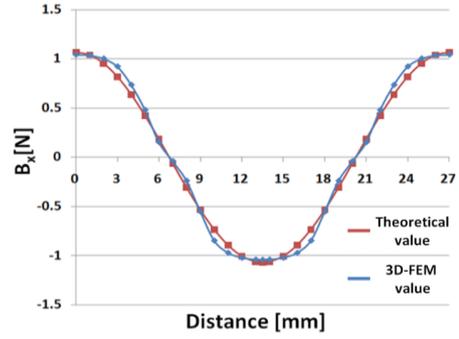


Fig. 5. The air gap flux density.

### 3.2 Detent force

With regard to calculation of detent force, the authors employed virtual work principle. Detent force of an armature unit can be expressed as (2).

$$\begin{aligned} F_{detent}(z) &= -\frac{dW}{dz} = -\frac{d}{dz} \left( \frac{B_g^2(z) V_g}{2\mu_0} \right) \\ &= \frac{k_l^2 B_g^2 \max \pi A_g g_d}{2\mu_0 \tau} \sin \left( \frac{2\pi z}{\tau} \right) = F_d \sin \left( \frac{2\pi z}{\tau} \right) \quad (9) \end{aligned}$$

In (2),  $V_g$  is the air gap volume. It is found that the period of detent force is the same with pole pitch  $\tau$  electrically.

The authors focused on slot-pole combination to reduce detent force because the authors had focused on simple structure, easy design and production. In the case of rotational synchronous machinery, the higher Least Common Multiple (LCM) of slot-pole is, the lower cogging torque can be achieved.

Since drive principle of linear synchronous machine is the same with that of rotational synchronous machine, the authors applied nine slot-eight pole combination to the proposed model in the stage of selecting numbers of armature cores and field poles [6]. Hence, nine armature cores are faced with eight magnets in a electric period.

The result of detent force in three-dimensional FEM analysis is shown in Fig. 6.

The maximum detent force considered three armature cores per one phase was 88.7N, which is nearly the same with the theoretical value considered the flux leakage coefficient  $k_l$ . The maximum value of total detent force considered nine slot-eight pole combination could be reduced to about 2.3N.

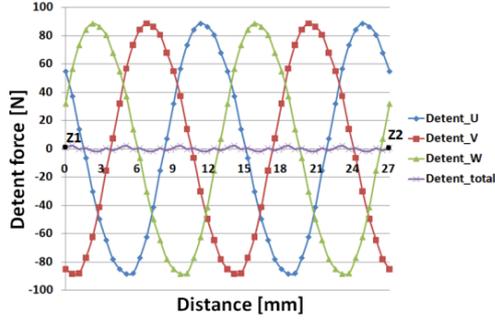


Fig. 6. Detent force.

### 3.3 Static Longitudinal Force

Static longitudinal force of an armature unit in the proposed model is (3).

$$\begin{aligned}
 F_{static}(z) &= \frac{k_f^2 B_{gmax}^2 \pi A_g g_d}{2\mu_0 \tau} \sin\left(\frac{2\pi z}{\tau}\right) \\
 &\quad + \frac{0.707 p \pi k_c k_t N I \phi_{gmax}}{\tau} \sin\left(\frac{\pi z}{\tau}\right) \\
 &= F_d \sin\left(\frac{2\pi z}{\tau}\right) + F_t \sin\left(\frac{\pi z}{\tau}\right) \quad [N] \quad (3)
 \end{aligned}$$

The first term is detent force expressed in (3) and the second one is thrust of the proposed model.

Thrust is proportional to the air gap flux  $\phi_{gmax}$ , applied magnetomotive force  $NI$  and inversely proportional to the pole pitch  $\tau$  in the proposed model.

In contrast with longitudinal flux machinery, increasing pole pairs in designated dimension results in a decreased pole pitch. This decreased pole pitch does not reduce the magnetic flux linking armature coil, which increases the back EMF with the rapid change of the flux for the same mover speed and results in drive as transverse flux type linear motor [7]. Hence, a higher thrust density can be achieved by optimizing pole pitch in the proposed model.

Fig. 7 shows the result of static longitudinal force considered three armature cores per a phase at 335AT.

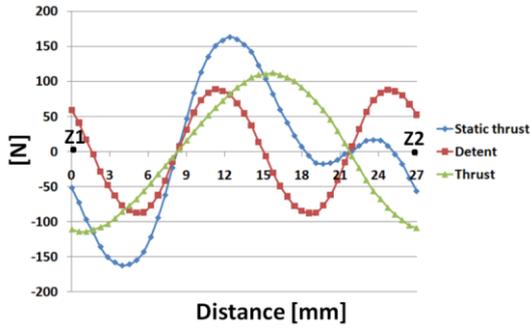


Fig. 7. Static thrust, detent force and thrust.

As shown in Fig. 7, the maximum value of static longitudinal force and thrust was 167.58N and 114.76N respectively. When considering nine slot-eight pole combination, the maximum value of thrust is 172.14N. In this point, detent force was 1.35% of total thrust, which

means a high positioning accuracy could be achieved in the core-typed proposed model. The main parameters for theoretical calculation and results of fundamental characteristics are shown in Table II.

TABLE II  
THE MAIN PARAMETERS FOR THEORETICAL  
CALCULATION AND RESULTS OF FUNDAMENTAL  
CHARACTERISTICS

An armature core size [mm]	59.2w×15h×7d
An field core size [mm]	15w×35h×9d
An magnet size [mm]	5.4w×15h×9d
The flux leakage coefficient $k_f$	1
Pole pitch $\tau$ [mm]	13.5
The winding factor $k_c$	0.88
The number of magnetic circuits in an unit $p$	1
Moving velocity $v$ [m/s]	1
Magnetomotive force per an salient pole $NI$ [AT]	335
The air gap flux density at no load $B_g$ [T]	1.088
The air gap flux at no load $\phi_g$ [Wb]	$2.136 \times 10^{-4}$
The maximum detent force in an armature unit $F_d$ [N]	36.21
The maximum thrust in an armature unit $F_t$ [N]	41.44
The maximum thrust in 9core-8pole combination $F_{thrust\_max}$ [N]	178.98

### 3.4 Thrust density

The authors calculated thrust density based on the total volume, the total dimension, the total weight of magnet used in area in which thrust is generated and the total weight of mover included in coil mass, non-magnetic material. Rated thrust is used in calculation. Table III shows the thrust density in the proposed model.

TABLE II  
THE RESULTS OF THRUST DENSITY

The total volume [m <sup>3</sup> ]	$0.43 \times 10^{-3}$
The thrust density based on volume [N/m <sup>3</sup> ]	$279.47 \times 10^3$
The total dimension [m <sup>2</sup> ]	$8.64 \times 10^{-3}$
The thrust density based on dimension [N/m <sup>2</sup> ]	$13.91 \times 10^3$
The total weight of magnet [kg]	0.18
The thrust density based on weight of magnet [N/kg]	667.6
The total weight of mover [kg]	1.82
The thrust density based on weight of mover [N/kg]	65.9

#### IV. CONCLUSION

In this paper, short armature core double-sided transverse flux type PMLSM is proposed.

Also, its characteristics are theoretically calculated by magnetic circuit method and numerically analyzed by FEM. Especially, the details of the theoretical calculation allowed for simple design and understanding of the fundamental characteristics of the proposed model without complex calculation.

In this research, it is found that the proposed short armature core double-sided transverse flux type PMLSM has the following advantage.

- (1) High thrust density can be achieved by transverse flux type structure, low flux leakage, short flux path and high occupancy ratio of space.
- (2) A high positioning accuracy could be achieved in the core-typed proposed model by reducing detent force to 1.35% of thrust with nine slot-eight pole combination.
- (3) Strong normal attractive force between the armature side and the field side can be cancelled by applying double-sided type structure.
- (4) Simple structure, easy design and production can be achieved by employing the lamination of square-shaped iron core, non-magnetic material and easy winding work, which is a large structural improvement compared with conventional transverse flux machine.

Future work will involve an optimal design in order to balance the electric and magnetic loading. Also, further characterization of the prototype model through static and dynamic testing including thrust, thrust ripple and positioning accuracy shall be done.

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