Proposal of a novel flux-concentrated type transverse flux cylindrical linear synchronous motor for high thrust

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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. Among characteristics required to PMLSM in industrial fields, high thrust can be an important technical requirement to PMLSM when considering conveyance of heavy materials such as large glass.

The authors propose a novel flux-concentrated type transverse flux cylindrical linear synchronous motor to gain higher thrust. In this paper, the structure and operational principle of the proposed motor are described. Also, its fundamental characteristics are both theoretically analyzed and numerically computed by field calculation using Finite Element Method (FEM).

Index Terms **— Flux concentrated type field, Transverse flux-type motor, Linear synchronous motor, High thrust, 3-dimensional field calculation, Finite element method**

I. Introduction

Linear motors are being employed increasingly in industrial fields. Such direct devices offer many advantages over ball-skrew 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, which results in high efficiency and compact size.

In general, characteristics required to PMLSM in industrial fields are high thrust, high positioning accuracy and simple structure etc. Among these characteristics, high thrust can be an important technical requirement to PMLSM when considering conveyance of heavy materials such as large glass.

The authors propose a novel flux-concentrated type transverse flux cylindrical linear synchronous motor to gain higher thrust. In this paper, the concept and advantages of the proposed model are introduced and its characteristics are both theoretically analyzed and numerically computed by field calculation using FEM.

II. The Proposal of High Thrust by Flux Concentrated Type Field

2.1 Point of new motor design

In design, the authors considered main points as below.

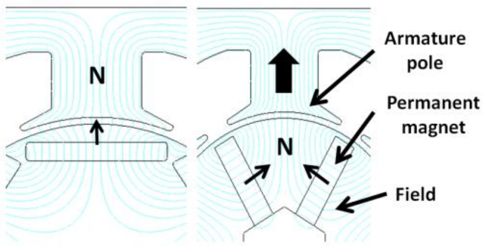
(1) High thrust, compact size, simple structure
(2) Low detent force
(3) Simple compatibility with conventional ball-skrew actuators
(4) Large 2nd moment of area, high bending stiffness
(5) Easy design and production
(6) Structurally compensated the normal attractive force

The authors decided to choose cylindrical shape from (3) and (4) and use generic armature cores for rotary machinery from (5) and (6) [1].

2.2 Concept of high thrust by flux concentration

The typical method to obtain higher thrust by concentrating flux to the air gap is Halbach array. In Halbach array, high thrust can be obtained by changing the direction of magnetization [2].

However, using Halbach array in the proposed model is not relatively effective because strong adhesive and equipment to attach and fix magnets are needed. This results in an increasing cost and can be a burden in the manufacturing stage. For that reason, the authors propose a new method of concentrating flux to the air gap. This concept is shown in Fig. 1.



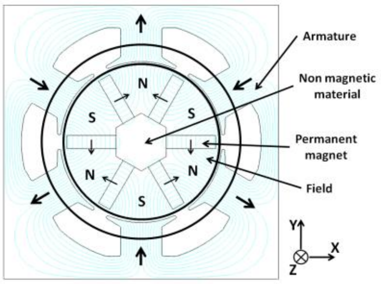
(a) The reference model (b) The proposed model

Figure 1: The concept of flux concentration.

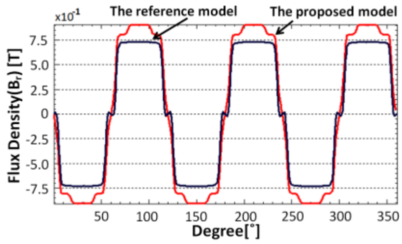
The concept of flux concentration is relatively simple. In the reference model, one permanent magnet makes one magnetic pole in PMLSM as shown in Fig. 1(a). The authors thought that flux could be concentrated to the air gap as simple form when magnets with same magnetic pole are faced each other. In other words, one magnetic pole can be made by two magnets. By facing each other, magnetic field lines from each magnet are concentrated in the field side and then they pass through the air gap and the armature side as shown in Fig. 1(b). Hence, higher thrust can be obtained.

If this concept can be realized, higher thrust could be obtained using the same amount of the magnet or less than the reference model in Fig. 1(a). Also, strong adhesive and equipment to attach or fix magnets are not needed because it is enough to insert magnets in holes of laminated steel plate. For that reason, low manufacturing cost and easy production will be achieved. To verify the effectiveness of the idea of flux concentration, the authors applied two-dimensional FEM field calculation to the cross-section of the proposed model and the reference model. One of the results is shown in Fig. 2.

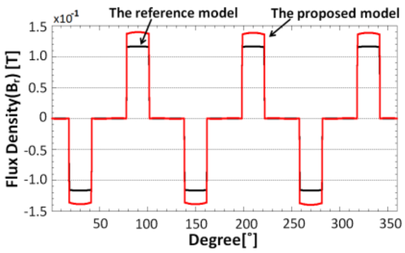
The normal attractive force between armature core and magnets can be compensated by the six balanced magnetic circuits as shown in Fig. 2(a). Hence, strong support mechanism to withstand the normal attractive force as in the case of single-sided PMLSM is not required.



(a) Flux distribution



(b) Air gap flux density (Marked as circle on the armature side in Fig. 2(a).)



(c) Flux density in armature (Marked as circle on the air gap in Fig. 2(a).)

Figure 2: Flux distribution of the cross-section and flux density of air gap and armature pole in the proposed model.

The maximum flux density in the air gap increased to 0.902T in comparison with the reference model which the maximum air gap flux density is 0.734T in the case of using the same amount of the magnet as shown in Fig. 2(b). This is increase of 22.89%.

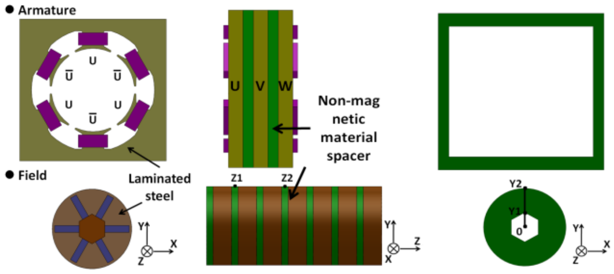
Also, the maximum flux density in the armature pole increased to 1.39T in comparison with the reference model which the maximum flux density in the armature pole is 1.168T as shown in Fig. 2(c). This is increase of 18.74%. For that reason, the possibility of high thrust is verified through the proposed idea.

III. Basic Structure and The Operational Principle of The Proposed Model

In the armature side, generic armature cores of brushless DC motor are used. One armature core has six salient poles and armature coils are wound around each salient pole as shown in Fig. 3(a).

Since generic armature cores for rotary machinery are used in the armature side, it is not necessary to consider new shape of armature core in the stage of new motor design. Hence, time and a burden to design a shape can be saved.

Multiple phase poles of the proposed model consist of multiple armature cores arranged to moving direction Z with non-magnetic material spacer as shown in Fig. 3(b) and Fig. 3(c). These arranged multiple armature cores with multiple phase coils make travelling field as a transverse flux type linear motor, whose substantial advantage includes large thrust at a low speed drive without large leakage of magnetic flux [3].



(a) The front side (b) The moving direction side (c) Non-magnetic material spacer

Figure 3: Fundamental configuration of three-phase units of the proposed model (Significant points in Fig. 3 are marked on the graphs in Fig. 4, Fig. 6 and Fig. 7.).

This cylindrical structure realizes relatively large second moment of area, *i.e.*, the field side is mechanically robust to bending external force. The distance between point Z1 and point Z2 shown in Fig. 3(b) is one mechanical period in the moving direction. Also, the distance between point Y1 and point Y2 shown in Fig. 3(c) is the length of non-magnetic material spacer in the y-direction.

IV. Theoretical and Numerical Calculation of the Proposed Model

In the initial design, the authors employed magnetic circuit method in order to estimate characteristics of the proposed model theoretically. And then, the authors analyzed of the proposed model using FEM method

4.1 Detent Force

Detent force of one armature core in the proposed model is

$$F_{detent} = \frac{k_l^2 B_g^2 R L \pi^2 g_d}{6\mu_0 \tau}\sin\left(\frac{2\pi z}{\tau}\right) \text{ [N]} \qquad (1)$$

where B_g is the maximum value of air gap flux density, k_l is flux leakage coefficient, g_d is air gap length, μ_0 is permeability of the air gap, R is the length from the center of the field side to air gap, L is the length of magnet to moving direction, τ is pole pitch, and z is the distance to moving direction.

The reduction of detent force in PMLSM is one of the most important factors required in industrial fields and this can affect to high positioning accuracy. Many methods to reduce detent force in PMLSM have been reported included in skewing, semi-closed slots and magnet length optimization etc. However, these methods can be a burden in the manufacturing stage and sometimes affect to manufacturing cost.

The authors focused on slot-pole combination to reduce detent force. In general, the higher Least Common Multiple (LCM) of slot-pole is, the lower cogging torque can be achieved in the case of rotational synchronous machinery. For that reason, nine slot-eight pole combination is usually employed in rotational synchronous machinery [4].

Nine slot-eight pole combination was applied to reduce detent force and achieve high positioning accuracy in the stage of selecting numbers of armature cores and field poles. Detent force of the proposed model in three-dimensional FEM analysis is shown in Fig. 4.

The maximum value of detent force could be reduced to about 2N when three armature cores moved in one mechanical period which is the distance from point Z1 to point Z2 as shown in Fig. 3 (b) and its wave form was nearly sinusoidal.

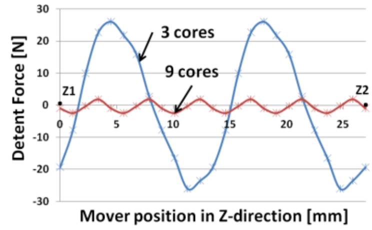


Figure 4: Detent force of the proposed model.

4.2 Static Longitudinal Force

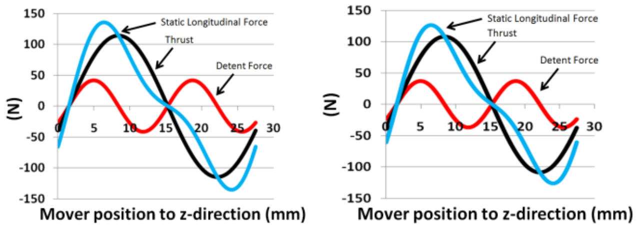
Static longitudinal force of one armature core in the proposed model is

$$F = \frac{k_l^2 B_g^2 R L \pi^2 g_d}{6\mu_0 \tau}\sin\left(\frac{2\pi z}{\tau}\right) + \frac{p\pi v N I k_l \emptyset_{gmax}}{\tau}\sin\left(\frac{\pi z}{\tau}\right) \text{ [N]} \qquad (2)$$

where N is the number of winding, $\emptyset_{gmax}$ is the maximum value of air gap flux, I is armature current, v is the moving velocity, p is the number of pole pairs.

The first term is detent force expressed in (1) and the second one is thrust of the proposed model. It is found that only detent force exists when I is 0. Also, increasing p in designated dimension results in a decreased pole pitch and thus the thrust will increase, which is one of the advantages of transverse flux type linear motor. Hence, a higher thrust density can be achieved by optimizing p in the proposed model.

This theoretical results of the proposed model and the reference model considered 3 cores in I = 5A, N = 50 turns is shown in Fig. 5.



(a) The proposed model (b) The reference model

Figure 5: The theoretical value of static longitudinal force, detent force and thrust.

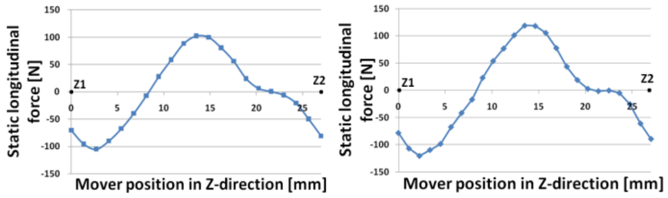
As shown in Fig. 5(a), the maximum value of static longitudinal force was about 135.52N and that of detent force and thrust were 41.42N and 114.46N respectively in the proposed model. Also, the maximum value of static longitudinal force was about 126.29N and that of detent force and thrust were 36.81N and 108.24N respectively in the reference model. Especially, static longitudinal force was increase of 7.09% in the same condition. The main characteristics based on theoretical values in the proposed model are shown in Table I.

4.3 Evaluation of static longitudinal force using FEM

In three-dimensional FEM analysis of the proposed model and the reference model, the authors considered three armature cores because it took extensive amount of time to analyze the whole model. One of the results in I = 5A, N = 50 turns is shown in Fig. 6.

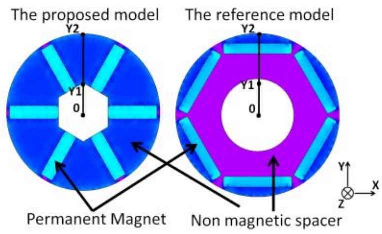
The maximum static longitudinal force of the proposed model was 102.3N and that of the reference model in the same condition was 119.2N in one mechanical period.

The authors expected that a higher static longitudinal force could be obtained because the air gap flux density of the proposed model was higher than that of the reference model in theoretical analysis. However, it was found that thrust of the proposed model would be lower than that of the reference model from the result of three-dimensional analysis. This is because of the flux leakage. This means the strong flux from faced magnets flows into not the air gap but non-magnetic material spacer because of a higher magnetic reluctance of the air outside the field side. Hence, its leaked flux cannot contribute to generate thrust. The flux density distribution in non-magnetic material spacer and of each model is shown in Fig. 7. From the result of the flux density between point Y1 and point Y2 in Fig. 7, it was found that the amount of flux leaking to non-magnetic material spacer in the proposed model was relatively higher than that in the reference model.

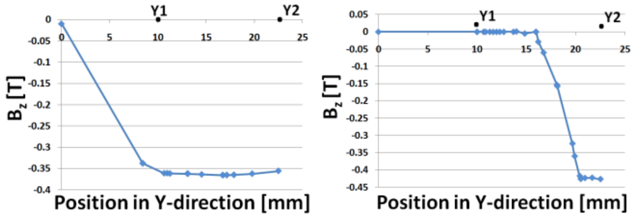


(a) The proposed model (b) The reference model

Figure 6: Static longitudinal force of each model.



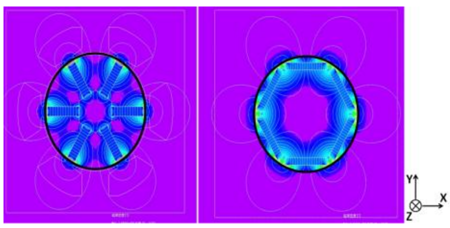
(a) The flux density distribution



(b) The proposed model (c) The reference model

Figure 7: The flux density in non-magnetic material spacer.

Also, flux distribution without armature core is crucial factor of generating thrust because linear motor is moving by attractive and repulsive force between moving field and the field magnets and not always facing the armature side with the field side like as rotational synchronous machinery. The flux density distribution without the armature side is shown in Fig. 8.



(a) The proposed model (b) The reference model

Figure 8: The flux density distribution without the armature side (The circle is an air gap section.).

When the armature side is located above the field side, the flux from field magnets flows to the armature core because of low magnetic reluctance of the armature core. Also, the air gap flux density of the proposed model and the reference model was respectively 0.7605T and 0.7164T which values are based on three-dimensional FEM analysis. However, as shown in Fig. 8, the flux distribution outside field in the proposed model is lower than that in the reference model. This means attractive force by field magnets laid in front of armature core is low.

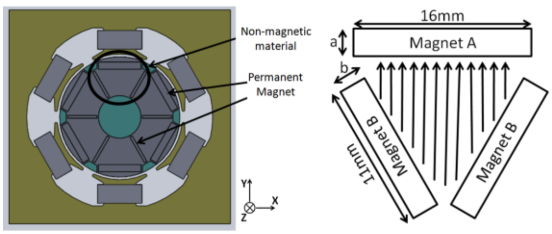
Table I the main characteristics of the proposed model

1 armature size [mm]	1 field size [mm]	1 magnet size [mm]
80w × 80h × 7d	22.5r × 10d	14.3w × 3.8h × 10d
Winding turn N [turns]	Armature current I [A]	Air gap length g_d [mm]
50	5	1.27
Slot-pole combination	Pole pitch τ [mm]	Slot pitch [mm]
9-8	13.5	12.5
Air gap flux density B_g(max) [T]	*Effective air gap flux density B_g(max) [T]	Flux leakage coefficient k_l
0.92	0.76	0.826

* is based on three-dimensional FEM analysis

V. OPTIMIZATION OF THE FIELD MAGNET CONFIGURATION FOR REDUCING LEAKAGE FLUX

In order to reduce flux leakage and concentrate flux from magnets into the air gap, the authors had to change the configuration of the field magnet. The revised model is shown in Fig. 9.



(a) The cross-section (b) Magnetization (Marked on circle in Fig. 9(a))

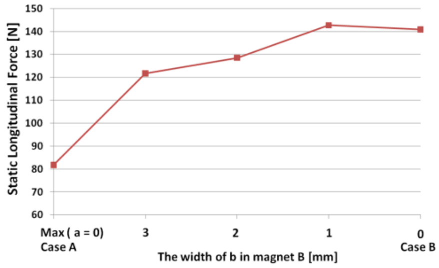
Figure 9: The revised model

In the revised model, the magnet A in Fig. 9(a), magnet configuration of the reference model is added to the proposed model in order to reduce the flux leakage to non-magnetic spacer.

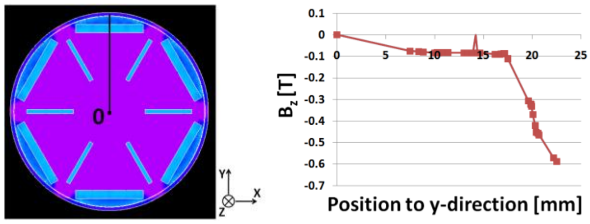
The width of magnet A and magnet B is 16mm, 11mm respectively considered spatial restriction and structural stiffness but the amount of magnets in one field unit is 2,916 mm^3 the same with the previous model and the reference model.

In order to find the magnet size by varying height a, b in magnet A, B and figure out an effect of static longitudinal thrust by flux-concentration, the authors applied three-dimensional FEM analysis to the revised model. If the total amount of magnet A and magnet B is fixed, b is varying with a under the same amount of magnets and the static longitudinal force is also varying. This result is shown in Fig. 10.

In the case A in Fig. 10(a), width a is 0, i.e the magnet configuration in the proposed model. Also, width b is 0 in the case B which is the magnet configuration in the reference model. From the result considered three armature cores, the maximum static longitudinal force could be increased to 142N when width a and b was 1mm and 0.306mm respectively. Also, the flux density leaking to non-magnetic material spacer was decreased as shown in Fig. 10(b). However, this is mainly considered as the effect of magnet A rather than magnet B. The smaller the amount of the magnet A is, the smaller static longitudinal force is obtained.



a) The flux density distribution



(a) The flux density distribution in non-magnetic material spacer (b) The flux density in non-magnetic material spacer

Figure 10: Static longitudinal thrust by varying magnet width and the flux density in the maximum point.

VI. CONCLUSION

In this paper, a novel flux-concentrated type transverse flux cylindrical linear synchronous for high thrust motor is proposed. Also, its characteristics are theoretically calculated and numerically analyzed by FEM. By facing magnet each other, magnetic field lines from each magnet are concentrated simply. Also, the normal attractive force can be cancelled and design becomes easy by using generic armature cores for brushless DC motor.

In FEM analysis, detent force was reduced to about 2N by nine slot-eight pole combination. However, in spite of our initial expectation, a higher thrust was not obtained by the proposed model because of the flux leakage in non-magnetic material spacer. In the revised model, the authors considered the magnet configuration that the reference model is added to the proposed model in order to reduce the flux leakage to non-magnetic spacer.

Although the flux leakage to non-magnetic material spacer could be reduced, the increase of static longitudinal thrust was only 1.4% compared with the reference model. This result could not reach to our initial expectation that higher thrust could be obtained. Therefore, it is found that careful design of magnetic circuit for avoiding the flux leakage in cylindrical type linear synchronous motor is important in order to realize the advantages of the proposed idea.

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