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Levitation and Thrust Forces Analysis of Hybrid-Excited Linear Synchronous Motor for Magnetically Levitated Vehicle

Han-Wook Cho*, Chang-Hyun Kim, Hyung-Suk Han** and Jong-Min Lee†**

Abstract – This paper proposes a hybrid-excited linear synchronous motor (LSM) that has potential applications in a magnetically levitated vehicle. The levitation and thrust force characteristics of the LSM are investigated by means of three-dimensional (3-D) numerical electromagnetic FEM calculations and experimental verification. Compared to a conventional LSM with electromagnets, a hybrid-excited LSM can improve levitation force/weight ratios, and reduce the power consumption of the vehicle. Because the two-dimensional (2-D) FE analysis model describes only the center section of the physical device, it cannot express the complex behavior of leakage flux, which this study is able to predicts along with levitation and thrust force characteristics by 3-D FEM calculations. A static force tester for a hybrid-excited LSM has been manufactured and tested in order to verify these predictions. The experimental results confirm the validity of the 3-D FEM calculation scheme for the description of a hybrid-excited LSM.

Keywords: Hybrid-excited linear synchronous motor, Magnetically levitated vehicle, Finite element method, Levitation force, Thrust

1. Introduction

Linear synchronous motors (LSMs) used in magnetically levitated (MAGLEV) vehicles are classified into two types on the basis of field location: short-primary LSM and long-primary LSM. Furthermore, there are two sub-types according to the source of the magnetic field. One utilizes electromagnets with iron-cores ("German-TRANSRAPID") and the other uses superconducting magnets with air-cores ("Japanese-MLX") [1].

In this study, we analyzed the characteristics of a linear synchronous motor (LSM) containing hybrid-excited electromagnets. The geometry of the LSM is characterized by hybrid-excitation, which combines the high-energy density of permanent magnets and the controllability of easily implemented electrical excitation. The hybrid-excited LSM has several advantages such as an increased levitation airgap height, a decrease in the total weight of the vehicle, and a large improvement in thermal conditions [2, 3].

The effective electric-gap of a hybrid-excited LSM is very large; the gap includes the height of the permanent magnet with the permeability of air and a large slot for the stator. Moreover, because the device is a three-dimensional (3-D) model and the leakage flux shows complex behavior, a detailed investigation involving 3-D electromagnetic field calculations are required. Therefore, the 3-D finite-element method (FEM) is used to calculate the levitation force and thrust so as to avoid calculation errors [4, 5].

The aim of this study is to investigate the levitation force and thrust characteristics of a hybrid-excited LSM with 3-D FEM. The results are compared to the measured data, which were obtained using an experimental device designed for the measurement of the static force characteristics of the hybrid-excited LSM. The feasibility of the hybrid-excited LSM for maglev vehicles is confirmed by testing the levitation force and the thrust.

2. Structure of Hybrid-Excited Linear Synchronous Motor

The hybrid-excited LSM is composed of a laminated rail/translator side core structure, high-performance permanent magnets, and DC-excited (control current carrying) coils [6]. Fig. 1 shows the detailed structure of the proposed hybrid-excited LSM. In the long stator on the ground, large slots were designed to allow the installation of copper or aluminum waveform coils. This device stabilized by an attractive force produced by strong permanent magnets, which are mounted on the translator core. In order to achieve stable levitation, the permanent magnet's flux must be modulated by the DC-excitation coil surrounding the permanent magnets.

† Corresponding Author: Dept. of Magnetic Levitation and Linear Drive, Korea Institute of Machinery and Materials (KIMM), Korea. (lee_jm@kimm.re.kr)
* Dept. of Electric, Electronic and Communication. Eng. Edu, Chungnam National University, Korea. (hwcho@cnu.ac.kr)
** Dept. of Magnetic Levitation and Linear Drive, Korea Institute of Machinery and Materials (KIMM), Korea. (chkim78@kimm.re.kr, hshan@kimm.re.kr)
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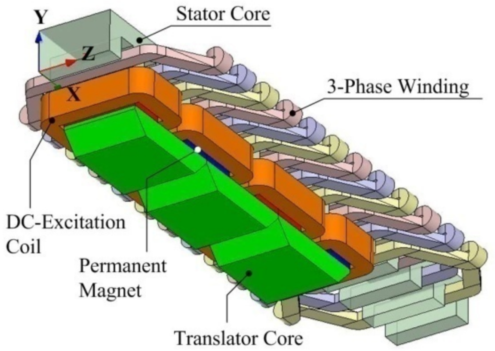


Fig. 1. Hybrid-excited linear synchronous motor for magnetically levitated vehicle.

The steel cores (long-stator and translator) are laminated so as to reduce the effects of eddy currents within them.

The specifications of the permanent magnet are selected to allow levitation without any added electric power at a desired airgap. The computer model uses the same-scale of physical dimensions as those used for the practical analysis and experiments. Table 1 lists the specifications and design parameters of the hybrid-excited LSM.

Table 1. Specification and Design Parameters of Hybrid-Excited LSM

Translator Part		Long-Stator Part	
Item	Value	Item	Value
Pole Pitch	312 mm	Pole Pitch	300 mm
Stack Length	200 mm	Stack Length	200 mm
Coil Turns	112 turns	Coils Turn	80 turns
PM Height	25 mm	Slot Height	65 mm
PM Width	200 mm	Slot Width	50 mm

3. Magnetic Field Analysis using 3-D FEM

In order to evaluate the basic characteristics of the hybrid-excited LSM, 3-D FEM is used to analyze both magnetic field distributions and static forces. The calculation mesh of the 3-D model is shown in Fig. 2. The model is composed of 211,246 tetrahedral elements. In the 3-D FEM calculation, a commercial FEM package named "Ansys Maxwell" was used.

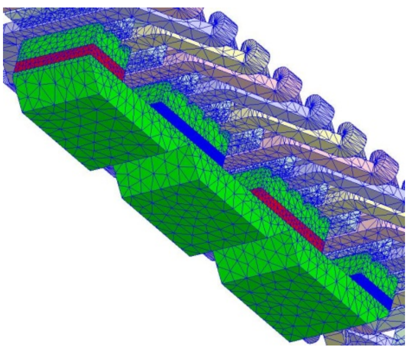
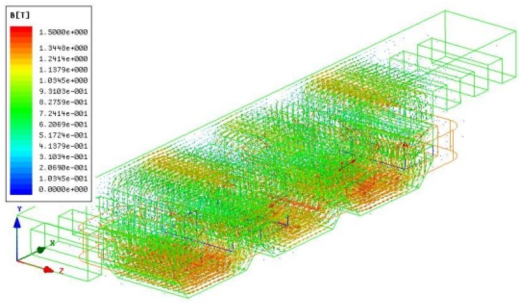


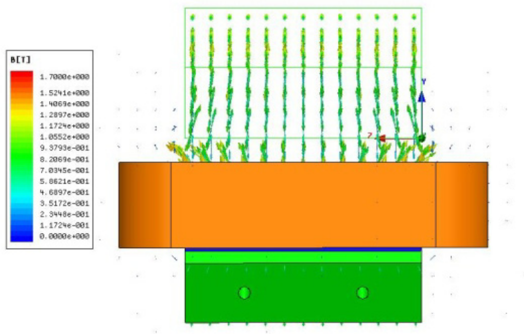
Fig. 2. Three-dimensional FEM model and calculation mesh.

The computing time and the achievable error limits are important evaluation criteria of our 3-D simulation. In order to get useful results with small errors, the airgap of the machine must be at least divided into 3 layers [5].

Fig. 3 shows the magnetic flux vector distribution in the stator and translator cores when there is no armature current and no DC-excitation current for an airgap height of 20 mm. There is a large leakage flux linking with the translator core in the lateral edge region. This lateral flux may lead to the errors that arise in two-dimensional FEM calculations [6].



(a)



(b)

Fig. 3. Magnetic flux vector distributions: (a) isometric view; (b) y-z plane view.

Fig. 4 shows the 3-D normal flux density distribution of the translator core and permanent magnets when the DC-

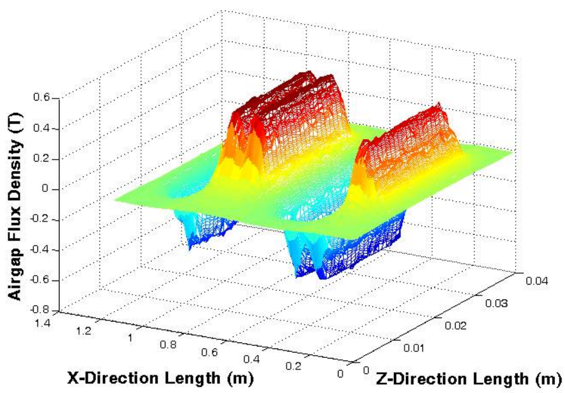


Fig. 4. Airgap flux density distributions (airgap = 20 mm)

excitation current is 0 A. The normal flux density is approximately 0.50 T at the center of the translator, and 0.22 T at the lateral edge.

Fig. 5 shows the airgap flux density distributions for three different values of the DC-excitation current (0 A, +40 A, and -40 A). Owing to the topology of the device, the airgap flux density distribution is non-sinusoidal and contains significant harmonic content. As seen in the figure, the magnitude of the normal flux density is weakened or strengthened depending on the direction of the DC-excitation current. The maximum value of the normal flux density is 0.63 T with a 20-mm airgap between the long-stator and translator cores. The minimum value of the normal flux density is 0.37T.

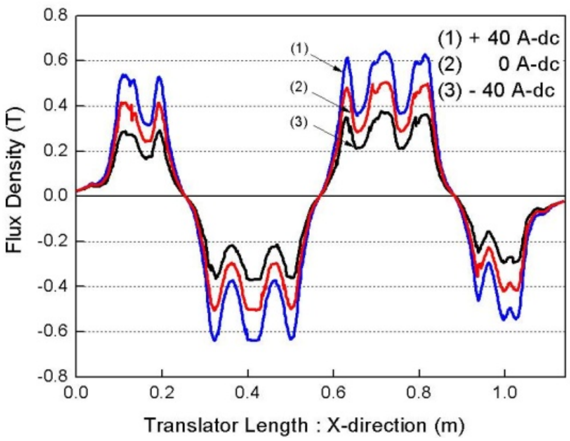


Fig. 5. Airgap flux density distributions according to three different DC- excitation currents.

In order to scale the level of flux control of the hybrid-excited LSM, the flux control coefficient α, is changed, as defined in (1) [7].

$$\alpha = \frac{B_\delta - B_{\delta 0}}{B_{\delta 0}} \times 100\% \tag{1}$$

where $B_{\delta 0}$ is the flux density of the airgap without the DC field current, and B_δ is the flux density with an applied DC field current. Fig. 6 illustrates the flux control capability versus DC-excitation field magneto-motive force (MMF). It can be seen from Fig. 6 that a relatively wide range of flux control can be achieved with a reasonably small variation in DC-excitation current. When a variation of ±40 A is applied, the flux control (with no load) ranges from roughly 27.4% in the flux-boosting mode (high-levitation force) to -27.6% in the flux-weakening mode (low-levitation force). Moreover, the figure shows the magnetic saturation present when the model operates with a positive DC-excitation current. The flux control capability of the machine is decreased by approximately 2.8% when the device operates at a +40 A DC-excitation current.

For practical maglev applications, armature turns per

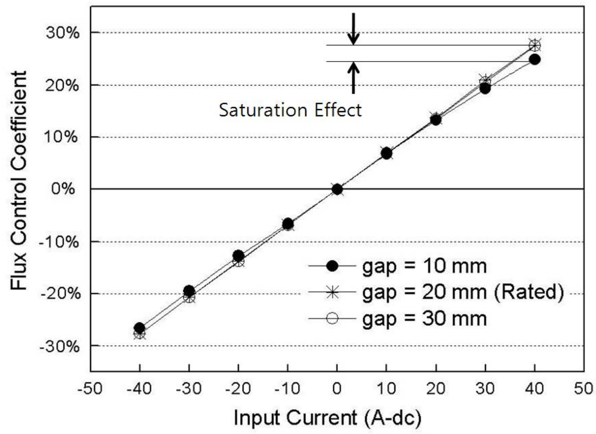


Fig. 6. Flux control capability at different DC field ampere turns.

slot is restricted to single-turn coils carrying a few thousands of amperes [8]. In order to implement a force test device with 3000-ATmax armature current, a device with 80 turns per slot and 37.5-Amax armature current has been developed. Fig. 7 shows the flux linkage of three-phase windings versus translator position with no load and no DC-excitation current. The figure shows the results of both the practical 1- turn per slot model and the experimental 80- turns per slot model.

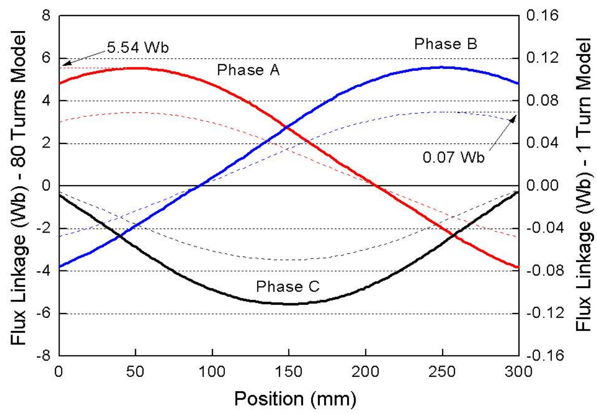


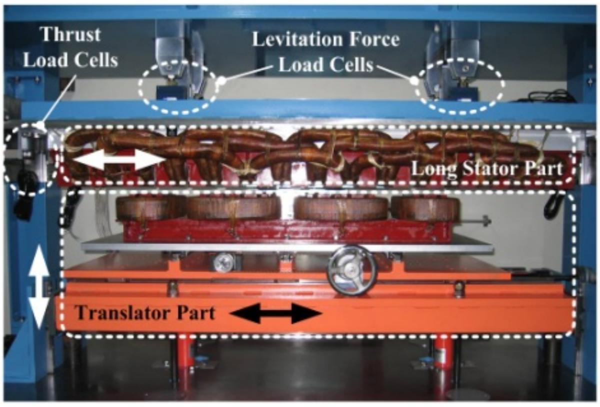
Fig. 7. Flux linkage of armature windings.

4. Force Analysis and Experimental Results

4.1 Static force tester for hybrid-excited LSM

In order to verify the modeled force characteristics, a static test facility for hybrid-excited LSM has been designed and manufactured. Fig. 8(a) shows the manufactured static force tester for hybrid-excited LSM. Fig. 8(b) shows the levitation and propulsion part of the system and its 3-DOF (degrees of freedom) structure and load cells. The hybrid-excited electromagnet has a levitation force of 8.77 kN at a 20-mm airgap. The LSM has a thrust force of 1.44 kN when operating at 3000- AT armature current. Table 2 lists the detailed system specifications including electrical parameters and the permanent magnet material.

(a)



(b)

Fig. 8. Static force tester for hybrid-excited LSM: (a) System overview; (b) Levitation and propulsion part.

Table 2. Specification of Static Force Tester for Hybrid-Excited LSM

Item	Value
Levitation Force	8.77 kN (at g = 20mm)
Thrust	1.44 kN (with 3000 AT)
Translator Coil Resistance	529.4 mΩ
Translator Coil Inductance	28.63 mH
Armature Coil Resistance	278.9 mΩ
Armature Coil Inductance	14.52 mH
PM Material	NdFeB (N40SH)

4.2 Magnetic field and static force characteristics

In this paper, the levitation and thrust forces, $f_{Levitation}$ and f_{Thrust}, are obtained using the Maxwell stress tensor as following [9]

$$f_{Levitation} = \frac{1}{2\mu_0}\left(B_y^2 - B_x^2\right) \quad (2)$$

$$f_{Thrust} = \frac{1}{\mu_0}\left(B_y B_x\right) \quad (3)$$

where B_y is normal magnetic flux density for y-direction to the integral surface, B_x is the tangential magnetic flux density for x-direction to the integral surface.

For different values of DC-excitation current from -40 A to 40 A, the maximum airgap flux density versus the current is shown in Fig. 9. It can be seen that the value of airgap flux density varies from 0.28 T(at -40 A, g = 30 mm) to 1.00 T (at +40 A, g = 10 mm).

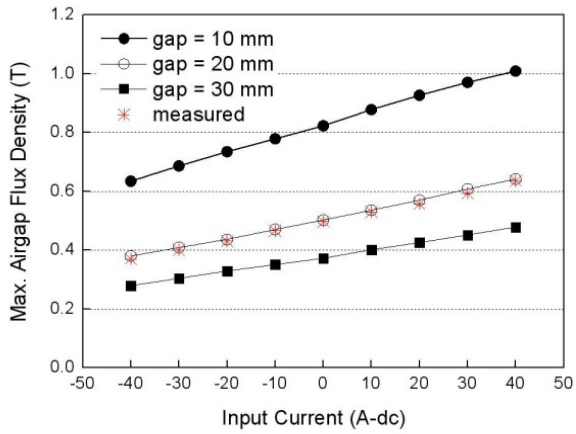


Fig. 9. Airgap flux density vs. DC-excitation current as a parameter of airgap.

Fig. 10 shows the levitation force as a function of the airgap length and input DC-excitation current. It can be seen that the rated airgap is 20 mm for a rated load of 880 kg at zero current. In addition, the figure shows the comparison between experimental and 3-D FEM calculations.

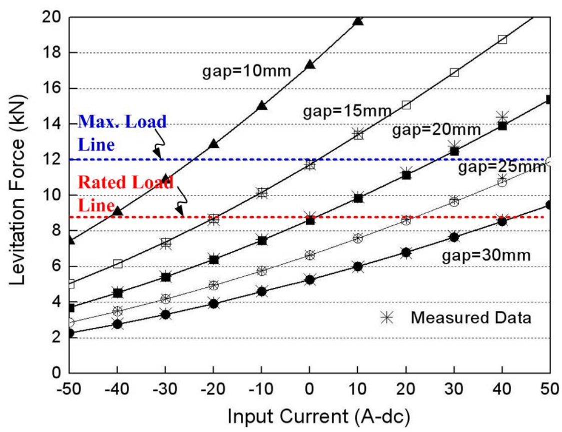


Fig. 10. Levitation force vs. DC-excitation current as a parameter of airgap.

The comparison of experimental and numerical results of the thrust force according to the load when the stable airgap is 20 mm and the stator input current is varied from 0 AT to 3.0 kAT is shown in Fig. 11. The experimental results at the *q*-axis are in good agreement with those obtained from the results of the FEM calculations.

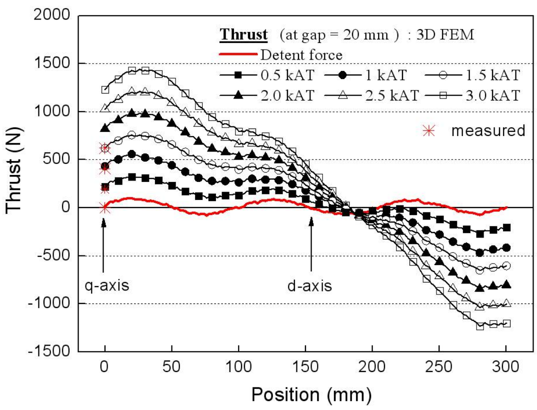


Fig. 11. Thrust vs. translator position as a parameter of armature current.

5. Conclusion

The levitation and thrust force characteristics of a hybrid-excited LSM that uses an electromagnetic field provided by both electromagnets and permanent magnets are presented. On the basis of 3-D FEM calculations, we predict the levitation and thrust force characteristics based on the airgap height and DC-excitation current. In particular, we manufacture a static force testing apparatus for hybrid-excited LSM and confirm that the experimental results are in good agreement with those obtained from 3-D FEM simulations.

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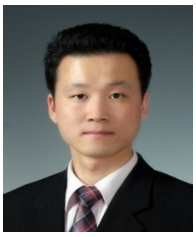

Han-Wook Cho received his B.S., M.S. and Ph.D degrees from Chungnam National University in 2002, 2004 and 2007, respectively. All these degrees are in the field of Electrical Engineering. From 2007 to 2010, he was with the System Engineering Research Division, KIMM(Korea Institute of Machinery and Materials), Daejeon, Korea. Since 2010, he has been with Chungnam National University, where he is currently an assistant professor with the Department of Electric, Electronic, and Communication Engineering Edu. His current research interests include design and analysis of motor/generator, electromechanical systems, and performance assessment of renewable energy systems.

Chang-Hyun Kim received the B.S., M.S. and Ph.D. degrees in electrical and electronic engineering from Korea Advanced Institute of Science and Technology in 2000, 2002 and 2009, respectively. He joined KIMM(Korea Institute of Machinery and Materials) in 2009, where he is currently a senior researcher. His research interest is the control of magnetic levitation and linear propulsion systems.

Hyung-Suk Han received the Ph.D. degree in mechanical engineering from Ajou University, Suwon, Korea, in 1997. Since 1997, he has been a Principal Researcher in KIMM(Korea Institute of Machinery and Materials). His research interest is the dynamic simulation of maglev vehicles

Jong-Min Lee received the B.S., M.S. and Ph.D. degree in mechanical design engineering from Chungnam National University in 1991, 1993 and 2011, respectively. Since 1993, he has been a senior researcher in KIMM(Korea Institute of Machinery and Materials). His research interest is the mechanical design of maglev bogies, guideways and switches.