A 3-D Electromagnetic Force Analytical Model for Air-core Halbach Permanent Magnet Linear Synchronous Motor

Jiaheng Duan[1,2], Kunlun Zhang[1,2], Wenlong Zhang[1,2], Song Xiao[1,2]

1 Key Laboratory of Magnetic Suspension Technology and Maglev Vehicle, Ministry of Education, P.R.C
2 School of Electrical Engineering, Southwest Jiaotong University, Chengdu, 610031 China, maglev.swjtu@gmail.com.

This paper presents a 3-D analytical model for Halbach permanent magnet synchronous motor with air-core windings. Firstly, the analytical model of magnetic field considering both longitudinal and transverse end effect of the Halbach mover is established by the theory of magnetic charge. Then the formulation of 3-D electromagnetic force is derived to study the static and dynamic characteristics of thrust. Finally, the proposed model is verified by 3-D finite element analysis. Also in order to reduce the fifth order component of the harmonics, a short-pitch coil is adopted in this design. The result shows the accuracy of the analytical model, thus providing theoretical basis in some extent to the optimization of air-core PMLSM.

***Index Terms*—Air-core permanent magnet linear synchronous motor, Halbach array, magnetic charge, thrust ripple.**

I. Introduction

THE air-core Linear Motor is widely used in the driving system of maglev, typically represented by the permanent magnet based Mag-plane vehicle [1], and the superconducting magnet based MLX system [2]. The conventional thrust model is actually a simplified 2-D analytical model, assuming that the motor stretches to infinity and with longitudinal end effect ignored [3]-[5]. As a result, the calculations always differ a lot from the maglev system and can hardly support the condition that the mover deviates from the axis of stator. In a practical maglev system, electromagnetic force caused by the deviation can exert an influence in the other two-dimensional electromagnetic force. Thus, an accurate 3-D analytical model for an air-core linear motor is required.

II. Model Of Air-core Motor

In this paper, a 3-D analytical model of linear motor with short Halbach permanent magnets mover and overlapping short-pitch air-core long stator is established, as shown in Fig. 1. Considering the thrust ripple caused by the harmonics, especially the 5th order component, stator with two-fifths pole pitch is designed as Fig. 2. The windings' order of power is A-X,Y-B,C-Z,X-A,B-Y,Z-C, among which A,B,C represent the current input terminals, X,Y,Z represent the outputs.

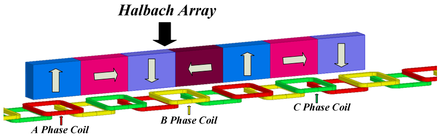


Fig. 1. Model of the linear motor

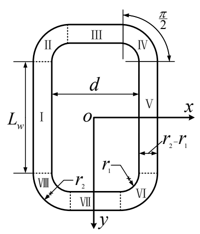


Fig. 2. Details of one stator coil

Detailed parameters of the air-core linear motor is shown in TABLE I.

TABLE I
Parameters Of The Linear Motor Model

Item	Symbol	Value/Units
Length of the Magnet	l	150mm
Width of the Magnet	w	50mm
Height of the Magnet	h	100mm
Remanence	B_r	1.25T
Magnetic Angle	α	90 deg
Pole Pitch	τ	300mm
Length of the Coil	d	110mm
Width of the Coil	L_w	140mm
Height of the Coil	h_w	10mm
Inner Diameter of the Coil	r_1	10mm
Outer Diameter of the Coil	r_2	20mm
Maximum coil current	I	11.546A
Air-gap	L_z	30mm
Windings of One Coil	N_s	50

III. Calculation Of The Magnetic Field

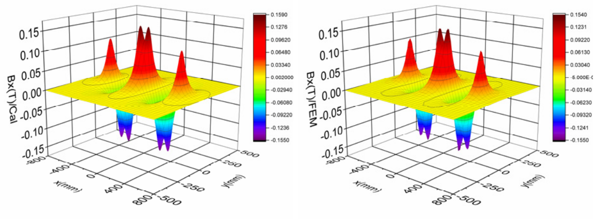
To achieve a more accurate 3-D magnetic field model, equivalent magnetic charge method is adopted. By equalizing the magnetic field of a radial magnetized permanent magnet to two magnetic charge surfaces, one is positive and another is negative, the magnetic field generated by single permanent magnet is calculated [6][7]. As shown in formulas (1)-(3).

$$\varphi_{+,-} = \frac{1}{4\pi\mu_0} \int_{+\ or\ -\ sheet} \frac{\rho_m}{r_0} d^3 r_0 \qquad (1)$$

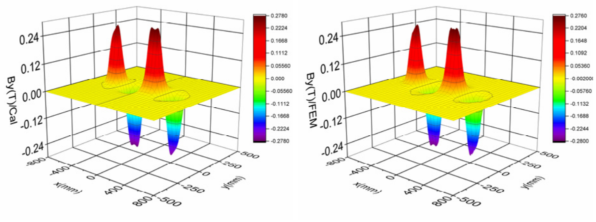
$$\vec{H} = -\nabla\varphi \qquad (2)$$

$$\vec{B} = \mu_0 \vec{H} \qquad (3)$$

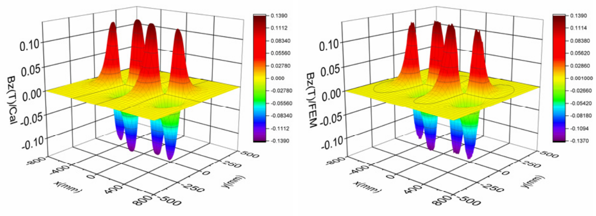
Then by using coordinate-transform, we can obtain the magnetic field generated by single magnet with different magnetization angle. Finally, all the calculations are superimposed to compute the Halbach mover's magnetic field which considering both longitudinal and transverse end effect of the mover. Fig. 3 shows the comparison of the results of magnetic flux density located in 35mm from the array surface respectively calculated by the analytical method and finite element method, and the maximum error is less than 3%.



(a) Comparison of B_x



(b) Comparison of B_y



(c) Comparison of B_z

Fig. 3. Comparison of 3-D magnetic field

IV. CALCULATION OF THE ELECTROMAGNETIC FORCE

With the assumption that: 1) the number of windings is sufficient to make the internal current density uniform; 2) the stator is infinite long. The coil is divided into eight parts, as shown in Fig. 2, in order to calculate the force respectively as follow

$$\vec{F} = \int_{Space} \vec{B} \times \vec{J} dV \tag{4}$$

For the rapidly falling entrance and exit of magnetic field caused by longitudinal end effect of the mover, the force generated by extra three coils(about one pole pitch) in both ends of the permanent mover should be considered to assure the accuracy.

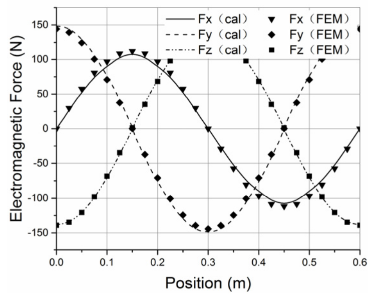


Fig. 4. Comparison of 3-D static force

Fig. 4 shows the trend of 3-D static force of the mover when it deviated from the stator axis between 0-600mm, namely double pole pitch. During the derivation, force in y axis may perform as a recovery force while the power angle changes to a certain value. Fig. 5 shows the peak force changed in three directions when the magnet deviates from the stator axis gradually in the range of 0mm to 250mm. It's obvious the peak value of electromagnetic force decreases gradually with the increase of mover derivation, and decreases rapidly once away from the coil width.

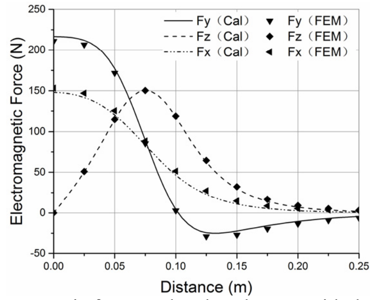


Fig. 5. The electromagnetic force peak value changes with the different position of mover

Fig. 6 shows the thrust comparison of analytical results with finite element calculation results under a speed of 20m/s, and the former can accurately reflect the fluctuation.

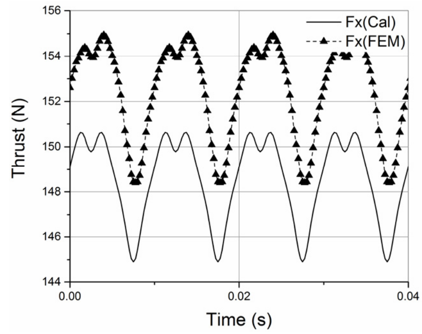


Fig. 6. Thrust ripple at speed of 20m/s

V. RESULT

In this paper, a method for calculating the 3-D electromagnetic force considering the longitudinal and lateral end effect is presented. The comparison of analytical results with finite element calculation results has shown the accuracy of the presented method. The full paper will provide the detailed derivation of the 3-D space magnetic field and the electromagnetic force.

REFERENCES

[1] J. Fang, A. Radovinsky, D. B. Montgomery, "Dynamic modeling and control of the Mag-plane vehicle". 2004.

[2] T. Murai, T. Fujimoto, S. Fujiwara, "Test run of combined propulsion, levitation and guidance system at Miyazaki test track," *Electrical engineering in Japan*, 1996, 117(2): 68-79.

[3] S. M. Jang, S. H. Lee, "Comparison of two types of PM linear synchronous servo and miniature motor with air-cored film coil," *IEEE transactions on magnetics*, 2002, 38(5): 3264-3266.

[4] M. J. Kamper, "Comparison of linear permanent magnet machine with overlapping and non-overlapping air-cored stator windings" *4th IET Conference on Power Electronics, Machines and Drives*. 2008.

[5] D. Zarko, D. Ban, T. A. Lipo, "Analytical calculation of magnetic field distribution in the slotted air gap of a surface permanent-magnet motor using complex relative air-gap permeance," *IEEE Transactions on Magnetics*, 2006, 42(7): 1828-1837.

[6] N. H. Malik, "A review of the charge simulation method and its applications," *IEEE Transactions on Electrical Insulation*, 1989, 24(1): 3-20.

[7] S. Paul, D. Bobba, N. Paudel, et al. "Source field modeling in air using magnetic charge sheets," *IEEE Transactions on Magnetics*, 2012, 48(11): 3879-3882.