

A Novel Design of an Air-Core Type Permanent Magnet Linear Brushless Motor by Space Harmonics Field Analysis

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Abstract—This paper presents a novel design technique and characteristic analysis of an air core type Permanent Magnet (PM) linear motor based on Space Harmonics Field analysis methodology. In the Space Harmonics Field analysis, Poisson equation is solved by the spatial distribution of current and PM, which is replaced by Equivalent Magnetizing Current (EMC). The process of magnetic field analysis is applied to the motor design and steady state analysis considering the driving characteristic. The validity of the proposed technique is confirmed with 2-D Finite Element (FE) analysis and experimental results.

Index Terms—2-D FE, air core type permanent magnet linear motor, EMC, Space Harmonics Field analysis.

I. INTRODUCTION

PERMANENT MAGNET (PM) linear motors drives could offer significant advantages, in terms of efficiency, speed control and positional accuracy. However, in slotted PM linear motor, there are cogging force, due to slotting and finite length of the moving parts, which have different wavelengths [1]. In order to minimize cogging force, the additional process, such as skewing and optimally disposing the magnets and the optimizing the length of the armature coil, is required [2]. As this reason, an air-core type PM linear brushless motor is strongly recommended for improving the accuracy in the speed and position control of linear brushless PM motor.

To obtain a precise design result of air core PM linear brushless motor it is necessary to analyze magnetic field in the whole analysis region including airgap and coil area. As one of the numerical methods in magnetic field analysis, the Finite Element (FE) method is known to allow an accurate analysis of electrical machines and can consider geometric details and the nonlinearity of magnetic material [2]. However, FE requires long computation time particularly at the initial design stage. The Space Harmonics Field analysis is usually adopted for magnetic field analysis because of their fast and flexible computation. It is to solve the Poisson equation by the spatial distribution of current and PM. The PM is replaced by Equivalent Magnetizing Current (EMC) [4], [5].

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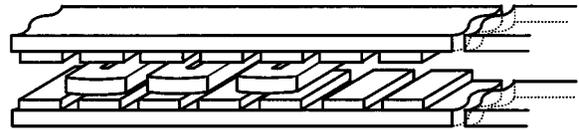


Fig. 1. Motor topology.

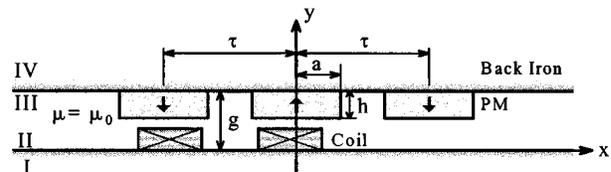


Fig. 2. Analysis model using EMC method.

This paper presents a novel design process to improve design quality by Space Harmonics Field analysis of EMC and a steady state analysis that is phase commutation thrust ripple taken into account the variation of relative pole position of conductor. The proposed analysis and design process is verified against the 2-D FE analysis and experimental results.

II. MAGNETIC FIELD ANALYSIS BY USING EMC

A. Magnetic Field Analysis by Space Harmonics Field

Fig. 1 shows the topologies of air core type linear motor studied in this paper. It consists of a double side the PM and an air core type moving coil which is concentrated winding having three isolated phase sets. Three phase coils are displaced symmetrically at every 120° circumferentially and the current waveform in the phases is a 120° squarewave. Exactly two phases are conducting at any and every instant [5].

Fig. 2 shows an analysis model for the magnetic field of air core type linear PM motor using Space Harmonics Field. Since the double side PM linear motor has symmetric structure along y-axis, only one side is selected as analysis region and followings are assumed to simplify the 2-D analysis [4], [5].

- All regions are extended infinitely in the $\pm x$ direction and PMs are magnetized in the $\pm y$ direction.
- PMs are periodically distributed along x-axis.
- Permeability of back iron is infinite.

The whole magnetic field can be obtained by the superposition of magnetic fields produced by PM and armature current respectively.

1) *Magnetic Field by Armature Current:* For unexcited PMs, the analysis model is applied to four regions as shown

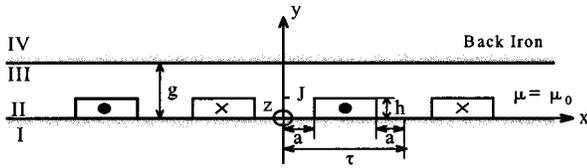


Fig. 3. Arbitrary current model.

in Fig. 3 and the governing equations of each regions derived from Maxwell's equations are as follows [1], [2].

$$\frac{\partial^2 A(x, y)}{\partial x^2} + \frac{\partial^2 A(x, y)}{\partial y^2} = 0 \quad \text{Region I, III, IV} \quad (1)$$

$$\frac{\partial^2 A(x, y)}{\partial x^2} + \frac{\partial^2 A(x, y)}{\partial y^2} = -\mu_0 J(x) \quad \text{Region II} \quad (2)$$

where A is the z -axis component of magnetic vector potential and J is armature current density.

The magnetic fields induced by armature current can be calculated by applying boundary conditions to the tangential components of magnetic field intensity and normal components of magnetic flux density at each boundary in appropriate regions. These are as follows [4]

$$B_{II}^x = -\mu_0 \sum_{n=1,3}^{\infty} \left(\frac{\sinh(nk(g-h))}{\sinh(nkg)} \right) \sinh(nky) \cdot \frac{b_n}{nk} \cdot \sin(nkx) \quad (3)$$

$$B_{II}^y = -\mu_0 \sum_{n=1,3}^{\infty} \left(1 - \frac{\sinh(nk(g-h))}{\sinh(nkg)} \cosh(nky) \right) \cdot \frac{b_n}{nk} \cdot \cos(nkx) \quad (4)$$

$$B_{III}^x = \frac{\mu_0}{2} \sum_{n=1,3}^{\infty} \left(\frac{\sinh(nkh)}{\sinh(nkg)} \right) \left(\frac{e^{nky}}{e^{nkg}} - \frac{e^{nky}}{e^{nky}} \right) \cdot \frac{b_n}{nk} \cdot \sin(nkx) \quad (5)$$

$$B_{III}^y = -\frac{\mu_0}{2} \sum_{n=1,3}^{\infty} \left(\frac{\sinh(nkh)}{\sinh(nkg)} \right) \left(\frac{e^{nky}}{e^{nkg}} - \frac{e^{nky}}{e^{nky}} \right) \cdot \frac{b_n}{nk} \cdot \cos(nkx) \quad (6)$$

$$b_n = \frac{4J_0}{n\pi} \cos(nka) \quad (7)$$

where k is π/τ .

2) *Magnetic Field by PM*: If the armature windings are not excited, the analysis model can be considered as Fig. 4(a). In Fig. 4(b), PM's are replaced by the EMC distribution and the characteristic equations of each region is as follows [4]

$$\frac{\partial^2 A(x, y)}{\partial x^2} + \frac{\partial^2 A(x, y)}{\partial y^2} = -\mu_0 J_p(x) \quad \text{Region III.} \quad (8)$$

The EMC distribution by PM's, $J_p(x)$, for the region III, is described as the Fourier series

$$J_p(x) = \sum_{n=1,3}^{infy} b_{pn} \cdot \sin(nkx) \quad (9)$$

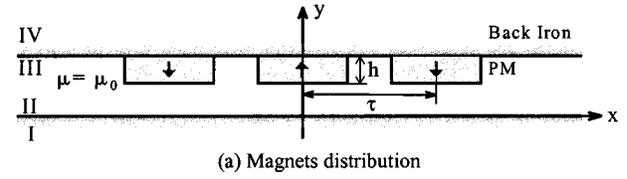


Fig. 4. Magnetic field analysis model by PM.

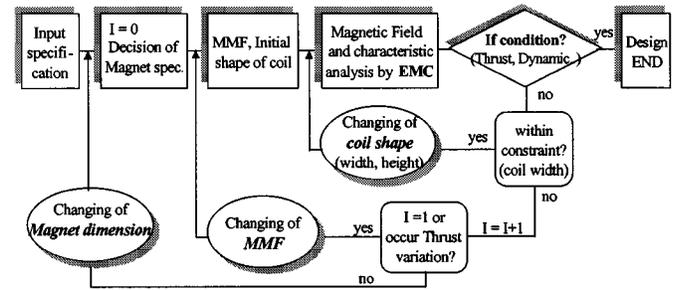


Fig. 5. Design process of air core type PM linear brushless motor by EMC.

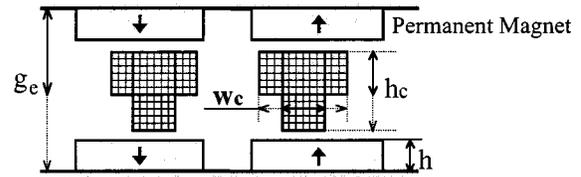


Fig. 6. The shape variation of winding coil area.

$$b_{pn} = \frac{4J_{pm}}{n\pi} [\cos(nka) - \cos nk(a + \delta)] \quad (10)$$

where δ indicates an arbitrary value which approaches zero and the current density of PM, J_{pm} , can be expressed by the magnetization M .

By applying the boundary conditions to the interfaces between different material regions, the characteristic equation given in (8) can be solved

$$B_{II}^x = \frac{\mu_0}{2} \sum_{n=1,3}^{\infty} \left(\frac{\sinh(nkh)}{\sinh(nkg)} \right) \left(\frac{e^{nky}}{e^{nkg}} - \frac{e^{nky}}{e^{nky}} \right) \cdot \frac{b_n}{nk} \cdot \sin(nkx) \quad (11)$$

$$B_{II}^y = -\frac{\mu_0}{2} \sum_{n=1,3}^{\infty} \left(\frac{\sinh(nkh)}{\sinh(nkg)} \right) \left(\frac{e^{nky}}{e^{nkg}} - \frac{e^{nky}}{e^{nky}} \right) \cdot \frac{b_n}{nk} \cdot \cos(nkx). \quad (12)$$

The resultant magnetic field is obtained by superposition of the magnetic field caused by PM and armature current.

III. DESIGN AND CHARACTERISTIC ANALYSIS

The novel design method of an air core type PM linear motor is shown in Figs. 5 and 6. Fig. 5 shows the design process by Space Harmonics Field analysis of EMC. Fig. 6 shows shape

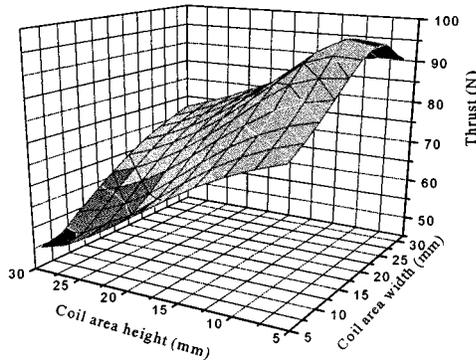


Fig. 7. Thrust characteristic according to shape variation.

TABLE I
SPECIFICATION OF DESIGN RESULT

Line voltage	100 (V)	Current	1.8 (A)
Stack length	100 (mm)	Thrust	100 (N)
Back iron thickness	10 (mm)	Coil	
Magnet		Core area	214 (mm ²)
Residual flux density	1.15 (T)	Turn number	302
Width	35 (mm)	Coil area width	23 (mm)
Thickness	5 (mm)	Coil area height	9.3 (mm)

variation of coil area which is designed to obtain maximum thrust under fixed design parameters. The armature winding area is divided into very small regions, and the flux density of each subdivision region is computed by the Space Harmonics Field analysis of EMC. If the cross sectional shape of the coil area changes, the magnitude and distribution of magnetic flux density are varied in the magnetic airgap, the generated thrust would be also varied in spite of the constant Magneto-Motive Force (MMF).

If the EMC of PM is moving, Electro-Motive Force (EMF) is computed from flux linkage and thrust is calculated by armature current with flux density in accordance with pole position. The equations are as follows.

$$F = \sum_{i=1}^n F_i^{(e)} = \sum_{i=1}^n J_i^{(e)} \cdot S_i^{(e)} \cdot B_y^{(e)} \cdot L \quad (13)$$

$$E = \omega_e N \sum_{i=1}^n \phi_i^{(e)} \cdot \sin p\theta \quad (14)$$

where

$S_i^{(e)}$ is the subdivided element of armature winding region,

L is z-axis length of machine,

ω_e is electric angular frequency,

N is turns per phase,

p is pole pair, and

θ is relative electric angle of PM and armature winding.

Fig. 7 shows the thrust characteristics for various winding area widths and heights under constant MMF and armature winding area. As the width of winding area is increased, the magnetic airgap is reduced and thrust is increased. However, thrust is found to be reduced for over the specific length. The specification of air core type PM linear brushless motor from the design process is shown in Table I.



Fig. 8. Equi-potential distribution.

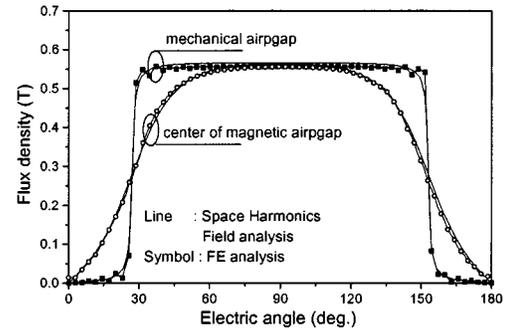


Fig. 9. Flux density distribution.

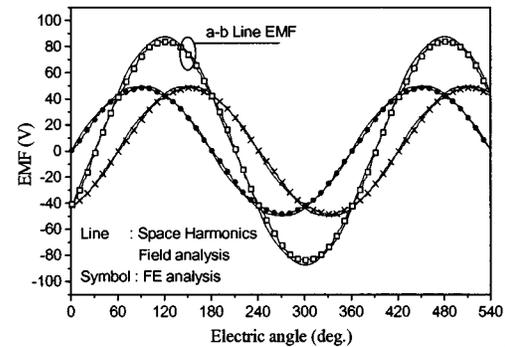


Fig. 10. Back EMF distribution.

IV. VALIDITY OF PROPOSED DESIGN AND ANALYSIS METHOD

The presented design and analysis method of air core type PM linear brushless motor is verified through comparisons with 2-D FE analysis and experimental data.

A. Comparison With 2-D FE Analysis

The FE analysis is known as an accurate analysis method that allows to include the nonlinearity of magnetic material [2]. Therefore, the proposed Space Harmonics Field analysis by EMC is verified with FE analysis result.

The Equipotential distribution is shown in Fig. 8. In air core type PM linear brushless motor, the effective magnetic airgap is increased since coil area is working as magnetic airgap. Fig. 9 shows the flux density distribution in mechanical airgap and the center of magnetic airgap. The flux density in mechanical airgap has a rectangular characteristic, meanwhile the flux density of magnetic airgap center has a sinusoidal waveform. It is fringing effect due to increased magnetic airgap and shows that the flux density distributions of both space harmonics field and 2-D FE analysis are in good agreement.

The characteristic of velocity EMF by moving of PM is shown in Fig. 10. The shape of EMF distribution in each phase is sinusoidal. It is due to flux distribution in magnetic airgap and raises a problem of thrust ripple according to driving method in brushless motor. The thrust computation process taken into account driving method is shown in Fig. 11. It is

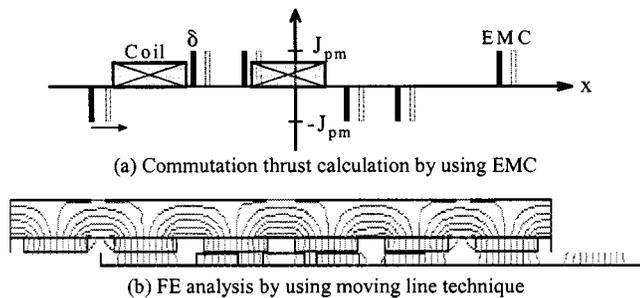


Fig. 11. Thrust calculation process during the on time.

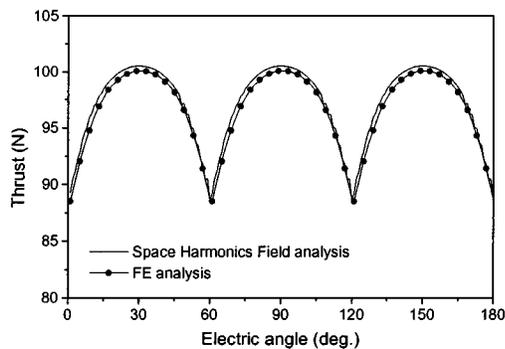


Fig. 12. Thrust distribution according commutation period ($I= 1.8$ A).

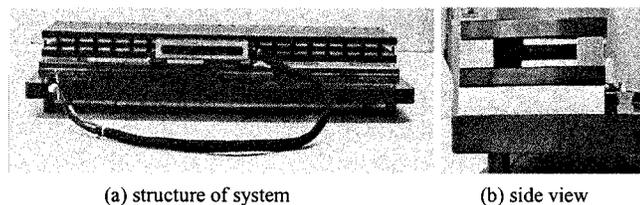


Fig. 13. The system of testing machine.

shown that EMC by PM is moving and thrust can be calculated from flux linkage and armature current. In FE analysis, moving line technique is applied then on time of current in each phase is a 120° and phase current is commutated by every 60° in electrical angle [6].

The result of thrust computation by using EMC and FE analysis are shown in Fig. 12. The phase current is considered square waveform, the other side characteristics of flux distribution has not perfect to square form. Therefore, thrust ripple during every 60° is generated by the characteristic of flux density distribution and the resultant thrust by FE analysis is somewhat less than that of EMC method. In FE analysis, the nonlinear characteristic of permeability in iron core is considered.

B. Comparison With Experiment

The proposed Space Harmonics Field analysis of EMC is compared with experimental results. The system structure of air core type PM linear brushless motor is shown in Fig. 13.

Fig. 14 shows the flux density distribution of the test machine for different airgap position and Fig. 15 shows velocity EMF. It is shown that an error of flux density and EMF amplitude is within about 3 percent which indicates the proposed Space Harmonics Field analysis is found in well agreement with experimental result.

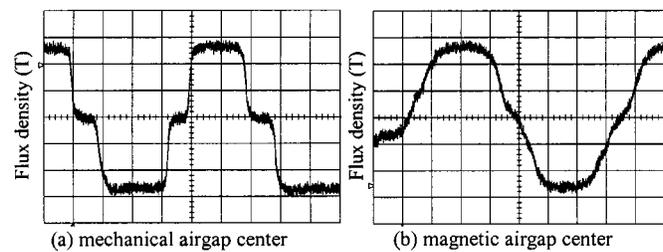


Fig. 14. Flux density distribution by Experiment (0.2 T/div.).

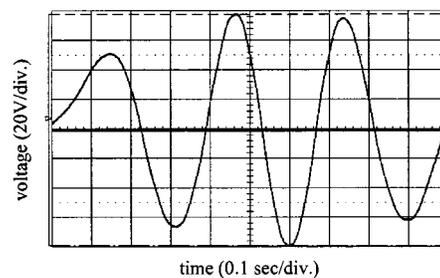


Fig. 15. Velocity EMF.

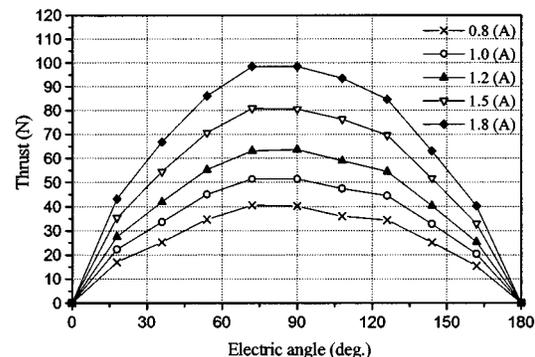


Fig. 16. Thrust distribution according to electrical angle.

In Fig. 16, the characteristic of thrust according to pole position is compared with experimental for each analysis results. In the comparison, the measured thrust value is less than that of two analysis results. It is believed that back iron in experimental equipment is not laminated and this causes increase of flux leakage. The thrust ripple in 60° of electric angle is observed for both of analysis and experimental results.

V. CONCLUSION

Magnetic field distribution has a very significant effect on the characteristic analysis and design process, for the air core type PM linear brushless motor. A Space Harmonics Field analysis has been developed to aid the magnetic field analysis of air core type PM linear brushless motors. It is based on the calculation of the spatial distribution magnetic field when the PMs are replaced by the EMC distribution.

In this paper, a design process and characteristics analysis by using EMC method are presented and the results are verified against the 2-D FE analysis and experiment. The shape of winding coil area has a significant effect on the thrust. The effect of various coil shapes under constant MMF has been investigated and thrust ripple taken into account a driving manner is analyzed by EMC method that is the moving of magnetization.

By comparing with the experimental results, the reasonable agreement of proposed process has been obtained by EMC method. From the comparisons with the experimental results, the proposed design and analysis process by using EMC is found reliable methodology for air core type PM linear brushless motor.

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