論 文
55B-9-5

Halbach 배열을 가진 SPMPM의 특성해석에 관한 연구

Characteristics Analysis of Synchronous Permanent Magnet Planar Motor with Halbach Array

周建配* · 黃蕊* · 李東燁** · 金奎卓†
(Jianpei Zhou, Rui Huang, Dong-Yeup Lee, and Gyu-Tak Kim)

Abstract - In this paper, a synchronous permanent magnet planar motor (SPMPM) with Halbach array is proposed. First, we give the equations of the magnetic scalar potential and a series of boundary conditions. The magnetization and flux density distribution of Halbach array are obtained by analytical method; then, the characteristics of this SPMPM such as inductance, back-EMF, and thrust are evaluated. At last, the experiment results are used to verify the analysis property of this SPMPM. By comparison, it can be concluded that the analysis of SPMPM with Halbach magnet array is credible and feasible.

Key Words : SPMPM, Analytical Method, Halbach Magnet Array, Characteristics Analysis.

1. INTRODUCTION

Until now, many kinds of linear motors have been applied in the machine tool industry and in robotics where linear motion (required for positioning and in the operation of manipulators) is a common requirement. In addition, reciprocating linear machines are being constructed for driving reciprocating compressors and alternators. Recently the planar motors are applied to drive in x and y directions. Compared with the conventional motor using two linear motors (one to drive in x axis, the other to drive in y axis), the planar motor only using one motor to drive in x and y directions has the advantages such as direct driving, simple structure, high accuracy, etc. So the planar motors are widely applied in the systems which require motion on a plane, for example, semiconductor waffles, printed circuits, and other precision control systems. According to the operation principles, most planar motors can be divided into variable reluctance planar motor, induction planar motor, and synchronous permanent magnet planar motor (SPMPM). The SPMPM, which has low cost, simple structure, high energy density, etc, is used widely in automation systems and other industrial fields [1]-[3]. Magnet array, an important part of SPMPM, has been paid more and more attention in recent years, and many new types have been proposed and presented in the patents and papers in [1]-[3].

Specially, Klaus Halbach of Lawrence Berkeley National Laboratory (USA) has discovered an interesting permanent magnet configuration that concentrates magnetic flux on one side of the array and cancels it on the others in 1980. Now, Halbach arrays are used in Maglev trains, motors and generators for the advantages including minimized drag from eddy current effects (drag decreases as speed increases), reduced power consumption (no giant electromagnets needed), and good magnetization distribution.

In this paper, the Halbach magnet array is analyzed by analytical method firstly, and then, the characteristics of SPMPM with Halbach magnet array are evaluated at last, the experiments on the test machine have been done, the data of analytical method and experiments are compared to verify the feasibility and credibility of this SPMPM.

2. Modeling and principle analysis

2.1 Modeling

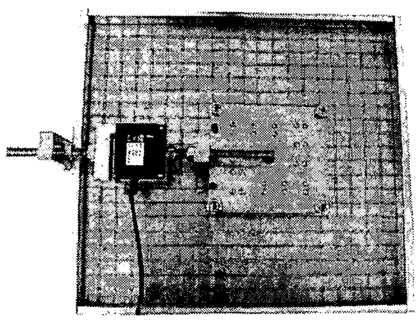


Fig. 1 The Prototype of the SPMPM machine with Halbach magnet array

† 교신저자, 正會員 : 昌原大學校 工大 電氣工學科 敎授 · 工博
E-mail : gtkim@sarim.changwon.ac.kr
* 學生會員 : 昌原大學校 工大 電氣工學科 碩士課程
** 正 會 員 : 昌原大學校 工大 電氣工學科 博士課程
接受日字 : 2006年 6月 23日
最終完了 : 2006年 8月 11日

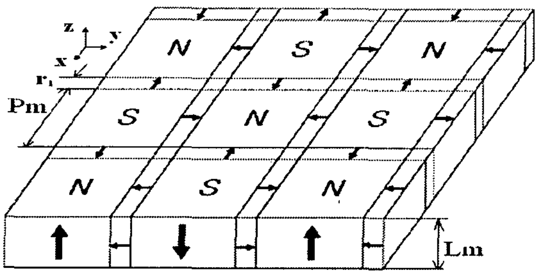


Fig. 2 Halbach magnet array

Fig.1 shows the prototype of the SPMPM with Halbach magnet array. Fig.2 reveals the Halbach magnet array which proposed in this paper.

2.2 Principle

The part-view of analytical model is shown in Fig.3. Unless otherwise stated, it assumes that the pitches of mentioned magnet arrays in the paper are equal.

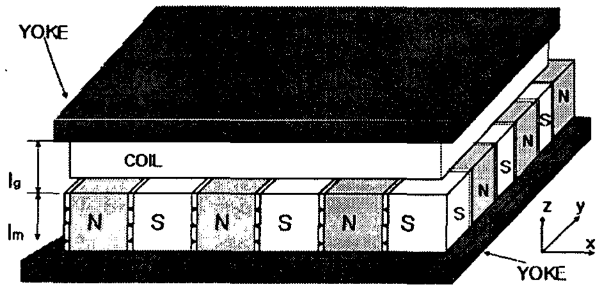


Fig. 3 The part-view of analytical model

2.2.1 Governing Equations

In this paper, the subscript m and g denote the magnet and gap, respectively, and x, y, and z are the components of the directions. Some conditions are assumed to simplify the model: the motor has the periodicity in the x and y direction; the magnetization is constant; the relative permeability of the iron yoke is infinite the magnetic saturation is neglected.

The magnetic scalar potential u_g in the air-gap and the basic equations can be expressed as

$$\nabla^2 u_g = 0 \tag{1}$$

$$\overrightarrow{H_g} = -\nabla u_g \tag{2}$$

$$\overrightarrow{B_g} = \mu_0 \overrightarrow{H_g} \tag{3}$$

Where B_g is the magnetic field density and H_g is magnetic flux intensity in the air-gap.

The magnetic scalar potential u_m in the permanent magnet and some equations can be expressed as

$$\nabla^2 u_m = \nabla \cdot \frac{\overrightarrow{M}}{\mu_r} \tag{4}$$

$$\overrightarrow{H_m} = -\nabla u_m \tag{5}$$

$$\overrightarrow{B_m} = \mu_0(\mu_r \overrightarrow{H_m} + \overrightarrow{M}) \tag{6}$$

Where B_m is the magnetic field density and H_m is magnetic flux intensity in the permanent magnet.

As $\nabla \cdot M = 0$, the magnetic scalar potential u_m can be expressed as $\nabla^2 u_m = 0$.

2.2.2 Boundary Conditions

The boundary conditions can be expressed as

$$\begin{aligned} &u_m = 0 \quad at \quad z = 0 \\ &u_g = 0 \quad at \quad z = l_g + l_m \\ &H_{mx} = H_{gx},\ H_{my} = H_{gy},\ B_{mz} = B_{gz} \quad at \quad z = l_m \end{aligned} \tag{7}$$

2.2.3 Solving Equations

The magnetization of the permanent magnet array is as follows

$$\overrightarrow{M} = M_x \vec{x} + M_y \vec{y} + M_z \vec{z} \tag{8}$$

The complex Fourier series is used to make the calculation easy. The magnetization distribution of the proposed magnet array is expressed as

$$M_x = -j\frac{B_r}{\mu_0}\frac{4}{\pi^2}\sum_{k=1,3,5..}^{\infty}\sum_{l=1,3,5..}^{\infty}\frac{1}{kl}\cos(a_k r_1)\sin(a_l r_1)\exp[j(a_k x + a_l y)] \tag{9}$$

$$M_y = -j\frac{B_r}{\mu_0}\frac{4}{\pi^2}\sum_{k=1,3,5..}^{\infty}\sum_{l=1,3,5..}^{\infty}\frac{1}{kl}\cos(a_k r_1)\sin(a_l r_1)\exp[j(a_k x + a_l y)] \tag{10}$$

$$M_z = -\frac{B_r}{\mu_0}\frac{4}{\pi^2}\sum_{k=1,3,5..}^{\infty}\sum_{l=1,3,5..}^{\infty}\frac{1}{kl}\cos(a_k r_1)\cos(a_l r_1)\exp[j(a_k x + a_l y)] \tag{11}$$

where

$$a_k = k\frac{\pi}{p},\ a_l = l\frac{\pi}{p}$$

The calculated result of the scalar potential in the air-gap is written as follows

$$u_g = \sum_{k=1,3..}\sum_{l=1,3..}\left\{\begin{aligned}&k_1\exp(ja(mx+ny)) \\ &\cdot\left(\exp(\lambda_{kl}z) - \exp(2\lambda_{kl}l_{gm})\exp(-\lambda_{kl}z)\right)\end{aligned}\right\} \tag{12}$$

where

$$k_1 = \frac{jP_{kl}C_{kl} - Z_{kl}}{2\lambda_{kl}D_{kl}}$$

$$C_{kl} = \frac{a}{\lambda_{kl}}\left(\frac{1}{\tanh(\lambda_{kl}l_m)} - \frac{1}{\sinh(\lambda_{kl}l_m)}\right)$$

$$D_{kl} = \exp(\lambda_{kl}l_{gm})\sinh(\lambda_{kl}l_g)\left(\frac{\mu_r}{\tanh(\lambda_{kl}l_m)} + \frac{1}{\tanh(\lambda_{kl}l_g)}\right)$$

$$P_{kl} = kX_{kl} + lY_{kl}$$

$$X_{kl} = -j\frac{B_r}{\mu_0}\frac{4}{\pi^2}\frac{1}{kl}\cos(a_l r_1)\sin(a_k r_1)$$

$$Y_{kl} = -j\frac{B_r}{\mu_0}\frac{4}{\pi^2}\frac{1}{kl}\cos(a_k r_1)\sin(a_l r_1)$$

$$\lambda_{kl} = \sqrt{a_k^2 + a_l^2} \quad l_{gm} = l_m + l_g$$

The dimensions and material properties of the proposed SPMPM are shown in Table 1.

Table 1 Dimensions amd Parameters

Part	Item	Symbol	Quantity	Unit
magnet	Residual flux density	μ_r	1.05	
	Magnet retentivity	B_r	1.3	[T]
	Pitch of the array	p	20	[mm]
	Thickness	l_m	10	[mm]
air-gap	length	l_g	6	[mm]
mechanical air-gap	length	l_{mg}	1	[mm]

Fig. 4 shows the magnetization distribution of Halbach magnet array.

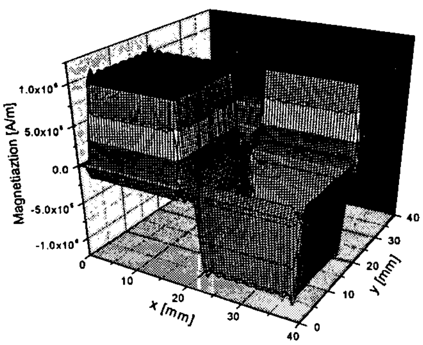


Fig. 4 The magnetization distribution

3. Characteristics analysis

The characteristics of a SPMPM with Halbach magnet array are evaluated in Fig. 5.

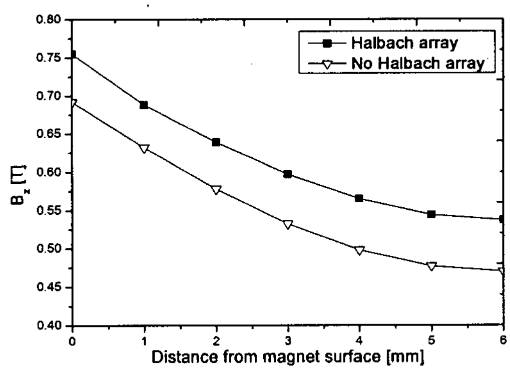
3.1 Flux Density Distribution

According to the equation (12), the flux density in the air gap is obtained as

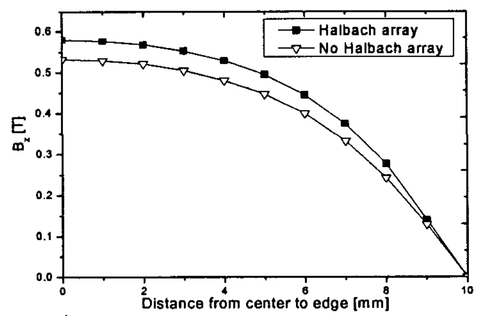
$$B_{gz} = \frac{8B_r}{\pi^2}\sum_{k=1,3\ldots}^{\infty}\sum_{l=1,3\ldots}^{\infty}\frac{1}{D_{kl}}\left\{C_{kl}\times J + \frac{1}{kl}\cos(a_l r_1)\cos(a_k r_1)\right\}$$
$$\times(\exp(\lambda_{kl}z) + \exp(2\lambda_{kl}l_{gm})\exp(-\lambda_{kl}z))\sin(a_k x)\sin(a_l y) \quad (13)$$

where

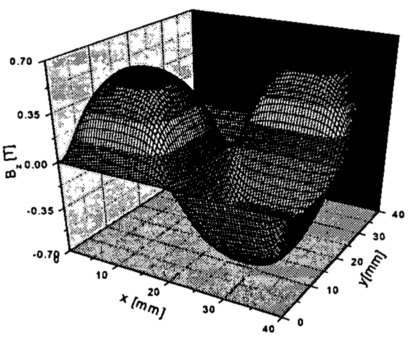
$$J = \frac{1}{k}\cos(a_k r_1)\sin(a_l r_1) + \frac{1}{l}\cos(a_l r_1)\sin(a_k r_1)$$



(a) Flux density along air-gap length



(b) Flux density from magnet center to edge (at z=13.5mm)



(c) Flux density with Halbach array

Fig. 5 The magnetization distribution

Fig. 5 (a) shows the flux density distribution from magnet surface to mover yoke at magnet center. The amount of flux density of the Halbach array is about 14[%] higher than that of the no Halbach array. Fig. 5 (b) shows the flux density distribution from magnet center to edge on the x-y plane which is 3.5 [mm] apart from the magnet surface. Fig. 5 (c) shows the air-gap flux density distribution of Halbach array on the x-y plane which is 3[mm] apart from the magnet surface.

3.2 Linkage Flux

The flux linking one turn square coil which each width equals one pitch is evaluated. It can be expressed as

$$\varphi = \iint B_{gz}\, dx\, dy = \frac{-2A}{a_k\, a_l}(\cos(a_k(x_0+p)) - \cos(a_k x_0)) \quad (14)$$

where

$$A = \frac{16B_r}{\pi^2}\sum_{k=1,3,\ldots}^{\infty}\sum_{l=1,3,\ldots}^{\infty}\left\{C_{kl}\times J + \frac{1}{kl}\cos(a_l r_1)\cos(a_k r_1)\right\} \times \frac{\sin(l_m \lambda_{kl})}{\lambda_{kl}(l_g - l_s)}\,\frac{\sin(\lambda_{kl}(l_g - l_s))}{\sin(\lambda_{kl} l_{gm})}$$

3.3 Back-EMF

The Back-EMF of one phase coil is expressed as

$$E = -N_t\frac{d\varphi}{dt} = -\frac{2AN_t}{a_l}(\sin(a_k(x_0+p)) - \sin(a_k x_0)) \quad (15)$$

where N_t is turn number of one phase coil.

3.3 Inductance

The inductance of one phase coil can be evaluated as

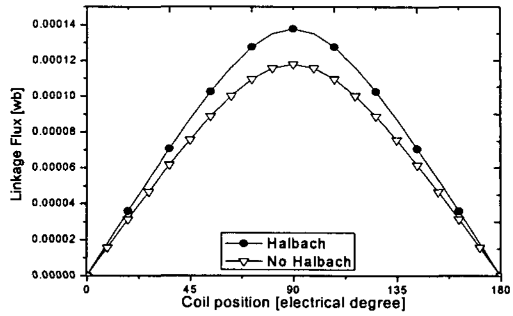
$$L = \frac{N_t\varphi}{i} = \frac{-2N_t A}{i\, a_k\, a_l}(\cos(a_k(x_0+p)) - \cos(a_k x_0)) \quad (16)$$

3.4 Thrust

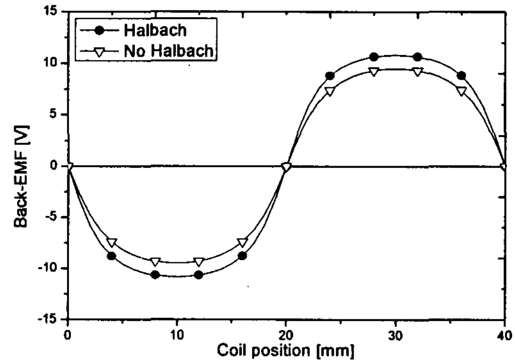
It was assumed that only the coil driving the mover in x-direction is thought about, the expression for the thrust of the multi-turn coil can be expressed as

$$F_x = \frac{-12N_t IA}{w_c a_l a_k}\sin(a_l y)\sin(a_l\frac{d}{2})\sin(a_k(\frac{w}{2}+1+\frac{w_c}{2}))\sin(\frac{a_k w_c}{2}) \quad (17)$$

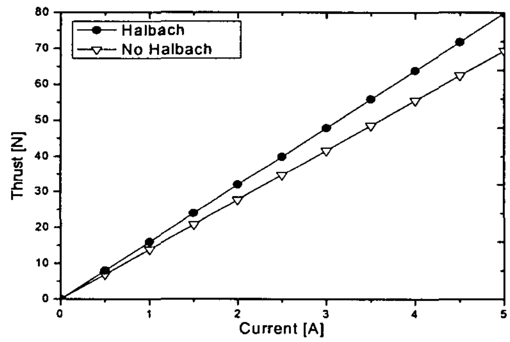
In the equation (17), w and d are the lengths of the two sides of rectangle winding respectively w_c is the width of winding.



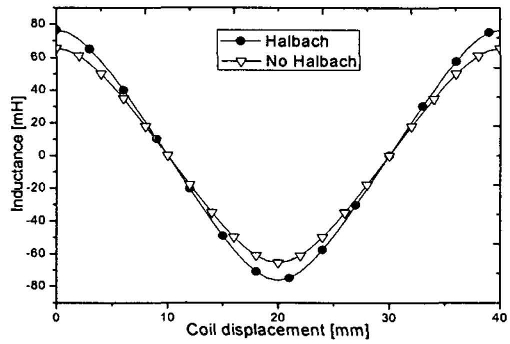
(a) Linkage flux



(b) Back-EMF



(c) Thrust



(d) Inductance

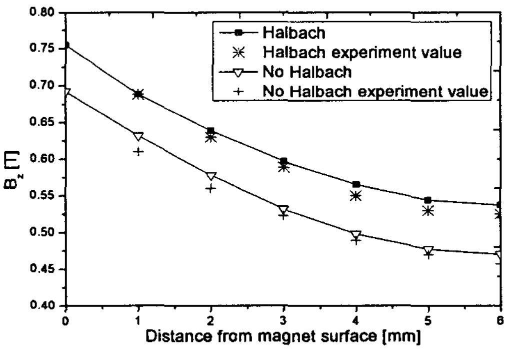
Fig. 6 The characteristic comparisons

For comparison, the characteristics of Askawa array, Chitayat array and no Halbach array are evaluated. The magnet arrays performances of Askawa array and Chitayat array are described in [2]. The characteristics such as linkage flux, back-EMF, thrust and inductance of no Halbach array, Askawa array and Chitayat array have been compared in [4,5], the no Halbach array characteristics are superior to Askawa array and Chitayat array ones. So, in this paper, only the characteristics of Halbach array and no Halbach array are compared.

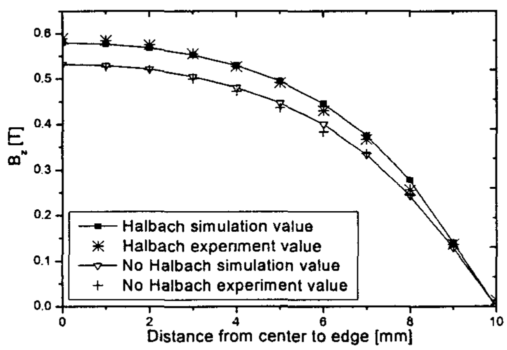
Fig. 6 (a) shows the results of the linkage flux. The peak linkage flux value of the Halbach array is 16.9[%] larger than that of no Halbach array. Fig. 6 (b) shows the back-EMF. The back-EMF of the Halbach array is 14.1[%] larger than that of no Halbach array. Fig. 6 (c) reveals thrust versus current. The force of the Halbach array is 16.6[%] larger than that of no Halbach array. Fig. 6 (d) reveals inductance comparison. The inductance of the Halbach array is 16.6[%] larger than that of no Halbach array.

4. Experiments and verification

To verify the analysis propriety of analytical method, the experiments of flux density distribution of Halbach array, back-EMF, and thrust of prototype machine have been done.



(a) Flux density along air-gap length



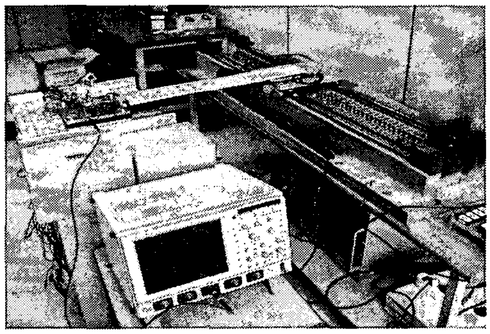
(b) Flux density from magnet center to edge

Fig. 7 The comparisons of flux density

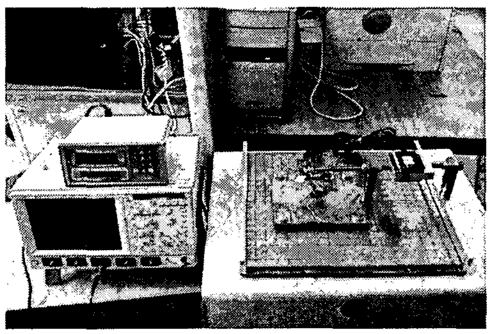
Fig.7 (a) and (b) show the comparisons of the flux density distribution between the simulation values and experiential results. The experiment values are measured by Gauss Meter. It is clearly described that the experiment results agree with the simulation values satisfactorily.

Fig. 8 shows the experimental equipments in Lab. Equipments in Fig 8 (a) are used to measure back-EMF and equipments in Fig 8 (b) are used to measure thrust.

As shown in Fig.9, the experiential peak back-EMF value is 11.65[V] and the simulation peak back-EMF value is 11.95 [V], taking account of the experiment equipments · error, the comparison is reasonable. Fig. 10 shows the back-EMF waveform from experiment.



(a) Back-EMF experimental equipments



(b) Thrust experimental equipments

Fig. 8 The experimental equipments

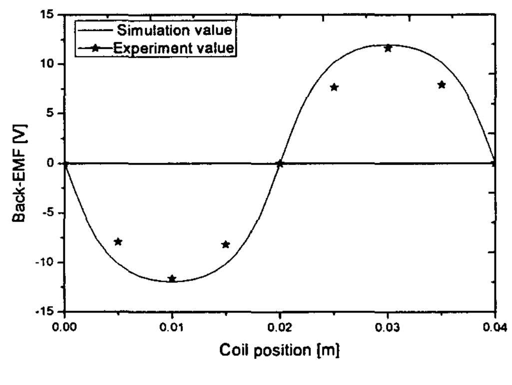


Fig. 9 The comparisons of back-EMF

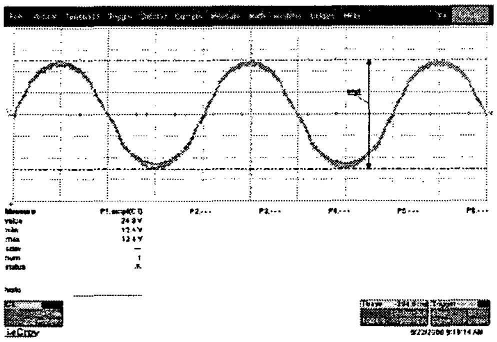


Fig. 10 Back-EMF waveform in experiment

In planar motor, normal force is an important factor which should be considered in motor design. The normal force is calculated maxwll stress tensors.

$$F_n = \frac{1}{2\mu_0} \iint (B_z^2 - B_x^2 - B_y^2) dxdy \qquad (18)$$

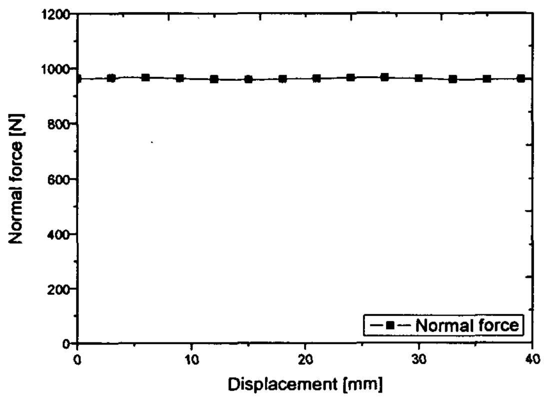


Fig. 11 Normal force of prototype motor

In the prototype motor, the normal force is shown in Fig. 11, the peak value of normal force is 966.14[N].

Fig. 12 shows the thrust verification. The experiment value is measured by load cell (model UU-K010 (cap. 10kgf), DACELL Co.). In this experiment, the error is mainly caused by the friction force which is generated by normal force. If the current is low, the friction of SPMPM will be increased correspondingly. In this case, the current is 1[A], the thrust peak value of simulation is 37.43[N] and that of experimental value is 27.32[N], so the error, about 10[N], between the experiment and simulation values occur. The thrust values calculated from experimental back-EMF values also are shown in Fig. 12, the data is close to simulation results.

By the contrast between the experimental values and the simulation values, the errors occur but they are reasonable. Consequently, the analysis of SPMPM with Halbach magnet array is proper.

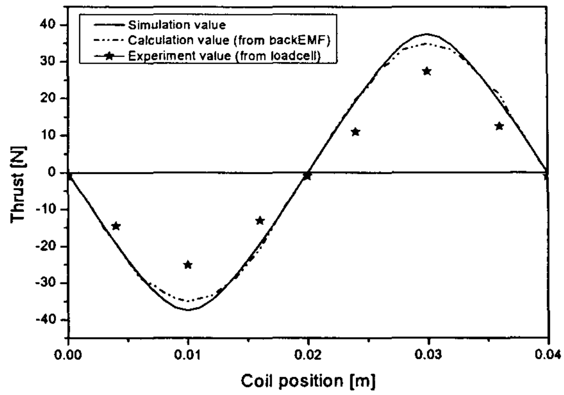


Fig. 12 The comparison of Thrust

5. Conclusion

The Halbach permanent magnet array has high energy density and good performance in magnet flux direction. This study investigated the characteristics of Halbach array by analytical method firstly. By compared with other arrays, it can be seen that the Halbach magnet array is superior and efficient.

The characteristics of the SPMPM with Halbach magnet array are evaluated by the analytical method. By comparing to the experiment values, the property of the analysis about Halbach magnet array performances, Back-EMF and thrust is verified. It can be concluded that the analysis of this SPMPM with Halbach magnet array is creditable.

감사의 글

본 연구는 2005년 창원대학교 연구비 및 산업자원부의 지원에 의하여 기초전력연구원(R-2003-B-271) 주관으로 수행된 과제임

REFERENCES

[1] H. S. Cho and H. K. Jung, "Analysis and design of synchronous permanent-magnet planar motors," *IEEE Trans. Energy Conversion,* vol.17, pp.492-499, Dec. 2002.

[2] H. S. Cho, C. H. Im, and H. K. Jung, "Magnetic field analysis of 2D permanent magnet array for planar motor," *IEEE Trans. Magn.,* vol.37, pp.3762-3766, Sept. 2001.

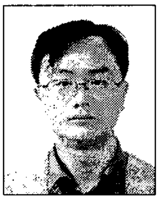
[3] J. Y. Cao, Y. Zhu, J. S. Wang, W.S. Yin, and G. H. Duan, "A novel synchronous permanent magnet planar motor and its model for control applications," *IEEE Trans. Magn.,* vol.41, pp.2156-2163,June. 2005

[4] Jianpei. Zhou, Rui. Huang, Gyu-Tak Kim, "Characteristics analysis and optimization of a Novel Synchronous

permanent magnet planar motor," *IEEE CEFC Digest Book.*, pp.153, April. 2006.

[5] Jianpei. Zhou, Rui. Huang, Donh-Yeup Lee, Gyu-Tak Kim, "Thrust optimization of synchronous permanent magnet planar motor with Halbach array by using genetic algorithm," *IEEE CEFC Digest Book.*, pp.475, April. 2006.

저 자 소 개



주 건 배 (周 建 配)

1979년 12월 4일생. 2002년 중국 심양 동북대학교 졸업. 2005년 창원대학교 전기공학과 대학원 입학. 현재 동 대학원 전기공학과 석사과정.

Tel : 055-279-7642

Fax : 055-263-9956

E-mail : zhoujp321@hotmail.com

황 예 (黃 蕊)

1979년 11월 27일생. 2002년 중국 심양 동북대학교 졸업. 2005년 창원대학교 전기공학과 대학원 입학. 현재 동 대학원 전기공학과 석사과정.

Tel : 055-279-7642

Fax : 055-263-9956

E-mail : misshuengrui@hotmail.com

이 동 엽 (李 東 燁)

1976년 3월 29일생. 2001년 창원대학교 공대 전기공학과 졸업. 2004년 동 대학원 전기공학과 졸업(석사). 2004년~현재 동 대학원 전기공학과 박사과정.

Tel : 055-279-7642

Fax : 055-263-9956

E-mail : dongyeuplee@changwon.ac.kr

김 규 탁 (金 奎 卓)

1961년 11월 12일생. 1982년 한양대학교 공대 전기공학과 졸업. 1984년 동 대학원 전기공학과 졸업(석사). 1991년 동대학원 전기공학과 졸업(공박). 1996~2000년 일본 早稻田大 客員硏究員. 현재 창원대학교 공대 전기공학과 교수.

Tel : 055-279-7515

Fax : 055-263-9956

E-mail : gtkim@sarim.changwon.ac.kr