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Halbach 배열 영구자석형 Planar Motor의 수직력 해석 및 영향

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A study of normal force and its effect in a SPMPM with Halbach array

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Abstract - This paper presents normal force analysis and its minimization of synchronous permanent magnet planar motor(SPMPM) with Halbach array. Firstly, the experimental error of thrust is investigated and it is caused by the friction force generated by normal force. Then normal force is analyzed by Maxwell stress tensor. At last, the normal force is minimized by using genetic algorithm and it is decreased from 672.83[N] to 144.24[N] remarkably.

1. Introduction

Planar motors are widely applied in many industry fields such as components insertion system, integrated-circuits fabrication, precision metal-cutting, etc. Compared with the conventional system using two linear motors to achieve a surface motion, the planar motor has the advantages such as direct driving and high accuracy. Especially, the synchronous permanent magnet planar motor(SPMPM) is widely used because of its low cost, simple structure, high energy density, etc [1] - [3].

This study is emphasized on normal force analysis and its minimization of the SPMPM. The thrust has been analyzed by Lorentz force[4]. The experimental values of thrust are smaller than the simulation ones because of the friction force which is generated greatly by normal force. So, it is necessary to analyze normal force and to minimize it.

2. Model and dimensions

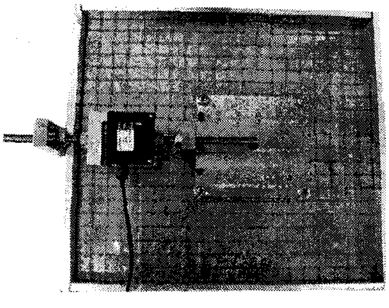


Fig.1 The prototype machine of the SPMPM

Fig.1 shows the prototype machine of the SPMPM with Halbach magnet array. It has the mover with four sets of three-phase armature windings and the stator on which the Halbach magnet arrays are mounted. The dimensions of the prototype machine are described in Table 1.

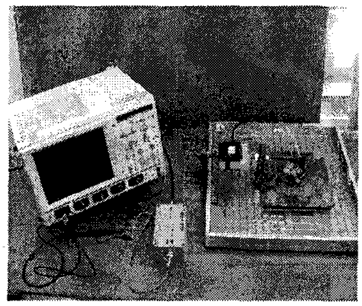
Table 1 Dimensions of the prototype machine

Parts	Items	Symbols	Quantity	Units
Permanent Magnet	Recoil permeability	μ_r	1.05	
	Magnet retentivity	B_r	1.3	T
	Pitch of the array		20	mm
	Thickness	l_m	10	mm
	Width	p	18	mm
Mechanical air-gap	length	l_s	1	mm
Armature winding	Width	w_c	9	mm
	Terminal length	w	6.6	mm
	Effective length	d	20	mm
	Inner radius	r	0.5	mm
	Phase interval	w_d	1.03	mm
	Thickness	l_c	6	mm
Turns/phase		N_t	770	

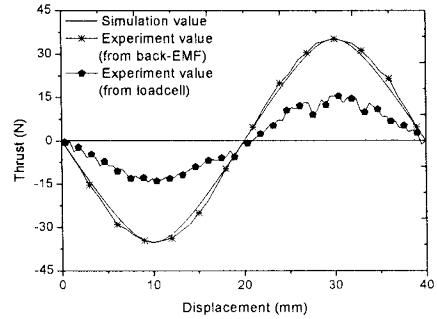
3. Experiment and investigation

To verify the propriety of the thrust analysis, the experiment of thrust is implemented. The thrust is measured by load cell (model UU-K010 (cap. 10kgf), DACELL Co.). The three-phase current is supplied to the armature windings of prototype machine, output voltage of Load cell is measured by Oscillo-Scope(model: LT364L). The magnitude of this voltage is very small and it is amplified by the Amplifier (model STT-100, SCALE-TRON).

The thrust experiment equipments are shown in Fig.2 (a) and the experimental results are revealed in Fig.2 (b).In this case, the input current is 1[A], the thrust values calculated from the experimental ones of back-EMF are close to simulation results well, but the values measured by Load cell are very smaller than simulation values and the calculation ones of back-EMF.



(a) The experiment equipments of thrust



(b) Thrust comparison
Fig.2. The thrust characteristic

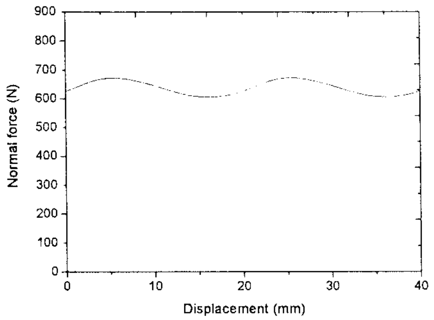
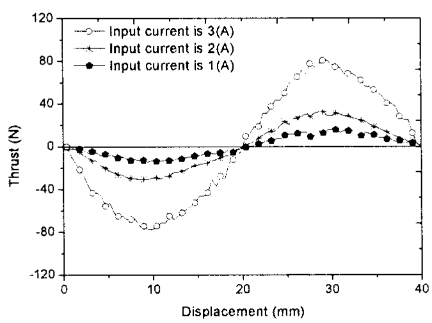


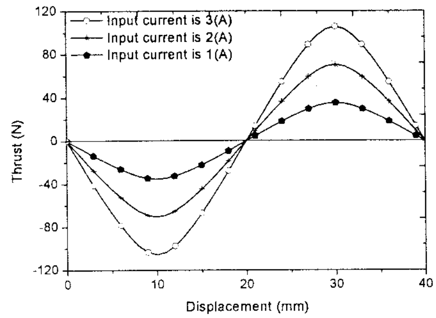
Fig. 3 The normal force characteristic

The normal force is analyzed by Maxwell stress tensor. Fig. 3 shows the normal force of the prototype machine, the peak value of the normal force is 672.83[N] when input current is 1[A] and it is about 19 times to the peak value of thrust which is 35.22[N], i.e. the maximum value of normal force is very larger than the peak value of thrust. Therefore, the measured values of thrust are very smaller than those of simulation because of the friction force generated by the normal force.

On the second thought, as shown in Fig.4, when the input current of armature windings is 1[A], the maximum experimental value of thrust is 44.04% of the peak simulation value; in case of the input current is 2[A], the ratio is 45.81%; and if the input current is 3[A], that ratio is 76.35%.



(a) Experimental values



(b) Simulation values
Fig. 4 Thrust Characteristics

From upper investigation, it can be concluded that the smaller the input current is, the larger the effect of fraction force generated by normal force is. so, it is necessary to minimize the normal force.

4. Normal force minimization

A. Identification of the minimization problem

In this minimization problem, there are six parameters are selected as optimal variables and the detail is defined in Table 2. As a consequence, the problem is defined as:

Find a global best solution $X=[x_1, x_2, \ldots, x_6]^T$
To minimize $f(x)=F_n(x)$ (1)

Where, $F_n(x)$ is normal force.
Some constraints are defined in subsequently.

Table 2 Variables and boundary conditions

Variables	Boundary
x_1 : magnet width p	15 [mm]<= x_1 <=18[mm]
x_2 : magnet thickness l_m	5[mm]<= x_2 <=12[mm]
x_3 : coil terminal length w	4[mm]<= x_3 <=9[mm]
x_4 : coil width w_c	4[mm]<= x_4 <=9[mm]
x_5 : coil effective length d	15[mm]<= x_5 <=20[mm]
x_6 : coil thickness l_c	4[mm]<= x_6 <=10[mm]

B. The constraints of minimization problem

There are some kinds of constraints of this minimization problem, regarding to search space, manufacture requirement and thrust. The search space boundary constraints are shown as Table 2. Other constraints are described as fellows:

$$g_1(x): F(x) - 35 \geq 0$$

$$g_2(x): 1 \leq 80/3 - 2x_4 - 1 - x_3 \leq 3$$

Where, $g_1(x)$ is the thrust constraints which is required larger than 35[N] and $g_2(x)$ is the clear space between the align armature windings and is constrained in 1[mm] and 3[mm].

C. Minimization program

Genetic Algorithm(GA), as a powerful and broadly applicable stochastic search and optimization technique, is perhaps the most widely known type of Evolutionary Computation methods today for its advantages in large scale calculation. In the case of this minimization problem, there are over millions points in search space, so genetic algorithm with penalty function is used to solve the minimization problem. The fitness function is defined as following formula:

$$Fitness = f(x) + p(x) \tag{2}$$

The penalty function, $p(x)$, is defined as follows.

$$p(x) = \epsilon \left[w_1 \times \sum_{i=1}^{c} \left\{ \frac{g_i(x)}{g^*} \right\} + w_2 \times \sum_{i=1}^{c} \left\{ \frac{\phi_i(x)}{\phi^*} \right\} \right] \tag{3}$$

Where, $g_i(x)$, $\phi_i(x)$ are level of violation and amount of violation for the i-th constraint; w_1, w_2 are weighting factors; g^*, ϕ^* are scaling factors; ϵ is -1 for maximization and +1 for minimization. Assigned values for w_1, w_2, are 0.2 and 0.5 respectively.

In this study, we use the elementary operations of genetic algorithm, such as selection, crossover, and mutation.

D. Minimization results and investigation

The generation iteration process of genetic algorithm can be seen in Fig.5. The parameters of the prototype machine are optimized and the results are shown in Table 3.

The contrast of characteristics between the original model and optimal model can be seen in Fig.6. To the original model, the peak value of the normal force is decreased from 672.83N] to 144.24[N] remarkably as shown in Fig.6 (a), but the peak value of thrust is decreased from 35.22[N] to 35[N] as shown in Fig.6 (b).

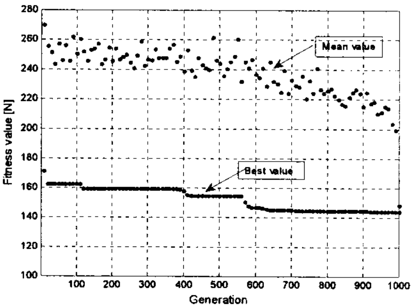
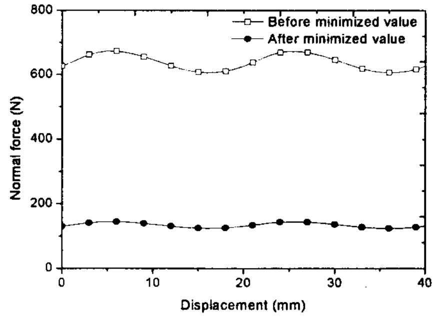


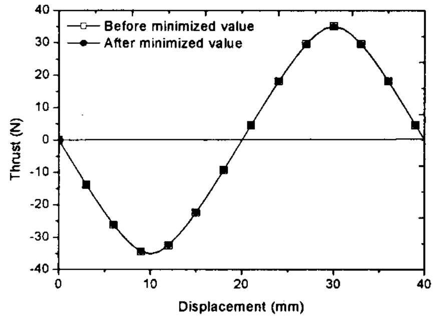
Fig. 5 The generation iteration process

Table 3 Parameters comparison after minimization

Symbols	Units	Before minimization	After minimization
magnet width p	mm	18	18
magnet thickness l_m	mm	10	7
coil terminal interval w	mm	6.6	6.5
coil width w_c	mm	9	9
coil effictive length d	mm	20	19.4
coil thickness l_c	mm	6	10
Turns		770	1284



(a) The normal force



(b) The thrust

Fig. 6 The characteristics comparison

5. Conclusion

The characteristics of the SPMPM with Halbach magnet array are evaluated by the analytical method. By compared to the experiment values and simulation ones, the propriety of the analysis is verified.

By analyzed the error in experimental values of thrust, the undesired effect of normal force is analyzed in detail.

Because of the undesired effect of the normal force, the efficiency of the SPMPM is low. So, in this paper, the genetic algorithm is applied to optimize normal force minimization and normal force is remarkably decreased from 672.83[N] to 144.24[N].

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