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# Characteristics Analysis of the Synchronous Permanent Magnet Planar Motor with New Permanent Magnet Array

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***Abstract* – In the paper, a new and simple permanent magnet array is proposed and analyzed by using magnetic scalar potential. The characteristics of the synchronous permanent magnet planar motor (SPMPM) with new array such as linkage flux, back-EMF, and thrust are calculated by analytical method. The superiority and feasibility of the new magnet array are verified by comparing with Asakawa array, Chitayat array, and experiment data.**

***Index Terms - Characteristics analysis; new permanent magnet array; planar motor.***

## I. INTRODUCTION

Early stage, rotary motor and the middle conversion device are used to realize the linear motion. With the emergence and development of linear motor, the x-y linear motors are used to realize the surface motion. But this device increases the complexity of the transmission system. So the research and development of the planar motor are urgently needed.

The planar motor, which is instead of x-y liner motor, can drive 2-D device directly. The planar motor has more advantages such as low friction, no backlash, easy packaging and high accuracy, so it has been applied in the various fields, such as, machining operation, electronic products production and even drive robot. Until now, some types of planar motors have been researched. According to their operation principles, most of the planar motors can be classified into three types, i.e., variable reluctance planar motor, induction planar motor, and the synchronous permanent magnet planar motor (SPMPM). Among them, the synchronous permanent magnet planar motor has the advantages of low cost, simple structure, high-power conversion ratio, etc [1-3]. It has been investigated by more and more researchers and engineers in the academic and engineering fields.

The electromagnetic thrust of SPMPM is generated by the interaction between the magnetic field of permanent magnet array and the current of coil array. The higher magnetic flux density of permanent magnet array is, the larger electromagnetic thrust is. So the topological structure and its analytical method of permanent magnet array are important for the SPMPM. The topological structure of permanent magnet array is the key to planar motor. At present, many permanent magnet arrays have been designed to obtain the desired magnetic field distribution in the patents and papers in [4-7].

Fig. 1 illustrates the magnet arrays for planar motor. Asakawa array and Chitayat array have been investigated in patents [4, 5]. A new and simple permanent magnet array is proposed in Fig. 1(c). The packing density of new array is 100% which is higher than that of Asakawa array, 50%. The new array is simpler than Chitayat array at edge. The magnetic field of the new array is analyzed by using scalar magnetic potential.

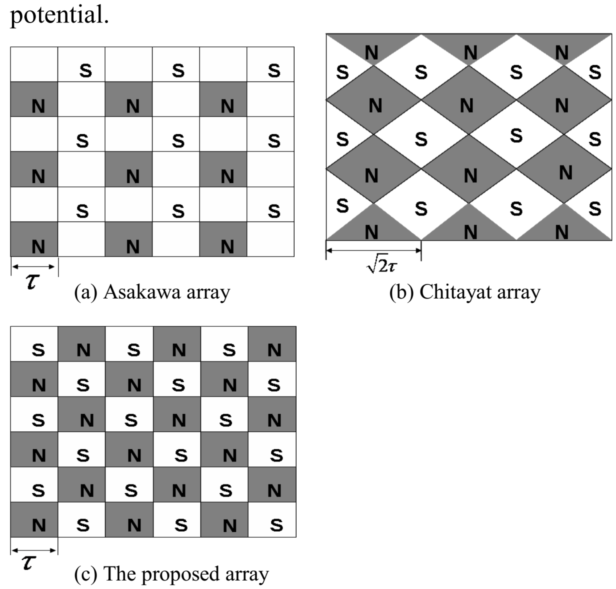



Fig. 1 Magnet arrays for planar motor

In general, finite-element analysis (FEA) is used to evaluate the characteristics of motors. Compared with FEA which costs a long time to calculate and needs a high performance computer, the analytical method can save the cost of the characteristics analysis. Therefore, in the paper the simple permanent magnet array is proposed and the characteristics of the prototype machine are evaluated by analytical method firstly; then the measured values are used to verify the propriety of the analytical methods; finally, the proposed array is comparing with Asakawa array, Chitayat array, and experiment data.

## II. STRUCTURE AND PRINCIPLE

### A. *Structure*

1) The structure of planar motor:

Like other electronic motors, the planar motor consists of stator, mover, position detection device and supporting equipment. The SPMPM has two types in the mover and stator collocation. One is the moving-magnet-type which chooses the magnet as the mover and the coil as the stator and another is moving-coil-type which chooses the coil as the mover and the magnet as the stator. In this paper, we study the moving-coil-type SPMPM which is suitable for the long stroke applications since the movers can move freely. Fig. 2 shows the outline view of the 3-phase SPMPM which employs permanent magnet array as the stator. There are four coil sets in the air-gap, two coil sets are used for driving in the x-direction and the others for y-direction. To move in the x and y directions, the coil sets need the appropriate magnet array arrangement that is same shape when viewed from the x and y sides. Fig.3 shows the part-view of analytical model of the planar motor. It employs permanent magnet array as the stator and coil as the mover.

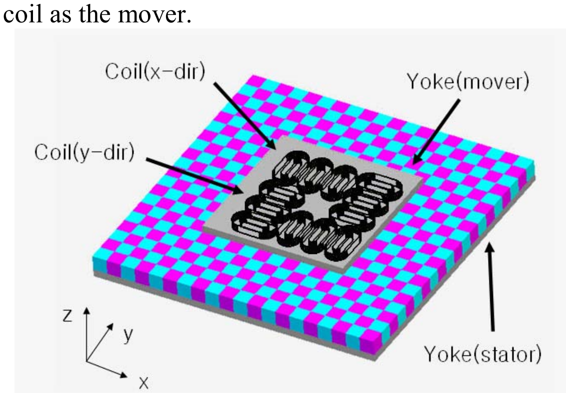



Fig. 2 Outline view of the 3-phase synchronous permanent magnet planar motor.

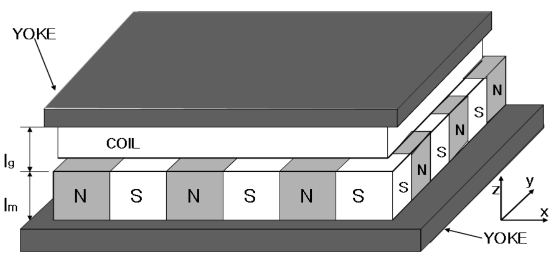



Fig. 3 The out line of analysis model

2) The structure of permanent Magnet array:

Fig.4 shows the proposed magnet array in this paper. For comparison convenience, the pitch of permanent magnet which mentioned in this paper is same unless otherwise statement.

3) The structure of coil Shape:

Fig.5 shows the shape of coil on the mover. There are four coil sets on the mover: two coil sets are used for x-direction motion and others for y-direction motion. Table I displays the dimensions and material properties.

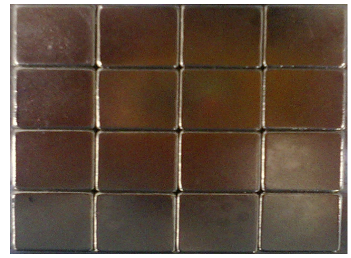


Fig. 4 The prototype top-view of proposed magnet array.

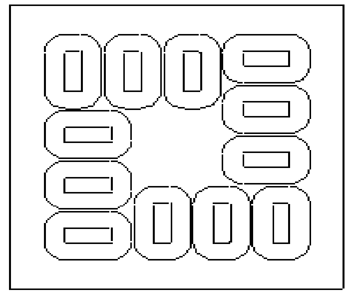


Fig. 5 Coil arrangement on the mover

TABLE I
Dimensions of the Prototype Machine

| Parts | Items | Symbols | Quantity | Units |
|---|---|---|---|---|
| Permanent Magnet | Recoil permeability | $\mu_r$ | 1.05 | |
| | Residual flux density | $B_r$ | 1.3 | T |
| | Pitch of the array | $\tau$ | 20 | mm |
| | Thickness | $l_m$ | 10 | mm |
| | Width | $p$ | 20 | mm |
| Mechanical air-gap | Length | $l_s$ | 1 | mm |
| Armature winding | Width | $w_c$ | 8.5 | mm |
| | Terminal length | $w$ | 8.0 | mm |
| | Effective length | $d$ | 20 | mm |
| | Inner radius | $r$ | 0.5 | mm |
| | Phase interval | $w_d$ | 1.03 | mm |
| | Thickness | $l_c$ | 5 | mm |
| Turns/phase | | $N_t$ | 600 | |

## B. *Principle*

In this paper, 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. By the method of Fourier series, the magnetization distribution of the proposed magnet array is expressed as

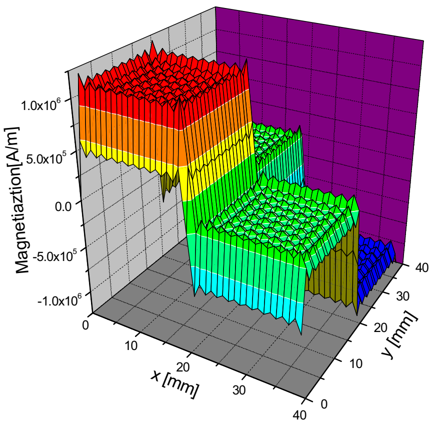
$$\overrightarrow{M} = M_x \vec{x} + M_y \vec{y} + M_z \vec{z} \tag{1}$$

where,

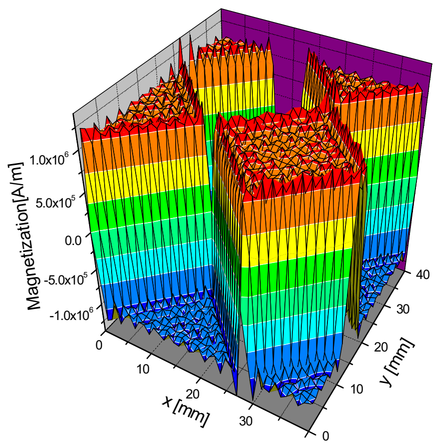
$$M_x = M_y = 0$$

$$M_z = \sum_{k=1,3...}^{\infty} \sum_{l=1,3...}^{\infty} M_{kl} \,\mathbf{sin}(a_k x)\,\mathbf{sin}(a_l y)$$

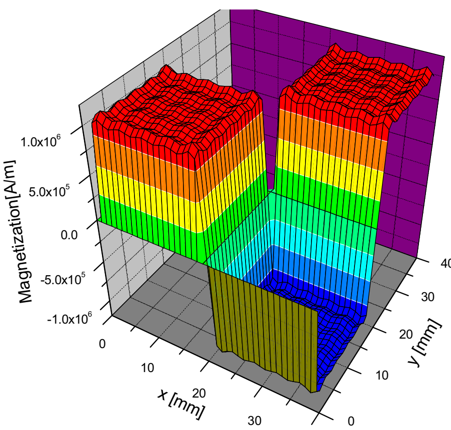
$$M_{kl} = \frac{B_r}{\mu_0} \frac{16}{\pi^2} \frac{1}{kl}, \quad a_k = k\frac{\pi}{p}, \quad a_l = l\frac{\pi}{p} \ .$$




(a) Asakawa



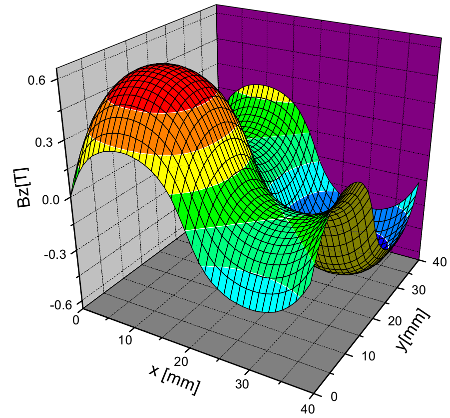

(b) Chitayat



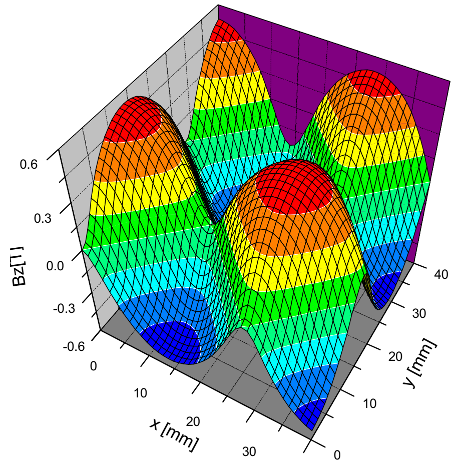

(c) Proposed model

Fig. 6 Magnetization distribution

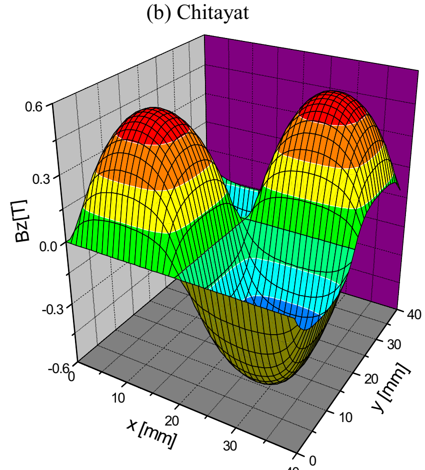
Fig.6 shows the magnetization distribution of Asakawa, Chitayat and proposed magnet arrays.




(a) Asakawa




(b) Chitayat




(c) Proposed model

Fig. 7 Flux density distribution

## III. Characteristics Analysis

The characteristics of the SPMPM based on the novel magnet array are evaluated in this section.

### *A. The z-component of Flux density*

The flux density in the air gap is obtained as follow:

$$B_{gz} = \mu_0 H_{gz} = -2\mu_0 \sum_{k=1,3...}^{\infty}\sum_{l=1,3...}^{\infty} B_{kl}\,\lambda_{kl}\, e^{\lambda_{kl}(l_g+l_m)} \times \mathbf{cosh}(\lambda_{kl}(z-(l_g+l_m)))\,\mathbf{sin}(a_k x)\,\mathbf{sin}(a_l y) \tag{2}$$

where,

$$B_{kl} = -\frac{M_{kl}}{2\lambda_{kl}}\frac{\mathbf{sinh}(-\lambda_{kl}(l_g+l_m))\,\mathbf{sinh}(\lambda_{kl}l_m)}{sch_{kl}}$$

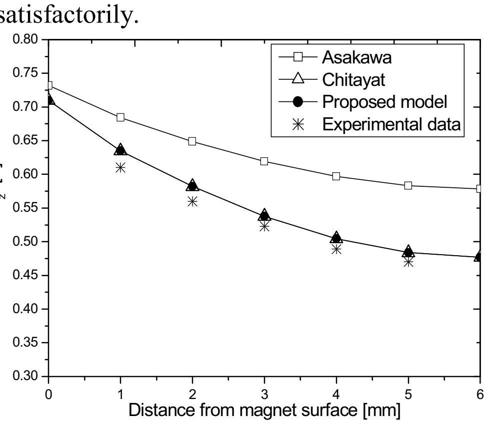
$$\lambda_{kl} = \sqrt{a_k^{\,2} + a_l^{\,2}}$$

$$sch_{kl} = \mu_r\,\mathbf{sinh}(\lambda_{kl}l_g)\,\mathbf{cosh}(\lambda_{kl}l_m) + \mathbf{cosh}(\lambda_{kl}l_g)\,\mathbf{sinh}(\lambda_{kl}l_m)$$

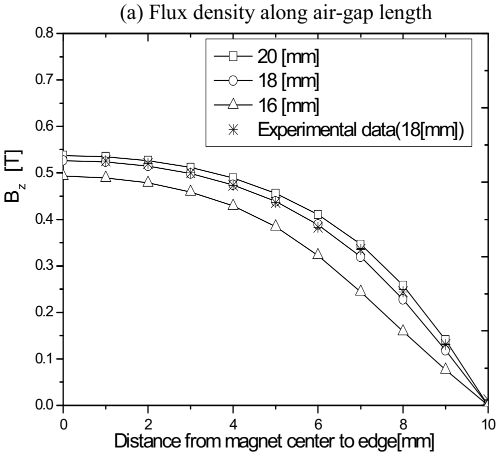
.

Fig. 7 shows the air-gap flux density distribution on the xy plane which is 3[mm] apart from the magnet surface.

Fig. 8 (a) shows the flux density distribution from magnet surface to mover yoke at magnet center. Fig. 8 (b) shows the flux density variety on the x-y plane which is 3.5 [mm] apart from the magnet surface according to reducing the sizes of permanent magnet of the proposed array. When the width of permanent magnet is reduced from 20[mm] to 18[mm], the z component of flux density is almost similar, the flux increment acts as leakage flux rather than linkage flux when the width of permanent magnet exceeds 18[mm]. The simulation values of proposed model agree with experimental values satisfactorily.




(a) Flux density along air-gap length




(b)Flux density distribution of z component according to magnet width

Fig. 8 The flux density characteristics

### B. *Linkage flux*

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

$$\varphi = \iint B_{gz}\; dx\; dy = \frac{A}{a_k\, a_l}(\mathbf{cos}(a_k(x_0+p)) - \mathbf{cos}(a_k x_0)) \tag{3}$$

where,

$$A = 2\mu_0 \sum_{k=1,3,...}^{\infty}\sum_{l=1,3,...}^{\infty} B_{kl}\;\lambda_{kl}(\mathbf{exp}(\lambda_{kl}z) + \mathbf{exp}(\lambda_{kl}(2(l_g+l_m)-z)))\ .$$

### C. *Back-EMF*

The Back-EMF of one phase coil is expressed as

$$E = -\frac{d\lambda}{dt} = -N_t\frac{d\varphi}{dt} = \frac{A}{a_l}(\mathbf{sin}(a_k(x_0+p)) - \mathbf{sin}(a_k x_0))\ . \tag{4}$$

### D. *Inductance*

The inductance can be evaluated as

$$L = \frac{N_t\varphi}{i} = \frac{2N_t C}{kl}(\mathbf{cos}(a_k(x_0+p)) - \mathbf{cos}(a_k x_0)) \tag{5}$$

where,

$$C = \frac{8B_r}{\pi^2 D}\frac{1}{kl}(\mathbf{exp}(\lambda_{kl}z) + \mathbf{exp}(2\lambda_{kl}(l_g+l_m)))\,\mathbf{exp}(-\lambda_{kl}z)$$

$$D = \mathbf{exp}(\lambda_{kl}(l_g+l_m))\,\mathbf{sinh}(\lambda_{kl}l_g)\left(\frac{\mu_r}{\mathbf{tanh}(\lambda_{kl}l_m)} + \frac{1}{\mathbf{tanh}(\lambda_{kl}l_g)}\right)$$

### E. *Force*

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

$$F_x = \frac{-12N_t IT}{w_c a_l a_k}\mathbf{sin}(a_l y)\,\mathbf{sin}(a_l\frac{d}{2})\,\mathbf{sin}(a_k(\frac{w}{2}+1+\frac{w_c}{2}))\,\mathbf{sin}(\frac{a_k w_c}{2}) \tag{6}$$

where,

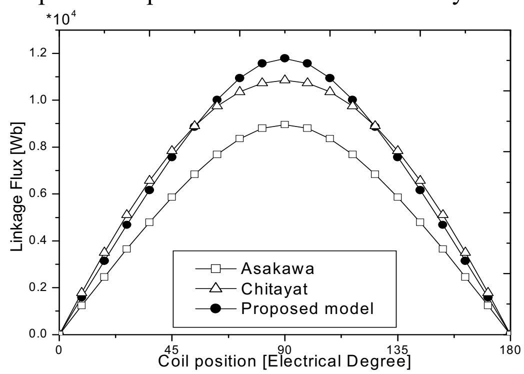
$$T = \frac{16B_r(l_g-l_s)}{\lambda_{kl}a_l a_k p^2}\mathbf{sinh}(\lambda_{kl}l_m)\,\mathbf{sinh}(\lambda_{kl}(l_g-l_s))\,\mathbf{sinh}(\lambda_{kl}(l_m+l_g))$$

Fig. 9 (a) shows the results of the linkage flux. The amount of peak flux of the novel array is 8.7% larger than that of Chitayat array and 31.6[%] larger than that of Asakawa array. Fig. 9 (b) shows the back-EMF characteristics. The back-EMF of the novel array is 9.8[%] larger than that of Chitayat array and 34.1[%] larger than that of Asakawa array. Fig. 9 (c) reveals force versus current at current is 1[A]. The force of the novel array is 9.1[%] larger than that of Chitayat array and 33.4[%] larger than that of Asakawa array. The experiment value is measured by load cell (model UU-K010 (cap. 10kgf), DACELL Co.). In case of the current is low, the friction will be increase correspondingly, so errors between the experiment and the simulation values occur.

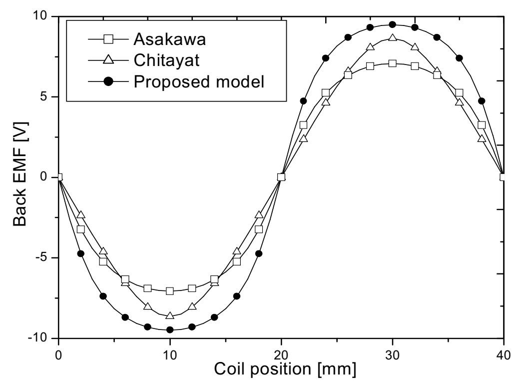
## IV. Conclusion

The synchronous permanent magnet planar motor with new permanent magnet array has been proposed. The analytical method for magnetic field calculation was developed. In order to evaluate the performances of the novel permanent magnet, linkage flux, back electromotive force and force were calculated and compared with those of Asakawa and Chitayat arrays. By experiment results, it can be verified that the proposed magnet array is proper.

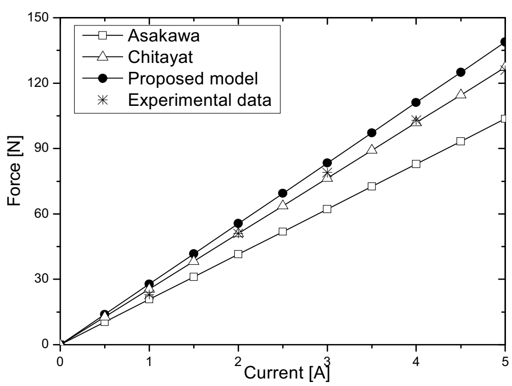
Through the analysis, it can be concluded that the new array is simple and superior to Asakawa and Chitayat arrays.




(a) Linkage flux




(b) Back-EMF




(c) Force

Fig. 9 The characteristic comparisons

## ACKNOWLEDGMENT

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