Design of a Magnetically Levitated Six Degrees-of-freedom Planar Motor using T-shape Halbach Magnet Array

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Abstract

We propose, and design a new magnetically levitated planar motor which increases force density and reduces force ripple. The key feature is to use newly developed T-shape Halbach magnet array. In order to maximize force density and minimize force ripple, we present design optimization framework based on analytic modeling method. We verify the effectiveness of the proposed planar motor.

1 Introduction

Smaller, faster, cheaper. These are the fundamental goals of the next-generation semiconductor industry [1]. To achieve these goals, a stage system should have several capabilities: six degrees-of-freedom motion, nano-positioing and scanning, long travel range, high speed, and high vacuum-compatibility.

Magnetically levitated planar motors have been developed to achieve these goals. They should generate high force to improve positioning accuracy and product throughput. They should have small force ripple to improve scanning performance.

We propose, and design a new magnetically levitated planar motor which increases force density and reduces force ripple. The key feature is to use newly developed T-shape Halbach magnet array. It generates higher force and lower force ripple than previously developed planar motors. In addition, the proposed magnet array can be easily constructed, and therefore reduce manufacturing cost.

2 Concept of the Proposed Planar Motor

In this section, the concept of the proposed planar is described. The newly developed T-shape Halbach magnet array is proposed.

2.1 Configuration

We adopt a moving magnet structure. The mover is contactless because no cable to the mover is necessary. Since the coils, which require power and cooling, are on the stationary part, the disturbances and heat transfered to the mover are reduced.

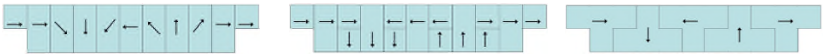
We adopt the configuration of a 2D magnet array with multiple short-coils. It can move over six degrees-of-freedom by controlling individual coils only below a magnet array. Therefore, power consumption is reduced. The stroke only depends on the stator size. It can, in principle, be made infinitely long by adding extra stator coils.

2.2 Proposed T-shape Halbach Magnet Array

We propose a T-shape Halbach magnet array. It consists of four T-shape magnet blocks per period, with the magnetization vector rotating by 90 degrees in each subsequent block. It generates higher magnetic flux density and low ripples than previously developed magnet arrays used in planar motors.

Previously developed planar motors adopt either a conventional NS magnet array or a 2-segmented Halbach magnet array [2]. Halbach magnet arrays generate higher magnetic flux density than conventional NS magnet array, and therefore generates higher force [3]. Halbach magnet arrays with more segmented magnet blocks per period generate higher forces and lower force ripple. However, since it is very difficult to construct, Halbach magnet arrays with four or more segmented magnet blocks have not yet been implemented for planar motors.

The T-shape Halbach magnet array generates higher flux density and lower ripples than a 2-segmented Halbach magnet array, since it is conceptually similar with a 4-segmented Halbach magnet array. Fig. 1 shows the conceptual similarity. A 4-segmented Halbach magnet array can be decomposed as shown in Fig. 1(b). The T-shape Halbach magnet array is made by composing magnet blocks magnetized in same directions, as shown in Fig. 1(c). It can be easily constructed since its rugged shape reduces the repulsion force between each subsequent magnet blocks.



(a) 4-segmented Halbach array (b) Decomposed array (c) T-shape Halbach array

Fig.1 Conceptual similarity between 4-segmented and T-shape Halbach magnet array

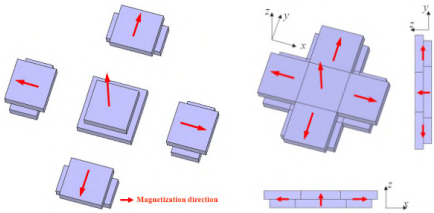


Fig.2 Single unit of T-shape Halbach array

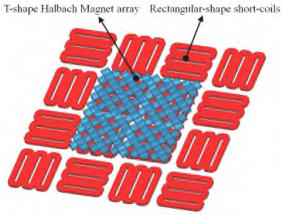


Fig.3 Concept of the planar motor

A unit of the T-shape Halbach magnet array is illustrated in Fig. 2. It consists of a normally-magnetized magnet block and four transversely-magnetized magnet blocks. Overall concept of the planar motor is shown in Fig. 3.

3 Design Optimization based on Analytic Modeling

3.1 Analytic Modeling

The T-shape Halbach magnet array is regarded as combination of multiple cuboidal magnets. The magnetic field of a cuboidal magnet is derived from Maxwell equations, using the magnetic surface charge method [4]. The magnetic field distribution of the proposed magnet array is obtained by coordinate transformation and superposition of the individual magnetic fields of all magnet blocks. Finally, forces and torques acting on the mover is calculated based on Lorentz force law.

3.2 Design Optimization

We define six design variables: Halbach ratio of upper and lower magnet, thickness of upper and lower magnet, thickness of coil, and coil turns.

Planar motor should generate high force density to improve positioning accuracy and throughput, and small force ripple to improve scanning performance. We present design optimization framework to determine optimal design variables. The objective is to maximize force density, defined by minimizing the cost function, $f = (m_{mover}/F_x)^2$. The optimization problem should satisfy constraints. In order to improve scanning performance, force ripple should be minimized. Temperature during operation should be maintained lower than allowable temperature. The voltage and current should be lower than maximum output of the power amplifiers.

Design optimization process is realized using MATLAB optimization toolbox based on a sequencial quadratic programming method. To guarantee global minimum, 12 optimizations are performed with different random initial points. All the results are converged to a global minimum statistically according to Bayesian stopping rule [5]. Final dimensions have been determined considering tolerance analysis.

We compared the force components of the proposed planar motor with that using a 2-segmented Halbach magnet array. The planar motor using a 2-segmented Halbach magnet array was optimally designed using the same optimization frameworks with a condition of same mover mass. Force components when the mover moves in x-direction with generating only propulsion force and only levitation force are

compared, respectively. The results are shown in Fig. 4. Mean values of forces in *x*-and *z*-direction are improved by 6.2% and 3.7%, respectively. Force ripples in *z*-direction are reduced by 39.2%.

Final design of the proposed planar motor is shown in Fig. 5. The size of mover and stator are 350x350x70mm^3 including the bar mirror, and 650x650x74mm^3 including water cooling plate, respectively.

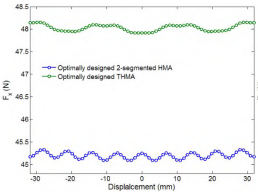


Fig. 4(a) F_x component

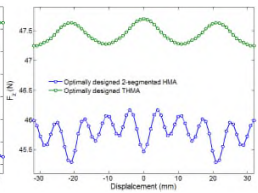


Fig. 4(b) F_z component

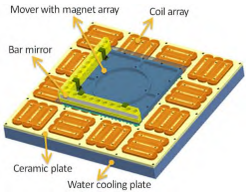


Fig.5 Designed planar motor

4 Conclusion

A new magnetically levitated planar motor using T-shape Halbach magnet array has been proposed and optimally designed. It generates higher force density and lower force ripple than that using a 2-segmented Halbach magnet array. This is due to the proposed magnet array is conceptually similar with a 4-segmented Halbach magnet array. It can be easily constructed. The dimensions have been determined using design optimization frameworks. We verified the effectiveness of the proposed planar motor by comparing forces and force ripples with that using an optimally designed 2-segmented Halbach magnet array.

References:

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