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Round layout Halbach array using cylinder-shaped permanent magnets

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Abstract

The purpose of the study was to examine the sliding performance of the magnetic field above a Halbach array constructed with cylindrical permanent magnets, and explore a variety of advanced layouts. Halbach arrays are effective in forming a strong magnetic field. However, the magnetic field in a conventional model is difficult to control because all the rectangular-shaped permanent magnets are strongly fixed. The proposed Halbach array was constructed with eleven cylinder-shaped permanent magnets magnetized in the radial direction. In the proto-model of a Halbach array using cylindrical permanent magnets and synchronized rotation in the same direction of all magnets, the slide of the magnetic field distribution was confirmed by quasi-static measurement and simulation of magnetic field. The slide performance of the magnetic field is believed to contribute to the high performance of magnetic actuation, and further, a novel layered or round layout Halbach array has led to the development of a new model actuator. In this paper, we present two round layout models having the characteristics of magnetic field control and constitutive flexibility and we show preliminary results by magnetic field analysis.

Keywords : Halbach array, Cylinder-shaped PM, Magnetic field control, Round layout, Magnetic actuation

1. Introduction

Recently, a non-contact actuator has been deemed effective for environmental protection in MEMS (microelectromechanical systems) processing in a production plant. Various performance improvements have been proposed to adapt the device for use in industrial settings. For example, in a non-contact magnetic suspension type actuator, improvement of the magnetic suspension force is the most important technical element for load characteristics. A Halbach PM (permanent magnet) array is effective in forming a strong magnetic field. The Halbach array that uses rectangular-shaped permanent magnets has a specific distribution of a strong magnetic flux density on one surface of the array and a very weak magnetic flux distribution on the opposite surface of the array. This configuration is currently the most promising in terms of forming an improved and strong magnetic field for magnetic suspension force. For this reason, the Halbach PM array has been applied to a lightweight compact and high torque motor and contact or non-contact magnetic actuators.

However, the conventional Halbach array model makes it difficult to control the magnetic field because all the rectangular-shaped permanent magnets are strongly fixed. If a strong magnetic field were generated and the magnetic field distribution formed by the Halbach array could be easily controlled it could greatly influence the development of magnetic suspension actuators applications with a functional expansion.

To solve the problem of magnetic field control of the Halbach array, J. E. Hilton and S. M. McMurry (2012) reported on magnetic field control by a linear Halbach array using cylindrical permanent magnets with magnetized in a radial direction. By alternate reverse rotation of all cylinder-shaped permanent magnets, the model formed a strong magnetic field that could be reversed from top side to the bottom side by magnetic field simulation.

In September 2013, instead of inverting the magnetic field, we proposed with magnetic field simulation that the magnetic field could slide along the array direction (x-axis) by synchronizing rotation of the magnets in the same direction (Fig.1, Fig.2 and Fig.3). In January 2014, a test stand consisting of 11 cylinder-shaped permanent magnets for magnetic field verification of the proposed model was produced. We confirmed validity of the magnetic field control functions of the proposed model by quasi-static measurement of magnetic flux density distribution using the test stand (Tsuchiya, et al., 2014, Tokunaga, et al., 2015) and detailed field simulation (Suzuki et al., 2015, 2016).

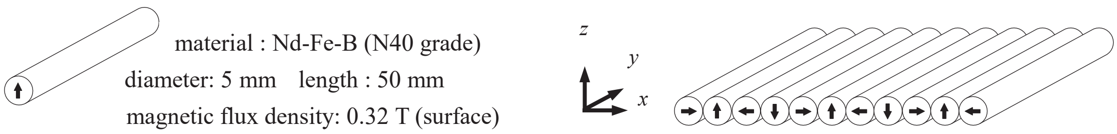
With this brand new concept, for instance, the flux-pinned bulk superconductor could move in the same direction of the sliding magnetic flux due to the rotation of the cylinder. Therefore, the proposed model seems to conform to the planer non-contact actuation mechanism.

In this paper, first, we show an overview of the proposed cylinder shaped PM linear Halbach model, propose two novel round layout models demonstrating magnetic field control and constitutive flexibility, and show preliminary results by magnetic field analysis.

2. Magnetic field performance of the cylinder-shaped PM linear Halbach array

2.1 Concept of the layout and magnetic field control

Fig. 1 shows the schematic view of a cylinder shaped permanent magnet and the basic arrangement of a linear Halbach PM array using eleven cylinder-shaped permanent magnets. Fig.2 shows a conceptual model of a Halbach array with cylinder-shaped permanent magnets and three arrangements at 0, 45, and 90 degrees with synchronized rotation of each cylinder in the same direction; the red line shows one of the maximum values of the magnetic flux density. Fig. 3 shows simulation results for the magnetic field distribution formed by the cylinder-shaped PM linear Halbach array depending on the three angle conditions shown Fig. 2. From the analysis of the rotation angles 0 deg and 90 deg where all of the cylinder-shaped magnets are rotated by 90 degrees, it can be confirmed that the magnetic flux above the array can slide toward the right by the width of permanent magnet.



(a) (b)

Fig. 1 Basic structure of linear Halbach PM array using cylindrical permanent magnets.

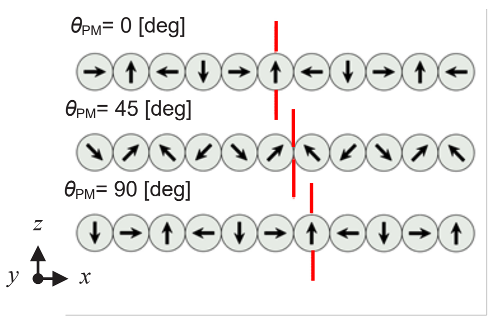


Fig. 2 Conceptual diagram of the magnetic field control in the Halbach array using cylindrical permanent magnets. (rotating all magnets clockwise)

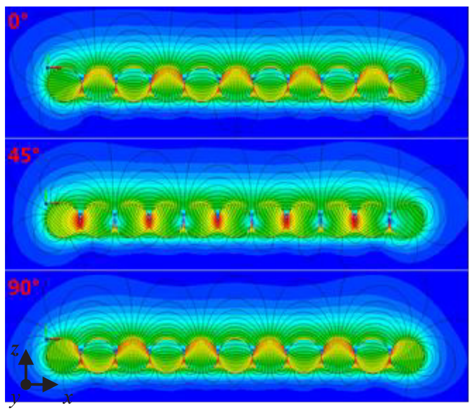


Fig. 3 Magnetic field simulation in three rotational angle conditions (0 deg, 45 deg and 90 deg).

Fig. 4 shows the conceptual model of a Halbach array with cylinder-shaped permanent magnets and seven respective arrangements with 15 degree rotation from 0 to 90 degrees. By causing the same angular rotation of each cylinder in the same direction, we examined whether the distribution of the magnetic flux density on the top side of the array could slide along the direction of the rotation of cylinders. Fig. 5 shows a measuring stand made of aluminum alloy. The linear Halbach array is constructed by using eleven cylinder shaped permanent magnets.

The distribution of the magnetic flux density on the top and bottom of the array was measured in order to check whether this result had the same distribution as Halbach arrays. These measurement results suggest if a Halbach array of cylinder-shaped permanent magnets can be configured. For practical verification of this array, the air gap is set to 2mm with an acrylic plate. Fig. 6(a) and (b) show the measurement results of the magnetic flux density of the top and bottom sides of the array, respectively. Fig. 6(b) shows the distribution of the magnetic flux density on the bottom side of the array is clearly smaller in comparison to the top side. These results confirm that the array has a distribution of the magnetic flux density similar to a Halbach array, by the magnetic field measurement of the actual prototype model.

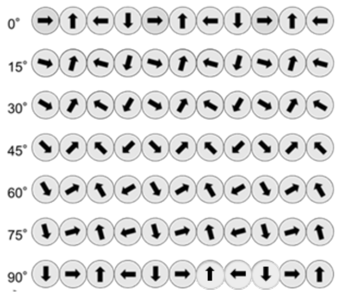


Fig. 4 Conceptual diagram of seven analysis patterns depending on the synchronized rotational angle of all cylinder-shaped permanent magnets.

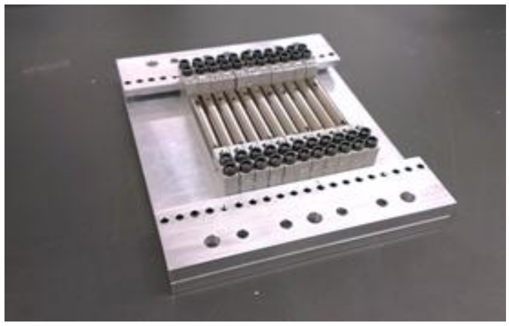
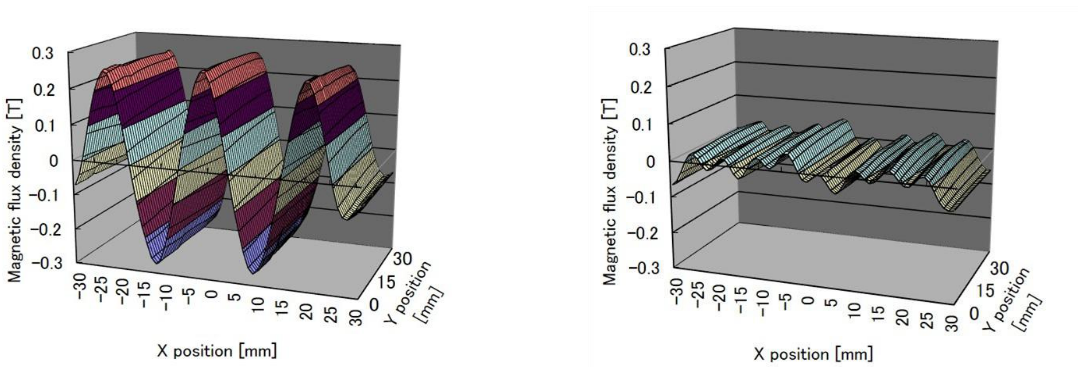


Fig. 5 Actual measuring stand of Halbach array arranged eleven holders with cylinder-shaped permanent magnets.



(a) top side

(b) bottom side

Fig. 6 Measurements of magnetic flux density distribution of the test Halbach array using cylinder-shaped permanent magnets with rotational angle at 0 deg.

2.2 Slide performance of magnetic flux density distribution

Fig. 7 shows the slide performance of the distribution of magnetic flux densities in direction z (Bz) detected by Hall probe line scanning in the x-direction at the center of the cylinder-shaped permanent magnet Halbach array. Fig. 8 shows the results of magnetic field analysis under the same conditions. The analysis of the magnetic flux density used magnetic field analysis software (JMAG-Designer); analysis of 3D models used SolidWorks2013.

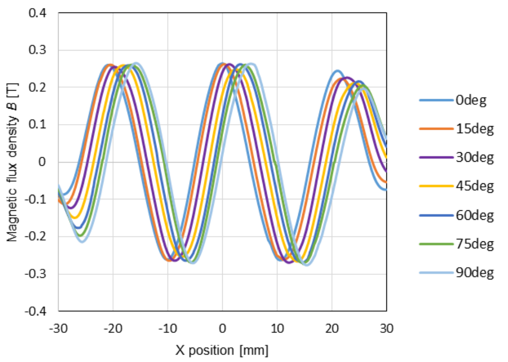


Fig. 7 Measurement of magnetic flux density distribution above the linear Halbach array using cylinder-shaped PMs at rotation angles from 0 to 90 deg.

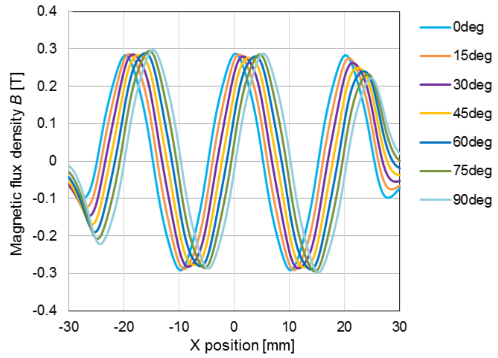


Fig. 8 Simulation of magnetic flux density distribution above the linear Halbach array using cylinder-shaped PMs at rotation angles from 0 to 90 deg.

As shown in Fig. 7 and 8, the specific magnetic field distribution of the Halbach array was confirmed by measuring the actual test model array as well as by magnetic field analysis simulation. Therefore, it is possible to configure a Halbach array with cylinder-shaped permanent magnets. Furthermore, the specific magnetic field distribution of a Halbach array was confirmed to be capable of sliding via synchronized rotation in the same direction and same angle of all magnets by both measuring the test model array and magnetic field analysis simulation. Therefore, the main performance element of our proposed "magnetic field control by the Halbach PM array using cylinder-shaped permanent magnets" was demonstrated by static magnetic field measurements and magnetic field analysis.

3. Proto-model of a round layout Halbach array using cylinder-shaped PMs

A linear Halbach array with cylindrical permanent magnets, not only enable magnetic field control function by rotation of the cylinder-shaped permanent magnets, but the linear Halbach array also imparts flexibility for layout. Therefore, a linear Halbach array may have a round layout. Unlike conventional linear drives, this round layout can extend to the spatial drive of the mover in a magnetic actuator.

As an example, Fig. 9 is a conceptual diagram of two semi-circular linear Halbach array placed around a certain circumference. We are calling this the round layout Halbach array using cylinder-shaped permanent magnets. Fig. 10 shows an enlarged diagram of each of the round layout Halbach arrays. The axes of all cylinder-shaped PMs on both types are placed on an arc of curvature R = 55 [mm].

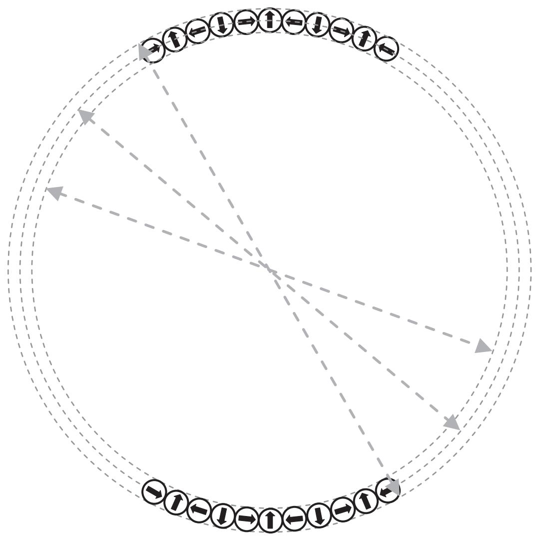
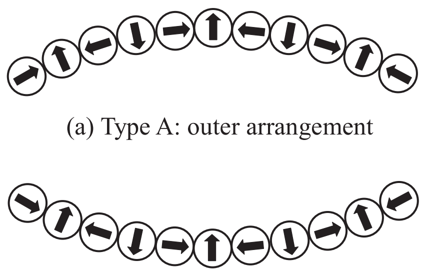


Fig. 9 Conceptual diagram of the cylinder-shaped PM linear Halbach array arranged on the circumference.

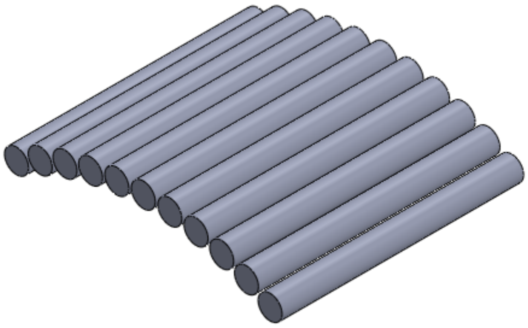


(a) Type A: outer arrangement

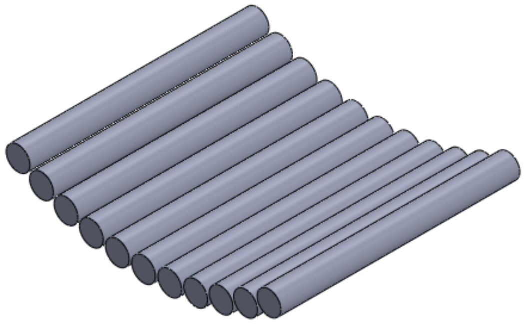
(b) Type U: inner arrangement

Fig. 10 Conceptual diagram of the cylinder-shaped PM linear Halbach arrays arranged in a semicircle.
(a) Type A: outer arrangement (b) Type U: inner arrangement

In the type A round layout model, a strong magnetic field distribution of the Halbach array is formed on the outside surface of the arc shape. In the type U arrangement, the magnetic field is formed on the inside surface. Fig. 11 shows the 3D-CAD model of two round layout linear Halbach arrays using cylinder-shaped PMs for magnetic field analysis. Preliminary magnetic field vector maps for the two kinds of arrangements are shown in Fig. 12 and 13. These results show clearly the sliding of the magnetic field distribution.

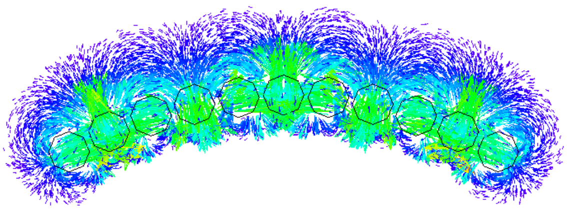


(a) Type A: outer arrangement

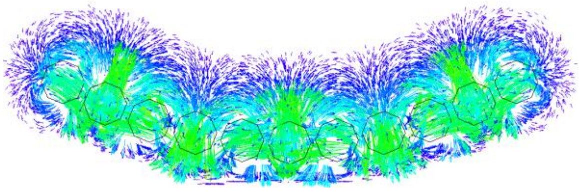


(b) Type U : inner arrangement

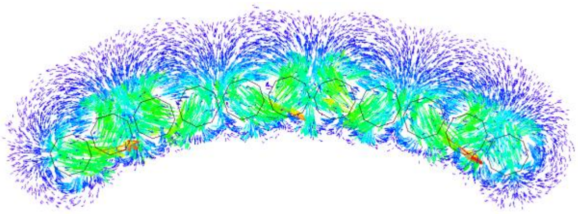
Fig. 11 3D-CAD model of the round layout linear Halbach arrays using cylinder-shaped PMs.



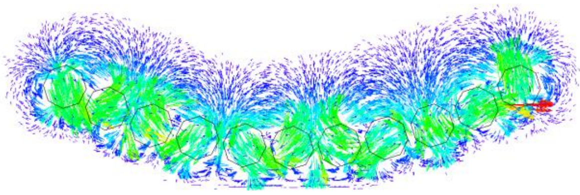
(a) rotational angle : 0 degrees



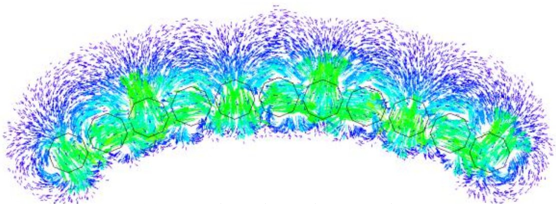
(b) rotational angle : 0 degrees



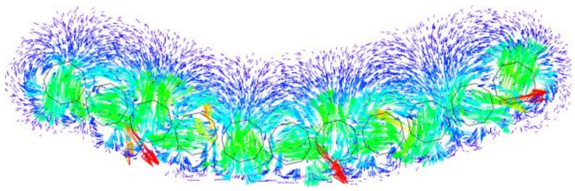
(a) rotational angle : 45 degrees



(b) rotational angle : 45 degrees



(a) rotational angle : 90 degrees



(b) rotational angle : 90 degrees

Fig. 12 Magnetic field vector map of outer arrangement (Type A).

Fig. 13 Magnetic field vector map of inner arrangement (Type U).

4. Conclusion

This study explored a new layout model of a linear Halbach array with cylindrical permanent magnets to achieve magnetic field control capability and layout flexibility. This report is an initial consideration using magnetic field simulation, but valid results were obtained for the two novel round layout Halbach arrays. However, a difference in the spatial arrangement of the inner and outer sides of a round layout Halbach array seems to have a large influence on the magnetic field distribution. Thus, in order to clarify the characteristics of the round layout, we would like to make a prototype model for quasi-static magnetic field measurement.

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