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Study of a Hybrid Magnet Array for an Electrodynamic Maglev Control

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This paper introduces an innovative hybrid array consisting of both permanent and electro magnets. It will enable us to develop an active control mechanism for underdamped electro-dynamic suspension (EDS) Maglev systems. The proposed scheme is based on the Halbach array configuration which takes the major technical advantage from the original Halbach characteristics: a strongly concentrated magnetic field on one side of the array and a cancelled field on the opposite side. In addition, the unique feature of the proposed concept only differs from the Halbach array with permanent magnets. The total magnetic field of the array can be actively controlled through the current of the electro-magnet's coils. As a result, the magnetic force produced by the proposed hybrid array can also be controlled actively. This study focuses on the magnetic characteristics and capability of the proposed array as compared to the basic Halbach concept. The results show that the proposed array is capable of producing not only an equivalent suspension force of the basic Halbach permanent magnet array but also a controlled mode. Consequently, the effectiveness of the proposed array confirms that this study can be used as a technical framework to develop an active control mechanism for an EDS Maglev system.

Keywords : magnetic levitation (maglev), magnetic fields, controllability, halbach array, hybrid magnet

1. Introduction

A MAGLEV system utilizes magnetic fields produced from external electrical power sources to produce suspension forces. The Maglev enables the development of a mass transportation of trains that provides substantially lower vibrations, faster speed, and is environmentally safe. Additionally, there has been much interest in the concept of Maglev technology for space launch-assistances. It may provide significantly improved safety, reduced cost, and reduced turnaround time for the next space launch. The frictionless and non-contacting features can also be applied to a broad range of energy production and storage systems in order to improve reliability and efficiency of the system [1, 2].

The EDS Maglev system is based on induced Eddy currents using either permanent magnets or superconducting magnets as the magnetic field source. The Lawrence Livermore National Lab has developed a passive EDS Maglev system utilizing the Halbach permanent magnet array. A small proof-of-concept scale system, Inductrack, was constructed and tested. This technical approach is particularly attractive because of the unique property: concentrating the magnetic field's flux on one side of the array and canceling it on the other side. Moreover, the concentrated magnetic field is stronger than simply using the same number of magnets of the array for the integrated permanent magnets [3]. The EDS systems are inherently stable under steady-state conditions, but have underdamped dynamic characteristics that show uncertain transient dynamics and vibrations. Thus, guideway irregularities and other disturbances may produce a negative damping phenomenon that destabilizes the system. Therefore, both active and passive damping mechanisms are required for EDS systems to ensure system safety and stable transient dynamics. While passive damping mechanisms need to be incorporated into the original maglev system design, an active damping mechanism may also be developed in order to properly compensate system's

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uncertain dynamics and perturbations from the operating environments [4].

In this paper, a novel magnet array based on the basic Halbach magnet configuration presents that an active damping mechanism can be implemented in order to dynamically stabilize an EDS maglev system. This variation is necessary to possibly control the system stability of the magnetic field, and it still holds major technical advantages of the Halbach magnet array concept. In addition, the proposed array provides a practical approach to resolve manufacturing problems of the large Halbach array using strong permanent magnets such as NdFeB.

Firstly, this paper introduces the Halbach permanent magnet array and the Finite Element Model (FEM) of the magnetic fields. Then, the analysis and modeling of the proposed magnet array is presented. The results show that the proposed magnet array is equivalent to the Halbach permanent magnet array, which demonstrates the effectiveness of the proposed scheme. Finally, damping capability of the proposed scheme and its application to a control system are addressed.

2. Analysis and Modeling of Magnetic Fields

A passive Halbach array, an array of permanent magnets with magnetic field orientations as shown in Fig. 1, is used to levitate a cradle moving above a track consisting of conductive plates or close-packed arrays of shorted coils. The Halbach array has the effects of polarizing the magnetic field on one side of the array with annulling magnetic field on the opposite side. Utilizing the vertical and horizontal components of the array's magnetization, the magnetic field can be represented by a Fourier series in which the solution shows magnetic profiles on both sides of the array, the enhanced and the canceled magnetic fields. Fig. 2 illustrates FEM of the magnetic field

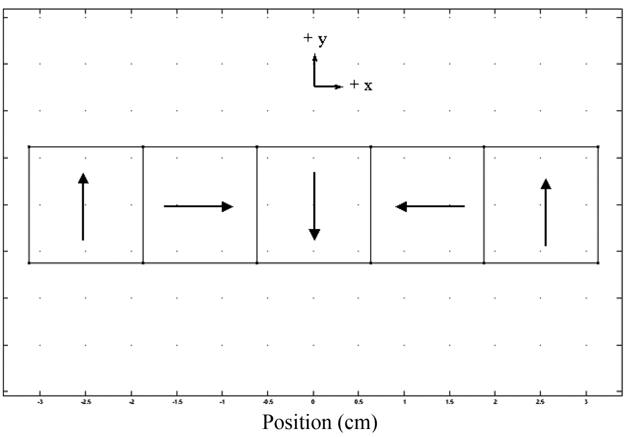

Fig. 1. Permanent magnet with magnetization orientation.

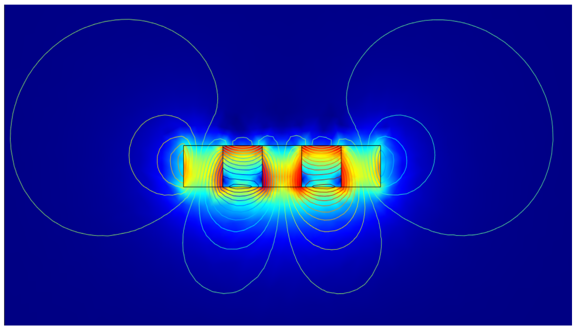

Fig. 2. (Color online) The Magnetic field of Halbach Permanent Magnet Array.

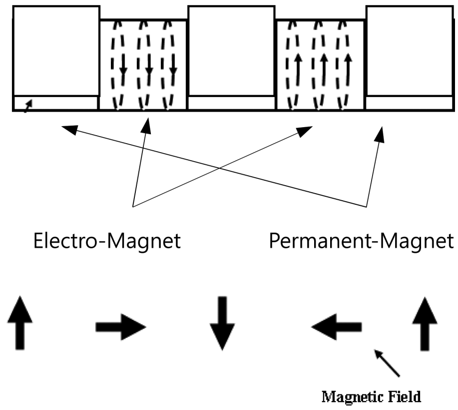

Fig. 3. Sketch of Novel Magnet Array.

that will be utilized as the reference to show the effectiveness of the proposed approach [1, 5].

As Fig. 3 illustrates, the proposed array consists of permanent magnets of alternating polarities and electro-magnets of which the current of coils is actively controlled. An electro-magnet is placed between each permanent magnet so that this derivative Halbach array can control the magnetic field. The unique feature enables us to achieve an active control capability for the overall magnetic field of the array, which can be used to compensate transient dynamics. From the definition, a magnetic field is generated when electric charge carriers such as electrons move through space or within an electrical conductor. The wound coil carrying a direct current produces a magnetic field. The proposed novel magnet array contains a set of coils wound around ferromagnetic materials.

For this modeling, the following assumptions are applied:

1. The proposed novel magnet array is based on the ideal relationship between the current and the magnetic field direction.

2. The current value for the designed magnetic field intensity is usually determined by the number of wounds.

3. The size of squared block is big enough to be wound

by a set of coils.

Fig. 3 shows the sketch of the proposed novel magnet array model that has two electro-magnets and three permanent magnets that produces one wave length of the magnetic field. In this figure, the squared block represents a ferromagnetic material, the dotted lines show the current direction and the arrow shows the magnetic field direction.

A mathematical model of the electro-magnet, shown in Fig. 3, is developed by starting with Ampère's law for static cases [5],

$$\nabla \times H = J. \tag{1}$$

The current is

$$J = \sigma v \times B + J^e. \tag{2}$$

where, σ is electrical conductivity, J^e is an external current density and v is the velocity of the conductor.

From the definition of magnetic potential,

$$B = \nabla \times A. \tag{3}$$

and the constitutive relationship,

$$B = \mu_0 \mu_r H. \tag{4}$$

Equation (1) is rewritten as

$$\nabla \times \left(\frac{1}{\mu_0 \mu_r} \nabla \times A \right) - \sigma v \times (\nabla \times A) = J^e. \tag{5}$$

Since only 2D case magneto-statics modeling is performed, there are no variations in the z direction, and the current is parallel to the z-axis. Therefore, $-\sigma\nabla V/L$ can be added to the definition of the current where ∇V is the potential difference over the distance L.

$$J = \sigma v \times B + J^e - \sigma \frac{\Delta V}{L}. \tag{6}$$

Finally, the equation is simplified to

$$\nabla \times \left(\frac{1}{\mu_0 \mu_r} \nabla \times A_z \right) = \sigma \frac{\Delta V}{L} + J_z^e. \tag{7}$$

Analysis and modeling of Halbach array is based on standard circuit theory that the induced voltages and currents on the conductive plate at the bottom of the array are solved for the steady-state conditions. The force produced by the integrated array of permanent magnets and electro-magnets are derived from the individual current density [6],

$$P_{avg} = \left[\frac{\mu_0}{4} \frac{J_{1m} + J_{1c}}{\beta} \left(\frac{\sinh(\beta h)}{\cosh[\beta(g+h)]} \right) \right]^2 \tag{8}$$

Where current density J_{1m} and J_{1c} are due to the magnets and coils, respectively, h is the height of the magnets, β is the wave number defined by π divided by the width of one permanent magnet plus one electro-magnet. It is assumed that

$$\frac{J_{1c}}{J_{1m}} = \frac{n i_c}{h H_c} \tag{9}$$

Where n is the number of coil's turn.

Note that in this paper the analysis of the proposed magnet array is focused on the modeling of the field profiles, which may illustrate its capability to produce an equivalent magnetic force only of the Halbach array with permanent magnets.

3. Modeling of the Proposed Magnet Array

3.1. Novel Magnet Array Modeling

In order for FEM of the proposed magnet array, the modeling configuration is defined as shown in Fig. 4 which ignores the back structure. In this configuration, copper is used to model the wound coils and iron is used as a ferromagnetic material.

Fig. 5 shows FEM of the proposed array's magnetic field. Compared to Fig. 2, the model of the novel magnet array has an equivalent magnetic field, exhibiting a strong magnetic field on the bottom side and a canceled field on

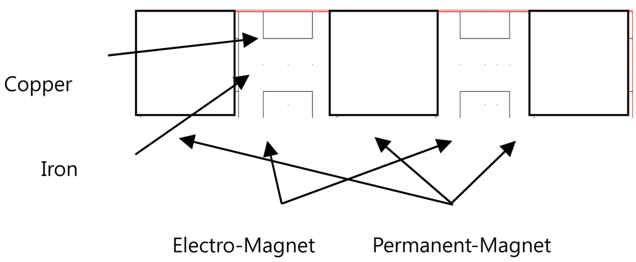

Fig. 4. (Color online) Modeling Configuration of Novel Magnet Array.

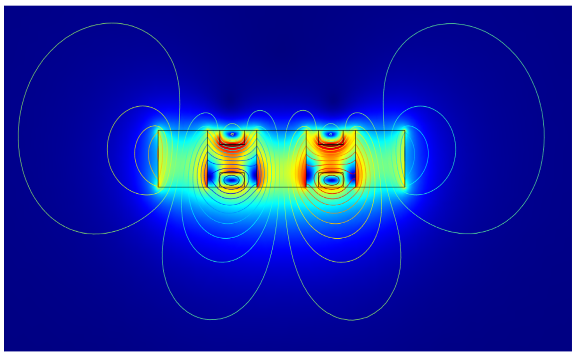

Fig. 5. (Color online) FEM of the Proposed Magnet Array's Field.

its upper side.

Note that in this paper only the analysis of the horizontal component of the array's magnetization is presented since the levitation is mainly dependent on the component. The vertical component may be utilized to produce the propulsion force in the moving direction [1].

3.2. Comparison between the Proposed Array and Halbach Permanent Magnet Array

In order to investigate the property of the proposed magnet array, the horizontal magnetic flux density of the Halbach permanent magnet array is illustrated in Fig. 6, which is the solution of a Fourier series for the horizontal component of the array's magnetization. In this figure, the *x*-axis is the length of Halbach array [cm] and the *y*-axis represents the magnetic flux density [T].

Fig. 7 shows the horizontal magnetic flux density of the proposed magnet array. The results illustrate an equivalent magnetic profile referring the Halbach array of permanent magnets.

The two results show that the Halbach permanent magnet array is capable of producing a slightly higher magnitude of magnetic flux density than the proposed array. Fig. 8 shows controlled magnetic field flux density by current values. In Fig. 8, three different currents are utilized in the simulation to show controlled magnetic flux density of the proposed array in active mode: *a* represents direct current of Ampere-turn (30×10^6 AT), *b* represents direct current of Ampere-turn (22.5×10^6 AT), and *c* represents direct current of Ampere- turn (15×10^6 AT). Finally, Fig. 9 shows the horizontal magnetic field profile of the proposed array without current, i.e. the passive mode. It indicates the minimum magnitude of magnetic flux density produced by the proposed magnet array.

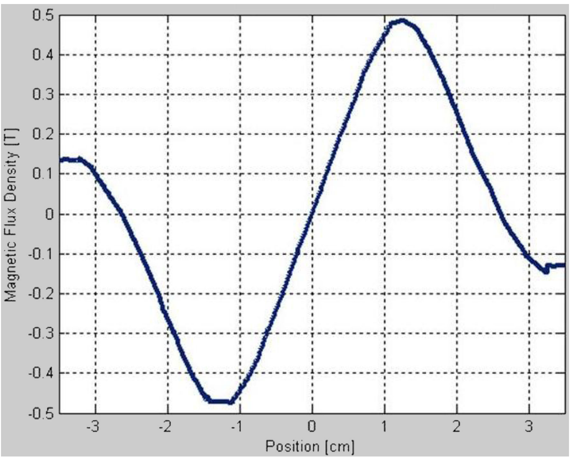

Fig. 6. (Color online) Magnetic Field Profile, Halbach Permanent Magnet Array.

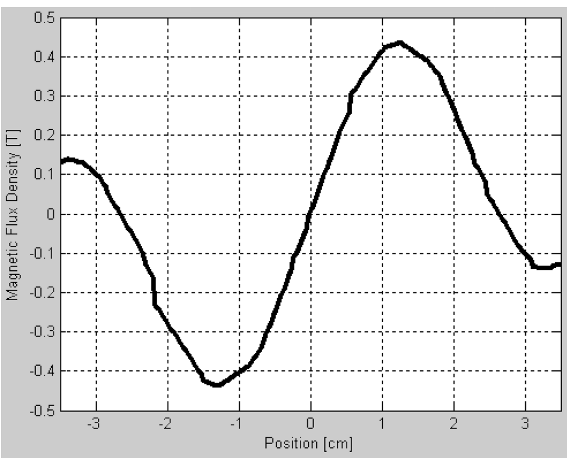

Fig. 7. Magnetic Field Profile, Proposed Magnet Array.

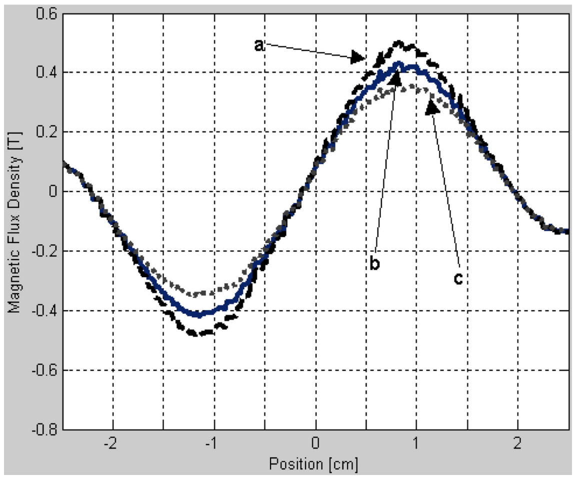

Fig. 8. (Color online) Controlled Magnetic Field Profile of the Proposed Array.

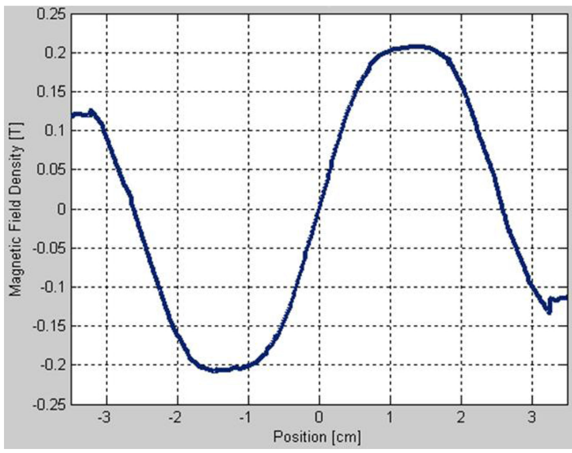

Fig. 9. (Color online) Magnetic Field Profile of the Proposed Array in Passive Mode.

4. Application to a Control system

The simulation results illustrate that the proposed hybrid magnet array holds major technical advantage from the original Halbach concept. In addition, the total magnetic field of the array can be actively controlled through the current of the electro-magnetic coils. Since the magnetic force of the array is proportional to the square of the magnetic field of the array [3], the force produced by the proposed hybrid array can also be controlled actively. This controlled force resulted from a variable magnetic field which is instrumental to provide a dynamic damping force, and compensates the instability of EDS Maglev systems caused by external perturbations and guideway irregularities.

In addition to the active magnetic field control capability, the proposed magnet array also provides better damping effects than the Halbach permanent magnet array. For the same dimension, its levitation force is smaller than that of Halbach permanent magnet array, but the electro-magnets can serve as damper coils regardless of their passive or active operating mode. While the passive mode improves the damping coefficient, the actively controlled electro-magnet is capable of compensating the underdamped dynamic response of EDS Maglev systems [3].

This study is a theoretical framework focused on analysis of a novel magnet array that may enable us to develop active control mechanisms for EDS maglev systems. Thus, it remains as a future study whether the proposed array may be utilized as a primary maglev technology or just for the control purpose of a certain system scale. However, it is certain that the control and damping capability of the proposed array clearly shows that it is more applicable to a group of EDS maglev systems than the Halbach permanent magnet array.

5. Conclusion

A novel magnet array was developed in which the controllability of the magnetic field and the damping capability can ensure stability of an EDS Maglev system. The active damping capability of the proposed array is instrumental for realizing stable EDS maglev systems. In addition, both FEM and analysis of the magnetic field profile confirmed the effectiveness of the proposed array. The results not only show an equivalent performance of the Halbach permanent magnet array but also an active control capability of the field. Consequently, the effectiveness of the proposed array confirms that this study can be used as a technical framework for developing an active control mechanism for the EDS Maglev system.

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