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Automatic alignment of multiple magnets into Halbach cylinders

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ABSTRACT

Halbach cylinders have found various applications for their ability to produce strong and homogenous magnetostatic fields. Contrary to their conventional manual fabrication, we introduce a novel approach to automatically align multiple permanent magnets into a Halbach cylinder. The approach uses the magnetic field distribution from a diametrically magnetized cylindrical magnet to simultaneously align multiple magnets. The extent to which the automatic assembly can approximate a Halbach cylinder was analyzed using 3D Finite Element Modeling. Prototypes were built that demonstrated automatic alignment of eight magnets into Halbach cylinders. Automatic alignment eliminates the complexity of manually aligning Halbach cylinders.

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1. Introduction

In the 1980s Klaus Halbach developed a unique magnet assembly, known as the Halbach cylinder, which produces a strong and homogeneous field inside the bore [1]. Since the invention, Halbach cylinders have been utilized for a diverse set of applications including Nuclear Magnetic Resonance (NMR) [2,3], Magnetic Resonance Imaging (MRI), magnetic refrigeration, magnetic separation, motors/generators, and charged particle manipulations [4]. The various applications have inspired different types of analysis and optimization on the Halbach cylinders [5]. These developments were primarily focused on obtaining high magnetic flux densities and field homogeneity [6,7] and [3]. Other considerations such as accessibility to the homogeneous field or the ability to obtain tunable fields have also been considered [8,9]. However, a key factor that is often overlooked when considering Halbach cylinders is the difficulty in their fabrication. Typically, Halbach magnets are fabricated manually, where multiple magnets have to be aligned in specific orientations in the presence of strong magnet–magnet interactions (e.g. $\sim 105\ \mathrm{N/m^2}$ for two NdFeB magnets in direct contact) and against their natural alignment tendency. Such assembly requires significant force and specialized tools. To date, there has not been any reported technique that can automatically align multiple magnets into a Halbach cylinder assembly.

In this work, we present a novel method that can automatically align multiple magnets into a Halbach cylinder array. The automatic assembly was investigated by using a model consisting of eight diametrically magnetized permanent magnet cylinders. The extent to which the automatic assembly can approximate a Halbach cylinder was analyzed by using finite element modeling. Finally, the ability to automatically assemble eight magnets to obtain higher flux densities and uniformity was investigated.

2. Model description

An ideal Halbach cylinder is essentially a ring magnet where the polarization direction varies continuously along the circumference such that the magnetic flux increases inside and reduces or cancels on the outside [1]. However, in practice, it may not be possible to magnetize a hard magnetic ring in a manner where the polarization direction can be varied continuously. Therefore, typical Halbach cylinders are built using discrete permanent magnets each with their own magnetization direction, approximating the Halbach distribution. The basis of our approach relies on the magnetic field distribution available from a diametrically magnetized cylindrical magnet where the direction of the magnetic field (Fig. 1(a)) varies continuously along the circumference in a manner that mimics the distribution in an ideal Halbach ring [10]. Therefore, we hypothesize that the magnetic field from a diametrically magnetized cylindrical magnet can simultaneously and automatically align a set of permanent magnets into a Halbach cylinder assembly.

In order to test our hypothesis we built a model (Fig. 1(b)), which consisted of three major components:

1. *Anchor*: A diametrically magnetized cylindrical magnet – the magnetic field distribution from this magnet will be used to align a set of magnets into a Halbach cylinder orientation. The diameter and the height of the anchor magnets were defined as

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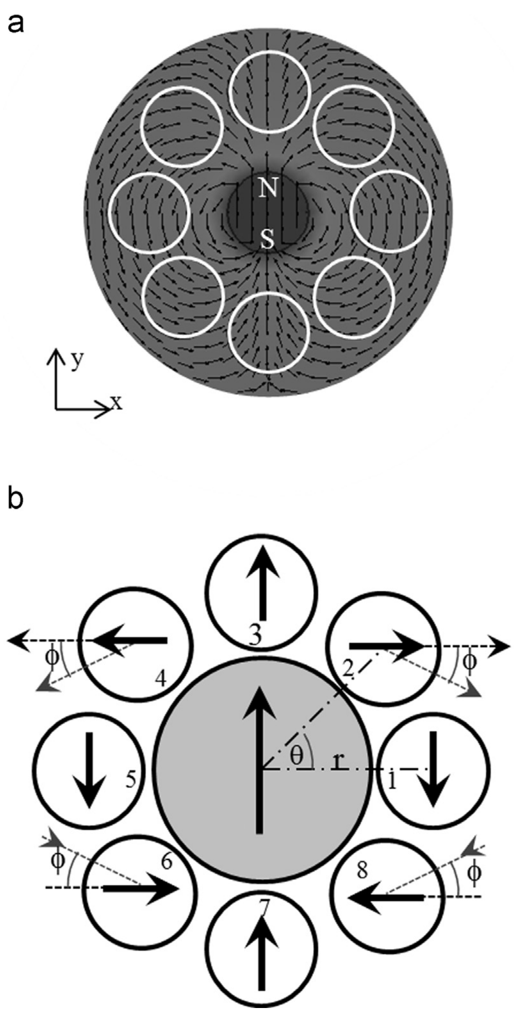

Fig. 1. (a) Schematic showing the concept of automatically aligning eight magnets into a Halbach orientation. Polarization direction of the magnetic field obtained from a diametrically magnetized cylinder located at the center of the figure is denoted by the arrows. The locations of the eight magnets to be aligned by the center magnet are denoted by white circles. (b) Schematic showing a model for the automatic alignment.

OD_A and h_A.

2. *Sections*: A set of n identical, diametrically magnetized, permanent magnet cylinders, which form the Halbach assembly. The sections were numbered in anti-clockwise direction for identification. The diameter and the height of the section magnets are defined as OD_S and h_S. The direction of magnetization of each section was defined as the angle η_i with respect to the x axis. The location of each section was defined by the cylindrical coordinate $(r,\ \theta_i)$, where $\theta_i = 360/n(i-1)$ and r was the radial distance of the center of the sections from the origin (0,0). It has been shown that a Halbach cylinder with eight segments can obtain $>90\%$ of the flux densities of an ideal Halbach cylinder [5]. Therefore, we chose to utilize eight ($n=8$) diametrically magnetized permanent magnet cylinders to test our hypothesis.
3. *Holder*: A nonmagnetic holder (not shown in Fig. 1(b)) that has slots to hold the anchor and the sections in a manner that the sections can rotate about their axis under the influence of the anchor magnet. The center of the slot for the anchor was aligned with the center of the holder. The holder consisted of eight slots for the sections. The coordinates of each section was defined by $(r,\ \theta_i)$. The holder also contains set screws to hold the sections in place while and after removing the anchor.

Since our objective was to utilize the influence from the anchor magnet to automatically rotate/align the section magnets, our model was restricted to the design condition where radial distance of the center of the section magnet from the origin was greater than and approximately equal to $(OD_A+OD_S)/2$. Such a condition would ensure the maximum influence of the anchor magnet on the section magnets to facilitate automatic alignment.

3. Analysis

Halbach cylinders are generally considered to produce a strong and homogeneous field inside the bore. The strength and the homogeneity from a Halbach design depend on the accuracy of the alignment of the constituent magnets. The orientation of each individual magnet can be determined by the equation [5]

$$\eta_i = 2\theta_i - 90\cdot \tag{1}$$

A prototype was built containing the three components. The anchor and section magnets used in this study were commercially available, diametrically magnetized, cylindrical NdFeB permanent magnets (Storch Magnetics, Livonia, MI, USA). The diameter and height of the anchor magnet were 1 and 2 in., respectively. The diameter and height of each section magnet was 0.5 and 2 in., respectively. The holder was machined form a block of aluminum. The magnetization direction of each section magnet was identified by drawing an arrow on the magnet from their south to north poles. Automatic alignment of the section magnets was first carried out in one single step (a Video S1 showing the automatic assembly is available as supporting online material). First, the sections were carefully inserted into their respective slots one at a time. The sections aligned themselves according to their natural interactions (Fig. 2(a)). The anchor was then inserted at the center of the holder such that the magnetization direction of the anchor is aligned with the section magnets #3 and #7. Under the influence of the anchor, the section magnets rotated according to the field from the anchor magnet (Fig. 2(b)). Set screws in the holder were used to secure the sections into their respective orientation. The anchor magnet was then removed to obtain the final magnetic circuit (Fig. 2(c)). The prototype built using this 'one-step' method produced 0.41 T field. Section magnets #1, #3, #5, and #7 oriented according to that calculated by Eq. (1). However, section magnets #2, #4, #6 and #8 showed deviations. This deviation (denoted by ϕ in Fig. 1(b)) can be attributed to the fact that the sections were not only in the presence of the anchor magnet, but also in the presence of magnetic interactions between the section magnets during the automatic alignment.

In order to predict the deviations and their effects on the overall magnetic field, three dimensional Finite Element Modeling (COMSOL 4.3, Burlington, MA) was utilized. In COMSOL, magnetostatic problems are solved by solving Possion's equation:

$$-\nabla\cdot(\mu_o\mu_r\nabla V_m - \mathbf{B}_r) = 0 \tag{2}$$

where μ_o is the permeability of free space; μ_r is the relative permeability of magnetically isotropic materials; V_m is the scalar magnetic potential, and $\mathbf{B}_r$ is the remnant flux density. Magnets align themselves to assume the least total magnetic energy for a given volume. Therefore, the total magnetic energy from an ensemble of permanent magnets such as that shown in Fig. 1(b) can be used to predict their alignment orientation with respect to each other after the automatic alignment. In a finite element model, the orientation of the section magnets could be systematically changed to calculate and find the lowest total magnetic energy. The total magnet energy is calculated by the equation