Examination of Permanent Magnets in different Halbach array configurations

[1]Sándor Nagy, [2]Sándor Semperger

[1]*Obuda University Doctoral School on Safety and Security Sciences, Budapest, Hungary. Contact: nagy.sandor@uni-obuda.hu*
[2]*Obuda University Doctoral School on Safety and Security Sciences, Budapest, Hungary. Contact: semperger.sandor@uni-obuda.hu*

Abstract

The aim of this study is to investigate the application of Halbach permanent magnets using numerical simulations and to determine the optimal magnetization directions and techniques for achieving a stable magnetic field around the Halbach magnet structure. The analysis includes a comparison of the magnetic flux distribution, magnetic field strength, and density of the tested magnets, taking into account various physical parameter changes. The research focuses on the linear configuration of Halbach arrays, supported by a simulation program, while considering the conditions for technical feasibility.

Keywords: Halbach magnet, permanent magnet, flux density

1. Introduction

Permanent magnets are solid objects that maintain a stable magnetic field beyond their physical boundaries without requiring external energy input, following initial magnetization by an external magnetic field. These magnets are characterized by their robust resistance to demagnetization, making them a significant focus of contemporary research. Our study is based on these properties. Although it is feasible to manufacture such magnets artificially, the process is complex and involves multiple stages. The intricacy of the magnetization settings varies with the direction of magnetization and the number of poles, and is also significantly affected by the material type, shape, and spacing of the magnets.

A Halbach array operates based on the interaction between a mobile charged particle and a magnetic field, which generates a net force on the particle. This principle enables the use of these magnetic fields to guide moving charged particles [4,5]. Applications of Halbach arrays include:

- electric motors,
- generators,
- particle accelerators,
- NMR experiment
- and magnetic strips.

The Halbach magnetic arrangement, also known as the Halbach Array (Figure 1), is a unique configuration of permanent magnets featuring a rotating magnetic pattern in space. This pattern eliminates the magnetic field on one side while enhancing it on the other. This distinctive property has led to significant advancements in the application of magnets, particularly in magnetic levitation railways. The primary advantage is that it minimizes the magnetic field on one side, resulting in a scattered field, and effectively directs the magnetic flux to the opposite side. This nearly merges with the magnetic effects of both sides. This phenomenon can be best understood by examining the magnetic flux distribution (Figure 2).

Discovered by Klaus Halbach, a researcher at Lawrence Berkeley National Laboratory, in 1980, this arrangement has since captured the interest of numerous research groups aiming to optimize its potential applications.

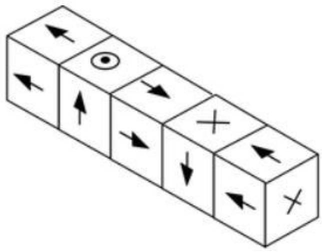


Figure 1. Halbach array layout [1]

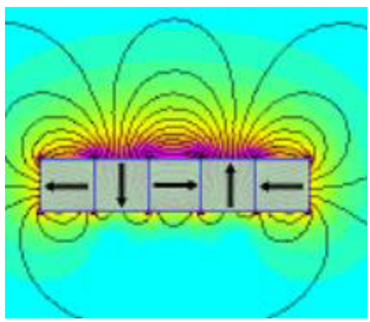


Figure 2. Halbach array flux distribution [1]

The use of Halbach arrays enhances the applicability of magnets. Starting with this configuration and subsequently combining it with the manipulation of magnetic flux density direction, it is possible to homogenize the distribution of magnetic field strength.

2. Examination of the modified arrangement of the linear Halbach configuration

The initial design of the study features a linear Halbach array consisting of 5 individual magnets, each with distinct magnetization directions, as illustrated in Figure 1. This configuration adheres to the basic Halbach arrangement. We modeled this setup using the FEMM 4.2 [3] simulation program [5], which lays the groundwork for the direction of physical research and implementation. Using the same type of magnet, the simulation program allows for the examination of various magnetic shapes and arrangements with scaled physical corrections. The results of these simulations were compared and evaluated.

2.1 Initial basic test status

The initial basic Halbach magnetic arrangement is illustrated in Figure 3, which also displays the initial dimensions.

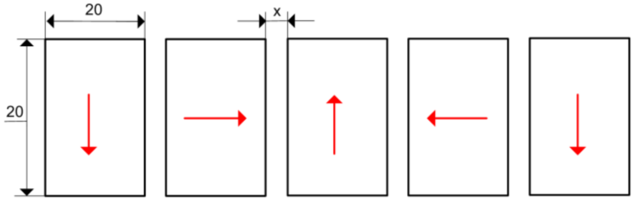


Figure 3. The primary configuration of the linear Halbach array is depicted in a two-dimensional format [1]

The type and properties of the magnet used in the research are shown in Figure 4.

	Characteristic	Units	min.	nominal	max.
Magnetic Properties	**Br**, Residual Induction	Gauss	12,800	13,150	13,500
		mT	1280	1315	1350
	H_{cB}, Coercivity	Oersteds	10,800	11,850	12,900
		kA/m	860	943	1027
	H_{cJ}, Intrinsic Coercivity	Oersteds	12,000		
		kA/m	955		
	BHmax, Maximum Energy Product	MGOe	40	42	44
		kJ/m^3	318	334	350

Figure 4. NDFeB N42 magnet datasheet [2]

2.2 Complex Halbach simulation study

In the following chapter, we present the results of the numerical cyclic analysis of various Halbach configurations. The alternating pole configuration (Figure 3) was used as the base magnetic arrangement, followed by physical rearrangements. In the simulation program, measuring lines were placed at three different distances, as shown in the magnetic flux distribution diagram of the base magnet (Figure 5). These measuring lines were positioned 1, 2, and 5 mm from both the lower and upper surfaces of the magnetic system, along which the magnetic inductions were examined.

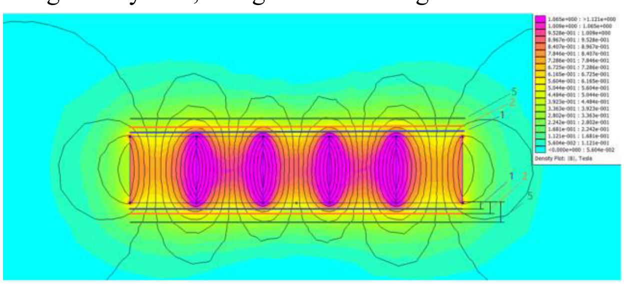


Figure 5. Based on the magnet flux distribution diagram [1]

The next chapter presents the two-dimensional structural diagrams of various physically modified Halbach magnets, where the magnetic flux density along the measuring lines is compared.

Magnetic flux density, also known as magnetic induction, is a vector quantity that represents the strength of a magnetic field. It is denoted by the symbol *B,* and its unit of measurement is the Tesla (T).

2.3 Comparison of magnetic structure modifications

The following chapter includes Table 1, which presents the compared structural configurations. The geometrical modifications were carried out using the FEMM4.2 program, wherein the structural setup was altered in 0.1 mm increments. At each step, the field strength values and flux density distributions were recorded. The table highlights key points, and the comparison helps determine the research pathway towards optimizing the modifications.

Table 1. Comparison of Magnetic Structural Modifications Based on Field Strength

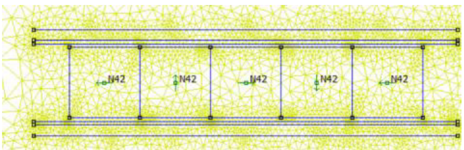
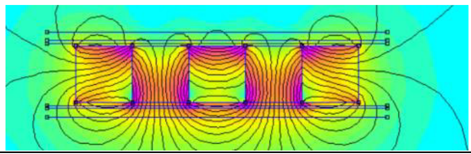
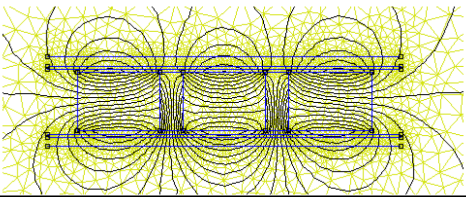
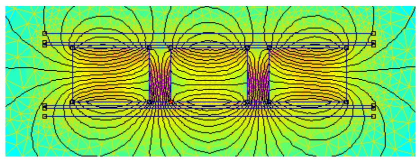
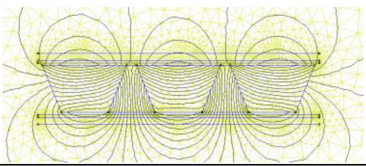
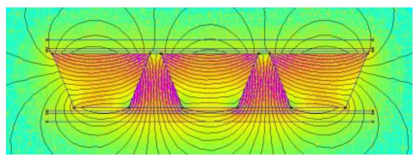
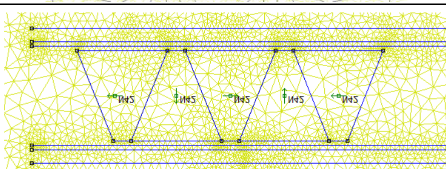
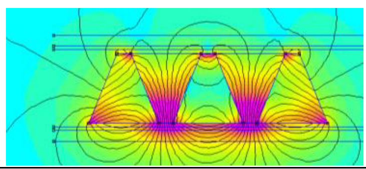
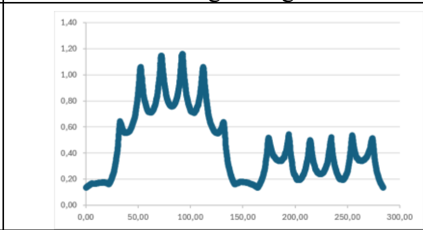
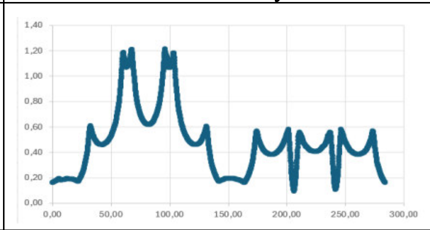
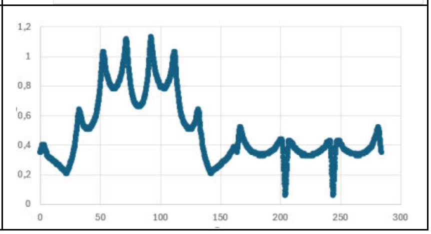
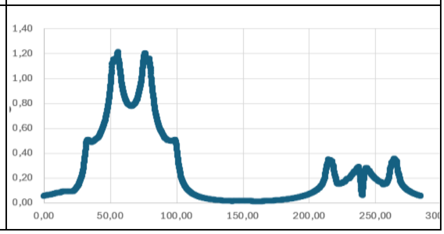
Type	Geometric shape	Flux density
1		
2		
3		
4		

Table 1 outlines the geometric configurations of the 4 tests, where we examined the results of structural modifications. The attached images demonstrate the extent to which geometric modifications influence the flux density.

Table 2 illustrates the changes in field strength within the previously discussed Halbach magnetic structures.

Table 2. Comparison of Magnetic Structural Modifications Based on Field Strength

Type	Field strength diagram	Type	Flux density
1		2	
3		4	

The table presents the dynamic changes in flux density. The diagrams in Table 2 illustrate the variations in field strength by structure. Each figure can be divided into two parts: the right side shows the upper field strength, while the left side depicts the lower field strength of the Halbach structure. The objective is to optimize the upper field strength while minimizing the lower field strength. The following table presents the maximum values of the results.

Table 3. Maximum Magnetic Field Strength of Investigated Halbach Structures

Type	Geometric shape	Maximum Flux density
1	Basic Halbach array	1.18 T
2	Halbach array with rectangular structure	1.21 T
3	Trapezoidal Halbach array	1.18 T
4	Halbach array with triangular structure	1.21 T

3. Conclusion

Based on the results obtained during the research process, it is evident that the maximum magnetic field strength cannot be significantly influenced in the investigated systems. However, it was observed during the modifications that the distribution of magnetic flux density can be altered, allowing the field strength to be regulated predominantly to one side.

The examination results indicate that the triangular structural configuration proved to be the best for homogenizing the field strength. In the future, we will continue geometric modifications in this direction, expanding our research calculations to include changes in the pole orientations of the magnet.

4. References

[1] S. Nagy and S. Semperger, "Investigation of different of arrangement of Halback array," in Proc. IEEE 7th Int. Conf. Workshop in Óbuda on Electrical and Power Engineering, 2024, in press

[2] Arnold Magnetic Technologies, "N42 Neodymium Magnet Datasheet," Nov. 2017. [Online]. Available: https://www.arnoldmagnetics.com/wp-content/uploads/2017/11/N42-151021.pdf

[3] "Magnetic Tutorial," FEMM, Accessed: Dec. 13, 2024. [Online]. Available: https://www.femm.info/wiki/magneticstutorial

[4] J. Ofori-Tenkorang and J. H. Lang, "A comparative analysis of torque production in Halbach and conventional surface-mounted permanent-magnet synchronous motors," in Proc. IEEE IAS 30th Annu. Meeting, Oct. 1995, pp. 657-663.

[5] J.M.D. Coey, Permanent magnet applications. J. Magn. Magn. Mater., vol. 248, no. 3, pp. 441-456, Aug. 2002.