MAGNETIC FIELD SOURCE WITH HALBACH PERMANENT MAGNETS CONFIGURATION

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Abstrakt
The work is devoted to a geometrical configuration of permanent magnets on the basis of opposing geometrically linear assemblies (e.g. Halbach arrays) for the generation of strong magnetic fields, which have been theoretically modeled and experimentally verified. The implementation of these opposing assemblies using NdFeB magnets of a total weight of 3.75 kg provided a value of magnetic induction in the middle of an air gap of a width of 20 mm that was higher by 56\% in comparison with the simplest possible design. When the air-gap width was 3 mm, the induction reached a value of 2.16 T, which represents an increase by more than 100\%. Simultaneously, however, unlike in the classic parallel configuration, opposing Halbach assemblies have shown in the middle of an air gap a significant decrease of the magnetic induction values when passing from the middle of the assemblies in the direction parallel to the x-axis.

Keywords: Magnetic field, Permanent magnets, Halbach arrays

1. INTRODUCTION
Numerous applications require the usage of magnetic fields with high values of magnetic induction, or with an extreme gradient of this parameter. Thanks to their high values of remanent magnetization and energy density, permanent magnets on the basis of rare earths are predetermined for these purposes. In the 1970s, the first work concerning the so-called one-sided magnetic fluxes with planar magnetic geometries was published [1]. Subsequently, Halbach described a new quadrupole configuration using cobalt permanent magnets [2]. Marble claims [3] that through a relatively simple arrangement of permanent magnets it is objective to achieve more than 80\% of the maximum possible magnetic field.

The authors in the work [4] describe a geometric arrangement of NdFeB-type permanent magnets for magnetic resonance, which in the implemented device of a total weight of 790 kg (of which 290 kg is the weight of the NdFeB magnets from the material N42) generates in an air gap of 0.06 m and a pole diameter of 0.2 m a magnetic field of an induction of 1.6 T. In the same work, the authors mentioned that using the Halbach ring structure would make it possible to attain high fields and reduce the weight of the device, but this structure is too complicated to be manufactured and assembled.

With simplified Halbach cylinders, values of up to 1.8 T were attained [5]: with Halbach cylinders with iron pole magnetic-flux concentrators, the maximum level shifted to a value of 3.9 T [6]. The work [5] describes also an original source of a magnetic field on the basis of permanent magnets (Halbach sphere), where the calculated value of magnetic induction in the central area (\(\phi 6 \text{ mm} \times h 2.8 \text{ mm}\)) exceeded the level of 4.3 T. Besides the size of the field generated, in many cases it is important to monitor the uniformity of this field as well. The solution to this problem has been discussed on the basis of Halbach geometrical configurations, i.e. ring dipole, square dipole and C-dipole [6]. At lower field values (below 0.4 Br), the constructions of a C-dipole type are the most advantageous, whereas square and ring dipoles have been shown to be the best in the resolution of fields with high values of magnetic flux.

In systems with magnetic cooling, it is necessary to create some areas with a high and others with a low value of magnetic flux. The application of the Halbach cylinder, where some of the permanent magnets have been replaced by a magnetically soft material with a high value of relative permeability, can make it possible...
to achieve an almost 50% increase in the difference between the magnetic induction values in the areas with high and low magnetic field levels [7].

Other publications have described constructions of autonomous sources of a strong magnetic field for magnetic separation chiefly in ceramic technological processes [8–10].

The aim of the work being presented is to build on these as well as mainly on other studies and knowledge concerning the simulation and implementation of strong magnetic fields [11–15]. It is devoted to the theoretical modeling, implementation and testing of a magnetic-field source based on the opposing linear Halbach assemblies of NdFeB magnets in comparison with the classic arrangement of the opposing permanent magnets from a material of the same type and quality.

2. EXPERIMENTAL

As the basis for the creation of these separate assemblies, NdFeB blocks from the N45 material with remanent magnetization $B_r$ equaling 1.354 T and a maximum energy product $(BH)_{max} = 348$ kJ/m$^3$ were used. The dimensions of these blocks (Ni coated) were $0.05 \times 0.05 \times 0.03$ m, preferentially oriented in the direction of the height of $0.03$ m. Smaller blocks necessary for the completion of these assemblies were created by cutting from the mentioned blocks with a diamond blade under intensive cooling with water to obtain the required dimensions always in such a way as to preserve the preferential orientation for the desired block-magnetization direction.

In the paper [11] the way of magnets assembling into chosen arrays is also described in details. A special device with the length $0.45$ m was used; this device made possible assembling only one chosen array with the length $0.1$ m.

In this work, above-mentioned original simple device for placing NdFeB magnets into assemblies [11, Fig. 4] was further modified and doubled so as to enable the creation of two opposing arrays magnets with a continuously adjustable distance between them. After the entire new preparation, depicted in Figure 1, is completed, it is possible to alter the distance between the arrays (the width of the air gap) in the range of 160–3 mm by moving the top array with respect to the solid bottom and measure both the corresponding magnetic induction value in the middle of this air gap and the magnetic induction in the middle of an air gap of a constant width at points on the axis parallel to the x-axis.

![Fig. 1 A device for placing NdFeB magnets into two opposing assemblies](image)

For creation of all opposite assemblies were used again as the basis the same NdFeB blocks as in the case of above-mentioned separate assemblies, i.e. those with sizes $0.05 \times 0.05 \times 0.03$ m from N45 material. These blocks were adapted similarly by cutting and assembled into selected assemblies.

The measurements of the magnetic fields in the individual configurations were conducted by F. W. Bell teslameter, type 5080 with the Hall transverse probe.
3. **PERMANENT-MAGNET ASSEMBLY CONFIGURATION**

During the measurements of the dependences of magnetic induction in the case of the opposing assemblies, the beginning of the coordinates x and y (point 0) was always selected in the middle of the surface of the bottom array as depicted in Figures 2, 3 and 4. It must be underlined that these Figures do not display any magnet designs, but actually realized magnet assemblies where a precision cuts and a way of assembling can influence measured values of magnetic induction. Therefore, for possibility of eventual further comparison and assessment of their impact are in Figures plotted also inner lines and displayed so all individual magnets from which are assemblies composed.

a) Assemblies 1 and 1´
This arrangement is the classic linear arrangement of the opposing magnets. The measured dependence is illustrated in Figure 4 (blue curve, diamonds).

b) Assemblies 2 and 1´
The arrangement is a Halbach array/assembly with the opposing classic assembly of magnets. The measurement was performed like in the previous case; the measured dependence Byw/2 = f(yw) is plotted in Fig. 3 (red curve, squares), the dependence Byw10 = f(x) in Fig. 4 (red curve, squares).

c) Assemblies 2 and 2´
This arrangement (two opposing Halbach arrays) is depicted in Fig. 2. The measurement was performed again in the same way as the previous one; the respective dependences are likewise plotted in Figs. 3 and 4 (green curves, triangles).

![Fig. 2 The opposing assemblies 2 and 2´](image)

4. **THEORETICAL AND EXPERIMENTAL RESULTS**

The measurement of the magnetic induction as a function of the air gap width with all of the arrangements above has provided the dependences declared in Fig. 3.
The measurement of the magnetic induction in the middle of an air gap of the constant width as a function of the parameter \( x \) with all of the above-mentioned arrangements has provided the dependences depicted in Fig. 4.

![Graph](image)

**Fig. 4** The dependences \( B_{yw10} = f(x) \) with the opposing assemblies for \( yw = \text{const.} = 20 \text{ mm} \)

A comparison of the values of the magnetic induction \( B_{yw/2} \) obtained through the modeling (Equations (8)–(10)) and measurement with the arrangement implemented (see Fig. 2) is clear from Fig. 3.
A comparison of the values of the magnetic induction $B_{yw10}$ obtained through the modeling (Equations (8)–(10)) and measurement with the arrangements implemented (see Fig. 4) is clear from Fig. 6.

5. CONCLUSIONS

Geometrical configurations of permanent magnets on the basis of Halbach assemblies for the generation of strong magnetic fields have been proposed, and the respective distributions of the implemented magnetic fields have been theoretically modeled and experimentally verified. A comparison of the results of the model approaches and experiments has shown that using current software products it is objective to find a high correlation between theoretical and experimental results.

Both the computer simulation and the implementation have confirmed that by means of the mentioned opposing linear Halbach assemblies equipped with NdFeB magnets with a high energy product, it is possible to achieve in the defined volume magnetic fields with magnetic induction values exceeding the level of the remanent magnetization of the permanent magnets used. The application of permanent magnets of larger
sizes (or magnetic blocks from the same material) thus opens a real possibility for the creation of a strong magnetic field in a greater volume for various applications.

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LITERATURE