STUDIA UBB PHYSICA, Vol. 68 (LXVIII), 1-2, 2023, pp. 13-24
(RECOMMENDED CITATION)
doi:10.24193/subbphys.2023.02

EXPERIMENTAL DEVICE FOR THE STUDY OF PERMANENT MAGNET ARRANGEMENTS

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ABSTRACT. In this paper we present a complex experimental device used for the study of the magnetic field created by neodymium magnet arrangements, with emphasis on the series and parallel connection of those magnets. The measurements performed are suitable and useful for both high-school or college/university-level students.

Keywords: *magnet arrangement; magnetic flux density; series, parallel and mixed connection; equivalent magnet*

INTRODUCTION

Magnets are objects used to produce magnetic field. This field is invisible for the human eye but it can be foreseen, computed, depicted, or experimentally mapped for some common geometric shapes [1, 2]. Because permanent magnets are extensively used in a wide range of applications from electrical and radio engineering, to household appliances, transportation, medicine, and many other fields [3-6] the understanding of the magnetic field by terms of magnetic flux density (or field strength) is very important for implementations.

Some applications require more sophisticated magnetic field configurations than those created by individual magnets, thus special arrangements of magnetic structures have been developed for both research and applications, also aiming the strongest possible field per mass of permanent magnet material. Historically

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speaking, one of the most spectacular structures is that increase the magnetic flux on one side of the arrangement while reducing, or even canceling it on the opposite side. Such arrangements were first theoretically proposed by Mallinson [7] and later realized by Halbach [8-10].

The topic of experimental measurements on magnet arrangements is a complex and challenging one, from both theoretical and experimental point of views and rises an excellent inter- and multidisciplinary subject for Engineering Physics undergraduate students.

The present paper describes the design and implementation of an experimental device used for the study of permanent magnet arrangements. It was proposed as a graduation project for Engineering Physics specialization, at Babeș-Bolyai University, Faculty of Physics [11].

It is organized as follows: in the first section some general considerations are presented about permanent magnets and magnetic flux density measurement techniques, with emphasis on some previous measurements performed in our laboratory. The design and implementation of the device are described in the subsequent sections and finally, the measurement results are presented and conclusions are made.

Permanent magnets and magnetic flux density measurement

A magnet is called permanent if its magnetic properties are perpetual and it generates its own persistent magnetic field outside the material without any external trigger (energy source) like electromagnets.

There are four material families of permanent magnets, each of them having properties and features which maintain both scientific and commercial interest about them. Their properties, advantages or inconveniences in their use are extensively discussed in scientific literature [6, 12, 13]

The magnetic behavior of those materials is described in terms of four interrelated vector quantities: $\vec{B}$ – magnetic induction or flux density (it is expressed in terms of flux lines per unit of cross-section area, describing the concentration of magnetic flux at a point in space), $\vec{H}$ – magnetic field strength or intensity, $\vec{M}$ – magnetization (it describes the magnetic state of the material, representing the vector sum of individual atomic magnetic moments per unit volume) and $\vec{F}$ – magnetic force (attractive/repulsive type, usually arises between electrically charged particles because of their motion, it is also used to describe strength).

Nowadays the measurement of the magnetic flux density is not a very difficult task, both commercially available magnetometers and Hall sensors are helpful for the user. The attraction or repulsion force between two magnets is also easily measurable using force measurement devices or sensors, but to find the force produced by a single magnet or a more complex arrangement is a tricky task – it requires the use of a ferromagnetic material attached to a force sensor in order to be able to have measurable information, thus all data will be relative to the selected material properties.

A manually operated prototype of an experimental device used for the study of the magnetic field and magnetic force created by axially symmetric neodymium magnet arrangements, was developed in our laboratory [14]. This device was re-designed, upgraded and fully automatized by means of operation and measurement, and will be presented in detail in the following sections.

The experimental device

Construction details about the upgraded experimental device is presented in Fig. 1 and a top view photo is given in Fig. 2.

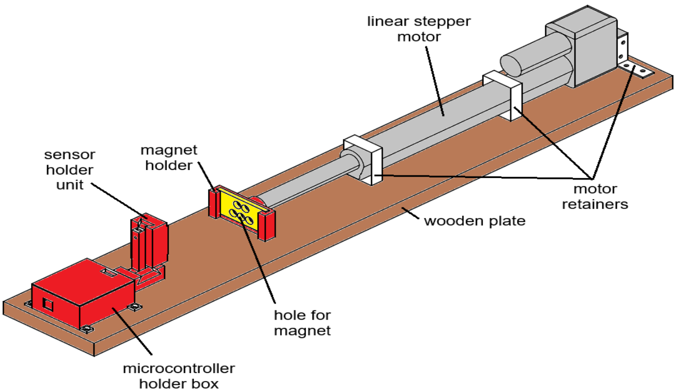


Fig. 1: Schematic drawing of the experimental set-up

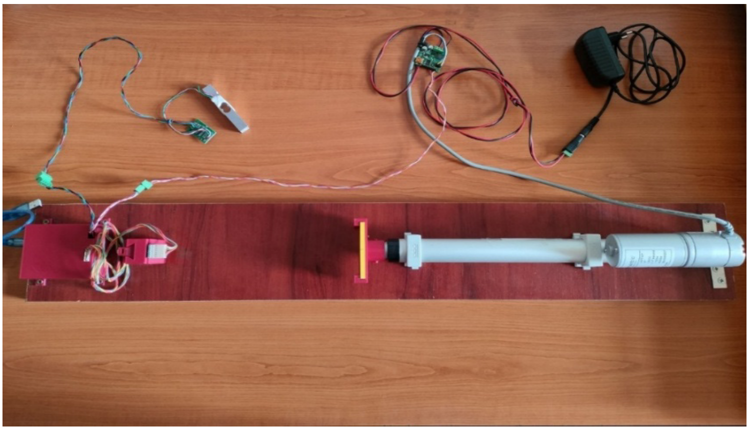


Fig. 2: Top view of the experimental set-up

As one can observe the apparatus is placed on a wooden plate, as it was the prototype too. One major difference is the relative movement. In this device the magnet holder (Fig. 3) is moved, by means of a computer controlled linear motor, towards the highly sensitive sensor which is hold in a fixed position (Fig. 4).

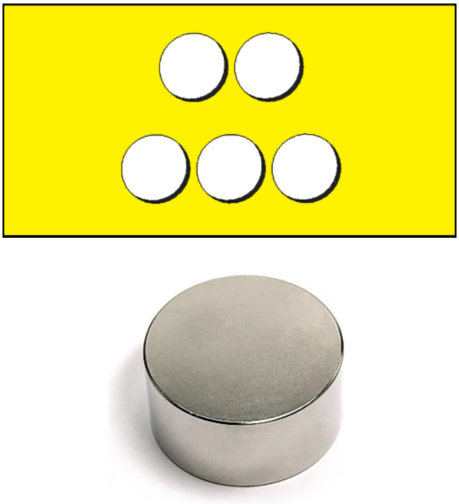


Fig. 3: The magnet holder and the neodymium magnet

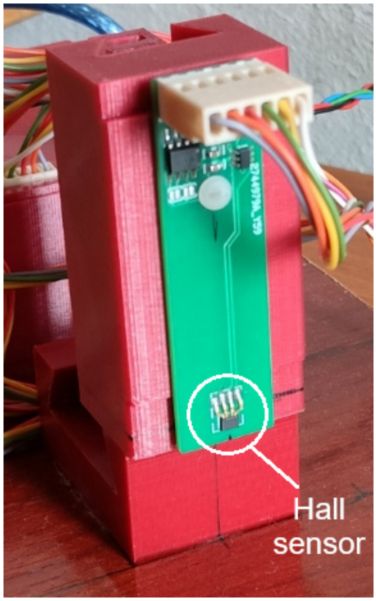


Fig.4: The magnetic sensor and its holder

Construction details about dimensions, materials and implementation are given in [11, 14].

Both device operation and data acquisition are microcontroller driven [15, 16], the user having a LabView [17] interface to operate the set-up. The front panel of the driving and measuring system is presented in Fig. 5., the description of it being presented elsewhere [11].

When started, the code waits for input data, these are: *the total length of the measurements* (in mm) which represent the distance on which the motor will move towards the sensor, *the distance between measurements* (in mm) representing the measurement step and *the number of measurements* in one measuring point. By pressing the *Send* button, a Python code is initiated [11] which creates an array containing all the data necessary for the motor movement and the sensor measurements. This array is returned to LabView and the measurements are initiated.

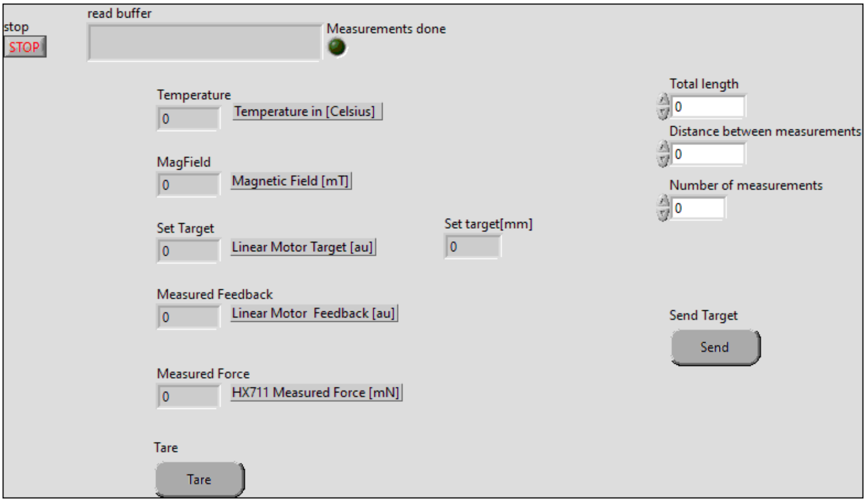


Fig. 5: Front panel of the driving and measuring system

The motor will do all adjustments and move in every position given by the code. In each position the sensor [18] will perform the given number of measurements, their average being stored in a file along with the position. All these steps will be repeated until the holder reaches the last measurement point.

Due to the characteristics of the motor [19], the maximum length on which measurements can be performed is about 2500 motor steps, namely 180 mm.

All programming codes are available in [20].

EXPERIMENTAL RESULTS

The magnetic field created by different magnetic arrangement was studied as function of distance. The dependences for individual, series or parallel arrangement of neodymium magnets have similar shape with those presented in [14]. A comparison of the measurements made by both systems in given in Fig. 6.

As one can see, the advantage of using the upgraded system is obvious (smaller measurement steps - larger number of data) and the results sustain the finding presented in both [11, 14], namely the magnetic sensitive sensor of the Hall probe used for the prototype is not at the end of the rod, but inside.

As a novelty, the antiparallel arrangement was studied. In our situation antiparallel means a parallel connection of two or three magnets where at least one magnet has a different pole side on the measurement side of the system (Fig.7).

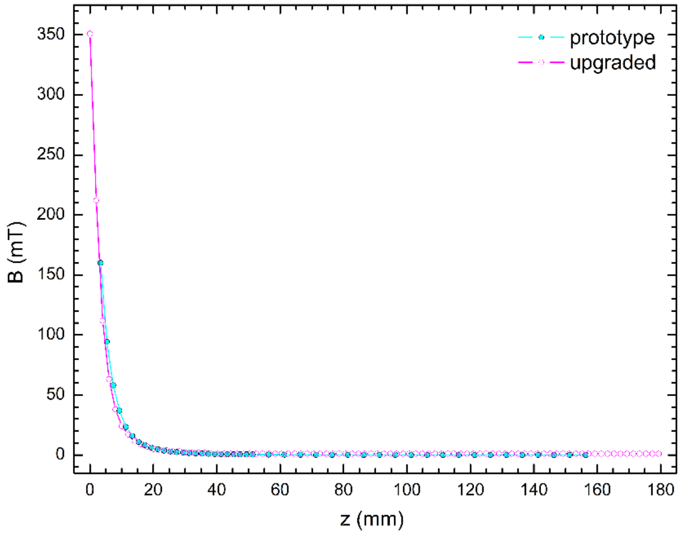


Fig. 6: Upgraded system vs. prototype

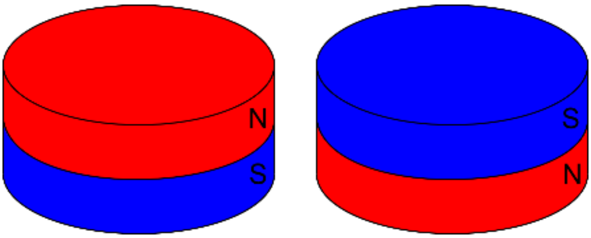


Fig. 7: Illustration of the antiparallel positioning of two magnets

The magnetic field lines as function of distance between magnets, simulated with the *Magpylib* package are [11] presented in Fig. 8.

The orientation of the Hall sensor in our setup is not suitable for this sort of measurements because it can only measure field in the Z direction. Attempts to make measurements along Z axis confirmed this assumption and all the results were only small fluctuation of noisy values due to slight misalignment between the Z axis of the magnet structure and the Z axis of the Hall sensor.

Rotation of the Hall sensor was not an option because several other types of measurements were performed and by modifying the position of the sensor would have made comparison between the results irrelevant.

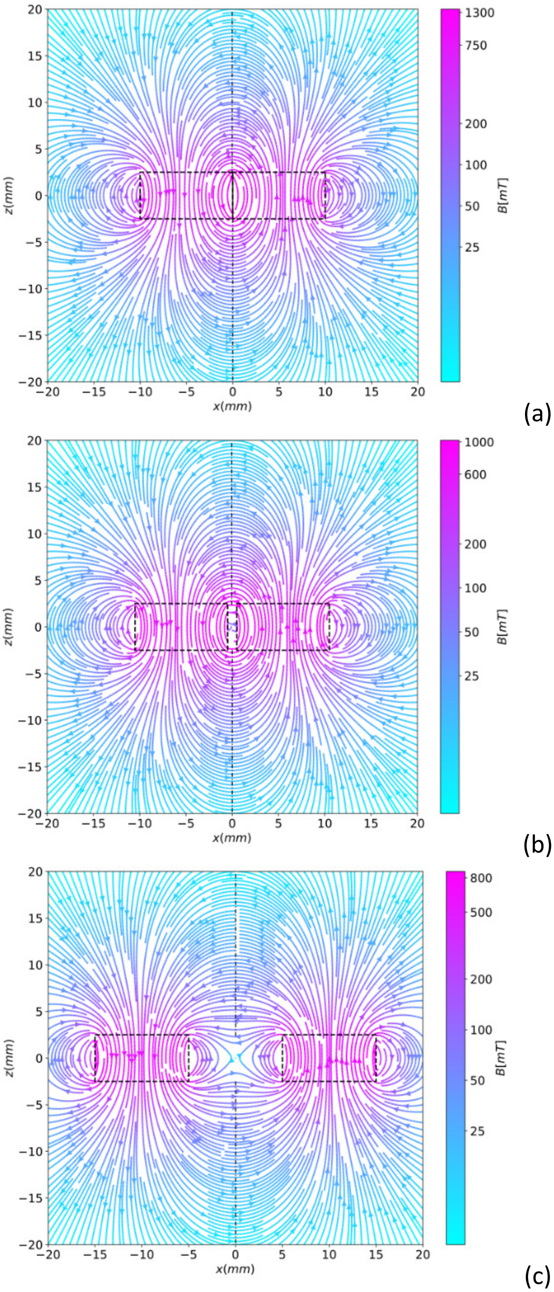


Fig. 8: Simulated magnetic field lines as function of distance between two magnets: (a) 0 mm, (b) 1 mm, (c) 10 mm

Measurements were performed for the antiparallel connection of three magnets and the results are depicted in Fig.9, Fig.10 and Fig.11 respectively.

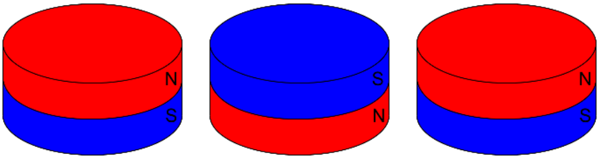


Fig. 9: Illustration of the antiparallel positioning of three magnets

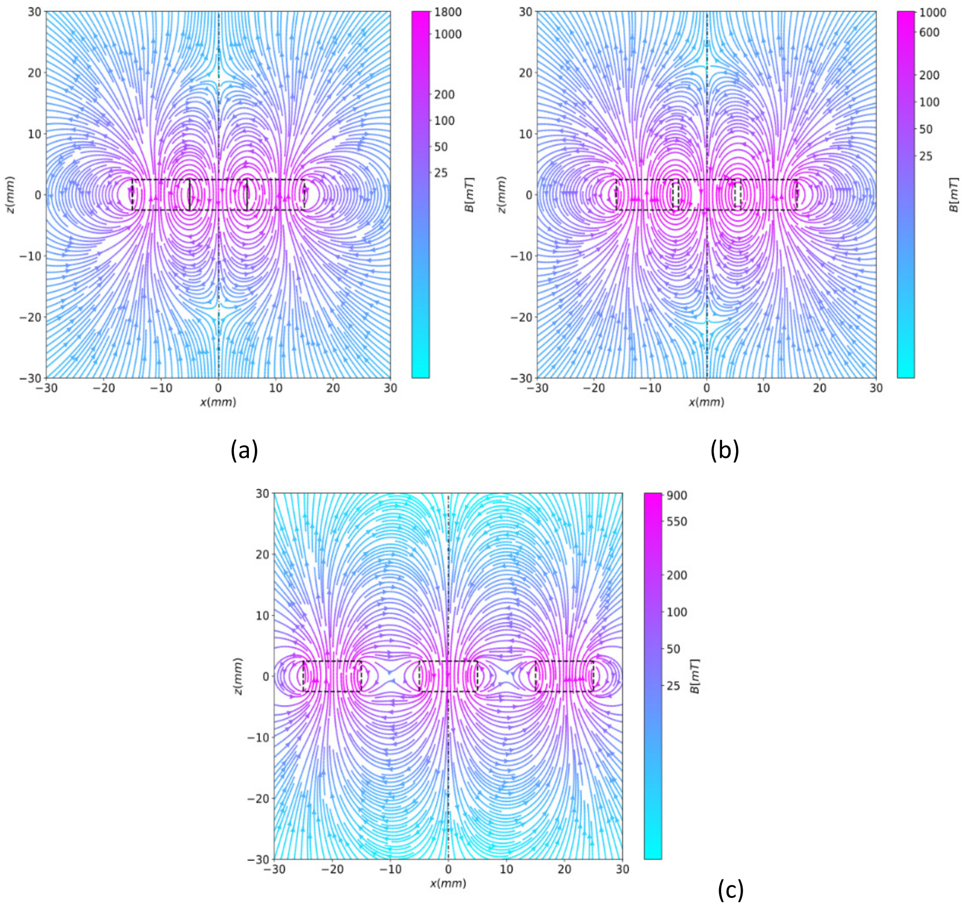


Fig. 10: Simulated magnetic field lines for different distances between three magnets: (a) 0 mm, (b) 1 mm, (c) 10 mm

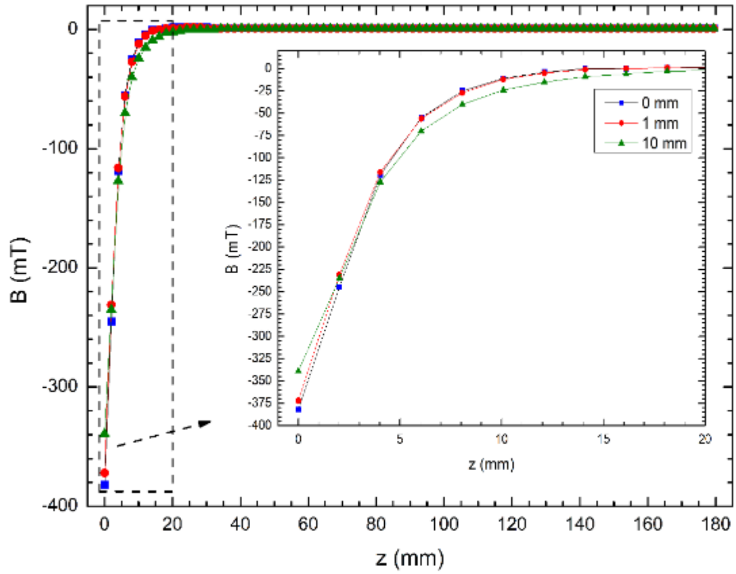


Fig. 11: Variation of magnetic flux density as function of z for three values of the distance between the magnets (0 mm, 1 mm and 10 mm) measured along the z axis in positive direction

In the case of three antiparallel magnets the measurement axis will be the symmetry axis of the system, which coincides with the symmetry axis of the middle magnet. The negative value of the measured field is due to the opposite pole side (South) of this magnet. When the distance between the magnets is 0 mm or 1 mm, the two magnets placed on both sides will enhance the field on the symmetry axis as demonstrated by the simulated field line plots and a more intense field is achieved. Simulation data shows a “zero-field” zone and a direction change in the field at distances around 20 mm. This cannot be pointed out by measurements because at such distances we are near the zone where the value to be measured is around or below sensor resolution or detection limit, respectively.

For 10 mm between magnets the resultant field shows a slightly different dependence with distance, having approximately the same aspect like that of a single magnet. This finding might suggest that, due to arrangement symmetry the contribution of the side magnets is not so relevant (are neglectable) in this case at such distances.

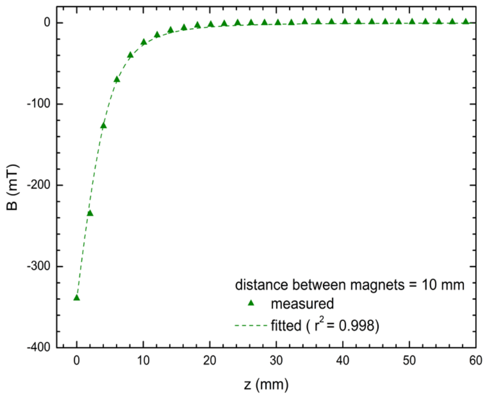
In order to verify these findings, the well-known relationship for the magnetic flux density at an on-axis point, at distance z from the face of an axially magnetized disk-shaped magnet (R radius, D thickness or height) [21-22] was fitted on our experimental data:

$$B(z) = \frac{B_r}{2}\left\{\frac{z+D}{[R^2+(z+D)^2]^{0.5}} - \frac{z}{[R^2+z^2]^{0.5}}\right\}$$

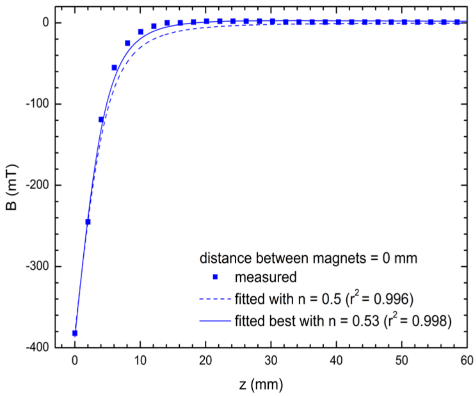
where B_r is the remanence field (value of B on the hysteresis loop, when the magnetizing external field has been removed), it is independent of the magnet's geometry and is given by the manufacturers [23, 24].

The results of the fitting are presented in Fig. 12. As one can observe, for a 10 mm distance between magnets there is a very good correlation between the experimentally measured data, and the fit made by using the formula for a single magnet.

For the 0 mm distance between magnets, the fit made by using the formula for a single magnet (dashed line) is satisfactory too, but there is a better fit using 0.53 in the exponent and not 0.5 like for one magnet, or for a 10 mm distance between magnets. The same findings are found for the 1 mm magnet distance. These later observations could explain the faster decay of the magnetic flux density for 0 and 1 mm as presented in the inset of Fig. 11.



(a)



(b)

Fig. 12: Fitting for the variation of magnetic flux density measured along the *z* axis, for different distances between magnets: (a) 10 mm, (b) 0 mm

CONCLUSIONS

The antiparallel coupling of neodymium magnets was studied by means of an upgraded measurement system designed for the study of the magnetic field created by different magnetic arrangements. The microcontroller driven data acquisition and measurement system and the linear stepper motor are excellent tools in performing precise and accurate experimental measurements.

The project was an important diagnostic tool for the students' performances and skills, and it was successfully presented at the final graduation exam.

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