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# Measurement system for testing the magnetic field uniformity

*Układ pomiarowy do badania jednorodności pola magnetycznego*

***Abstract**. The article presents a precise measurement system based on CNC (Computerized Numerical Control) technology and a Hall probe for analyzing magnetic field uniformity. The system enables detailed mapping of magnetic fields to evaluate the impact of coil design on field quality. The results demonstrate the system's effectiveness, particularly in magnetostrictive applications, where field uniformity ensures stability and precision.*

***Streszczenie.** W artykule opisano precyzyjny system pomiarowy do analizy jednorodności pola magnetycznego, oparty na technologii CNC (ang. Computerized Numerical Control) i wykorzystujący sondę Halla. System umożliwia dokładne mapowanie pola magnetycznego w wybranym obszarze, co pozwala na ocenę wpływu konstrukcji cewek na jakość generowanego pola. Badania potwierdzają skuteczność i precyzję systemu, szczególnie w zastosowaniach magnetostrykcyjnych, gdzie jednorodność pola jest kluczowa dla zapewnienia stabilności i precyzji układów wykonawczych.*

**Keywords:** CNC scanner, magnetic scanner, magnetic field map, magnetic field uniformity
**Słowa kluczowe:** skaner CNC, skaner magnetyczny, mapa pola magnetycznego, jednorodność pola magnetycznego

## Introduction

Precise measurements of the magnetic field are crucial in many fields of engineering, such as electrical engineering, medicine, and industry. Applications like Magnetic Resonance Imaging (MRI), wireless charging, and magnetometer calibration require coils that generate a highly uniform magnetic field. The growing demand for such coils necessitates continuous development and optimization of their design to meet increasingly stringent technical requirements.

Ensuring field uniformity is also essential in magnetostrictive systems, where magnetostriction, resulting in the deformation of ferromagnetic materials under the influence of a magnetic field, is used in actuators and sensors. In such systems, the quality and uniformity of the magnetic field directly affect the precision of displacement measurements and the stability of actuator performance.

Recent studies show that field uniformity can be improved through advanced coil design methods. For example, flexible PCB coils used in NMR spectroscopy allow for the generation of a uniform magnetic field, and their design enables easy adaptation to various applications, including medical ones [1, 2]. In the case of traditional solutions like Helmholtz coils, studies emphasize the need for precise adjustment of geometric parameters and minimization of manufacturing errors to ensure optimal magnetic field distribution [3, 4]. However, there are cases where coils have non-standard shapes, making precise optimization through simulations challenging. Innovative approaches also include designing coils for operation in shielded rooms, which minimizes the impact of external disturbances and ensures field stability under various environmental conditions. Such solutions are used in medical systems and laboratory devices where the quality of the magnetic field is crucial. In some cases, such as designing coils in cylindrical ferromagnetic shields, it is possible to increase field uniformity through appropriate optimization of materials and shield design [5].

Coils used in magnetostrictive systems have to generate a uniform field to ensure homogeneous deformations of magnetostrictive materials, such as GMM rods (made of high-strength magnetostrictive materials, e.g., Terfenol-D). A non-uniform magnetic field can lead to unpredictable fluctuations in deformation, affecting the precision and repeatability of the system. Therefore, when designing such coils, it is essential to optimize their design to generate a uniform magnetic field along the entire length of the magnetostrictive material [6, 7, 8].

On the other hand, there is also a need to measure the magnetic parameters of ferromagnetic materials, including magnetostriction. Coils, both for inducing the magnetic field and for detection, should be characterized by high uniformity of field distribution. Several factors influence this, such as the distance between coils, the number of layers, and the geometric parameters of the windings. In commonly known solutions, standard formulas are used to determine coil parameters, while in non-standard shapes, simulations are used to determine the level and uniformity of the magnetic field. However, it is recommended to verify the coil parameters through measurements.

Modern approaches to coil design include geometric modelling and optimization of electrical parameters, such as the number of turns and current intensity, which allows for obtaining a more uniform field. For example, studies on Helmholtz coil systems and PCB coils show that precise winding arrangement and optimization of magnetic systems can significantly increase field uniformity, especially in magnetostrictive systems where a precise field along the actuator axis is necessary.

The aim of this article is to investigate the magnetic field uniformity of various types of coils and determine how coil design affects the quality of the generated field. The research used an advanced measurement system based on CNC technology, which allows for detailed mapping of the magnetic field and precise assessment of the impact of coil design on field uniformity.

## Measurement system

The measurement system consists of three main components: a CNC manipulator equipped with a Hall probe, a magnetic field meter, and a central control unit (Fig. 1). The system was developed to precisely map the magnetic field distribution in a selected spatial area [9]. The device acts as a scanner, where the CNC manipulator controls the movement of the measuring head with the mounted Hall probe.

The measurement head moves within a working space of 200×200×100 mm, according to programmed trajectory. The plotter's drive transmission is based on toothed belts and 8 mm diameter guides for the X and Y axes, ensuring smooth and precise movement in these directions. Movement along the Z-axis is achieved using a trapezoidal screw, guaranteeing accurate vertical positioning of the probe. The plotter is controlled via a module based on the ARDUINO UNO platform, which includes stepper motor drivers. The entire system is managed by GRBL software, allowing the interpretation of standard G-code commands commonly used in CNC devices.

During scanning, the Magnet-Physik FH-54 magnetometer measures the flux density values from the Hall probe, which are simultaneously assigned the XYZ coordinates of the examined point in space. The data obtained during measurements are stored in a database, enabling the user to select a specific procedure and later save the results in tabular form in an Excel file. This functionality allows for full utilization of the collected data, enabling their visualization using three-dimensional magnetic field distribution maps.

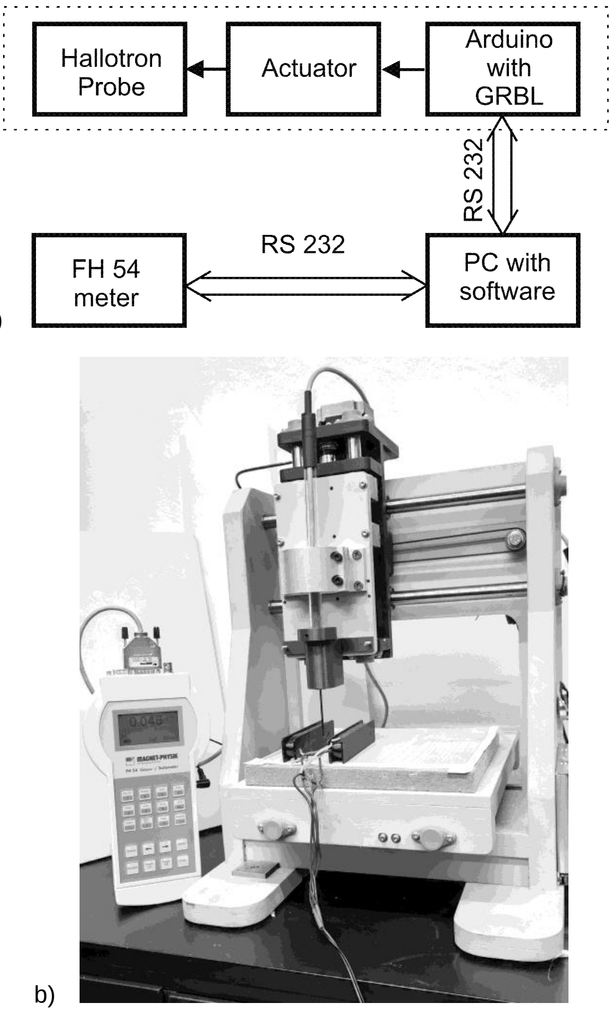


Fig. 1. Measurement system: a) block diagram, b) the device

**Measuring methodology**

The measurement procedure includes several essential steps, starting from sample preparation, setting scanning parameters, to performing the actual scanning.

The object under study is a part of the system for determining magnetostriction using the SAMR (Small Angle Magnetization Rotation) method. It consists of two coils inducing a transverse alternating field (AC). Due to size constraints and the declared field intensity level, it was not possible to use a typical Helmholtz setup. Therefore, a modified system of two oval coils was used, as proposed in the publication [10]. The coils were made on a frame printed from polyamide using the powder method (SLS) - Fig. 2. Two cases were considered for the study – coils with a winding height of 7 and 15 mm. Each coil is 100 mm long and 10 mm wide. Enamelled winding wire with a diameter of 0.45 mm was used for the windings. The frames contain several additional mechanical elements facilitating both winding and assembly in the target system. The coils were mounted parallel to each other on the working plane at a specified distance. A flat Hall probe head was used in the measurements, initially positioned at the lower left corner of the scanned plane between the coils.

The next step is configuring the scanning parameters, such as defining the dimensions of the measurement area, the shape of the scanned surface, and the intervals between successive measurement points. These parameters are selected each time depending on the type and size of the coils being studied, allowing the measurements to be optimally adapted to the specific system. Then, after positioning the measuring head at the desired starting point, the operator zeros the X, Y, and Z coordinates using the "Zero CNC" function in the control software. This defines the reference system, enabling precise control of the head movement relative to the selected starting point.

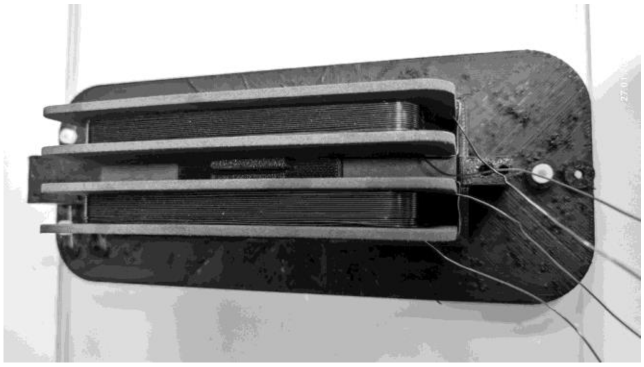

Fig. 2. 3D printed polyamide coil formers for windings, created using the SLS method

The control application allows for the adjustment of scanning parameters, such as the head movement speed (standard 200 mm/min), measurement time (standard 2000 ms), and offset settings. This makes it possible to tailor the scanning process to the specific type of sample or measurement conditions.

An additional advantage of the software is the estimation of the time required to complete the scan, as in some cases, it may take longer than a day.

**Measurements**

The main objective of the measurements was to present and evaluate the magnetic field distribution generated by oval coils, which are part of the developed test stand for magnetostriction measurements. A key requirement was the ability to achieve a magnetic field intensity of up to 100 A/m in a strictly defined area of 50×5×1 mm, which is necessary for the effective stimulation of amorphous and nanocrystalline tape samples. An additional design criterion was the minimization of the oval coils' dimensions, as they must be placed inside a solenoid generating a longitudinal field in the final configuration. Achieving the smallest possible coil dimensions requires careful optimization of both geometric parameters and the number of turns or the type of winding wire used.

To verify the suitability of the designed coils for studies using the SAMR method, a series of magnetic field distribution measurements were performed in the plane between two oval coils. Each series included mapping the magnetic flux density for a specified distance *d* between the coils and a given supply current *I*, with the coils arranged parallel to each other. A flat Hall probe was used in the measurements, oriented in two orthogonal planes to assess the impact of the head orientation on the meter readings.

The scanning of the examined area with dimensions X×Y (where X=*d* and Y was adjusted to the coil geometry) was carried out with a 2 mm step in both axes, allowing for a regular grid of measurement points. At each point ($x_i$, $y_i$), the magnetic flux density value $B_i$ was read using the Hall probe. The collected data {($x_i$, $y_i$, $B_i$)} were used to calculate the average magnetic flux density value, standard deviation, and other indicators of magnetic field uniformity.

Example measurement results, processed into a 3D map, are shown in Fig. 3. This visualization clearly indicates areas of highest and lowest magnetic flux density and assesses the extent to which the field remains uniform in the strictly defined measurement area.

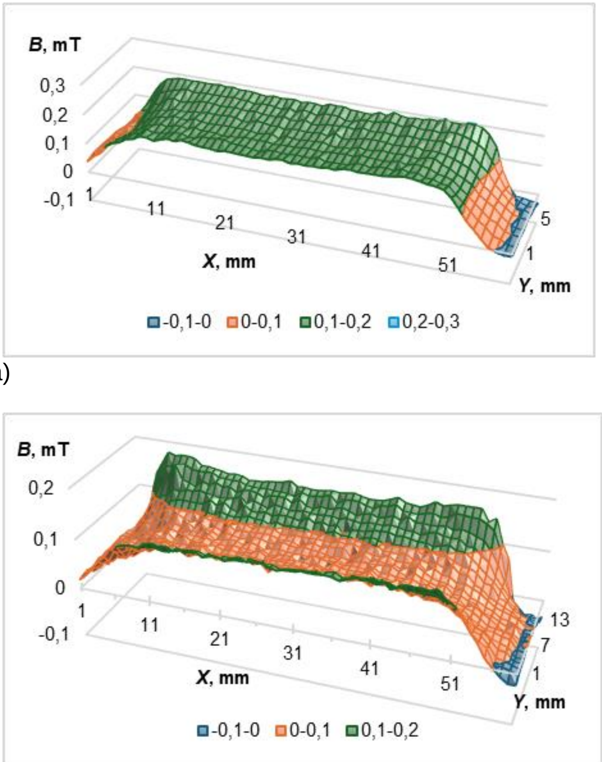


Fig. 3. 3D map of the distribution of magnetic flux density for *I*=200 mA and distance between coils: a) 20 mm, b) 40 mm

**Results**

To numerically assess the uniformity of the magnetic field, key statistical quantities were determined from each such map (i.e., from a single scan). The average flux density:

$$\overline{B} = \frac{1}{N}\sum_{j=1}^{N} B_j \tag{1}$$

where *N* is the number of measurement points in a given series, and $B_j$ is the flux density reading at the *j*-th point.
The standard deviation of a single result:

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}\left(B_j - \overline{B}\right)^2} \tag{2}$$

Uniformity coefficient:

$$U_{\mathrm{B}} = \frac{\sigma}{\overline{B}} 100\,\% \tag{3}$$

The lower the value of $U_B$, the more uniform the field is in the area considered. The accepted thresholds are often defined as follows:

- $U_B \le 2\%$: the very good uniformity,
- $2\% < U_B \le 5\%$: the good uniformity,
- $5\% < U_B \le 10\%$: the moderate uniformity,
- $U_B > 10\%$: the low uniformity.

Range of flux density values:

$$\Delta B = B_{\max} - B_{\min} \tag{4}$$

where $B_{max}$ and $B_{min}$ are the maximum and minimum values of $B_j$ in the scanning area, respectively.
The magnetic field gradient determines the rate of change in individual directions. The average gradient in the X direction is determined as:

$$\nabla B_{\mathrm{x}} = \frac{1}{N-1}\sum_{j=1}^{N-1} \frac{\left|B_{j+1} - B_j\right|}{\Delta x} \tag{5}$$

where $\Delta x$ is the scanning grid step in the X-axis, and $B_{j+1}-B_j$ denotes the difference in flux density values at points adjacent to the X-axis. The gradient in the Y direction is determined analogously.

Based on the presented formulas, the most important parameters evaluating the quality and uniformity of the magnetic field were calculated. For each measurement configuration defined by a specific distance between the coils and the supply current, a full scan of the examined area was performed. Numerical parameters were calculated from each scan, and the most representative results are presented in Table 1.

Table 1. Summary of magnetic field measurements at different distances between coils and supply current values.

| *d*, mm | *I*, mA | *B*, mT | *σ*, μT | $U_B$, % | Δ*B*, μT | ∇$B_x$, μT/mm | ∇$B_y$, μT/mm |
|---|---|---|---|---|---|---|---|
| 10 | 100 | 0,11 | 4,3 | 4,01 | 19 | 1,9 | 2,1 |
| 10 | 200 | 0,22 | 4,1 | 1,87 | 22 | 2,4 | 1,9 |
| 20 | 100 | 0,07 | 4,8 | 6,73 | 24 | 2,0 | 1,8 |
| 20 | 200 | 0,16 | 4,2 | 2,65 | 26 | 2,5 | 2,0 |
| 30 | 100 | 0,05 | 3,7 | 7,19 | 14 | 1,8 | 2,2 |
| 30 | 200 | 0,11 | 3,9 | 3,59 | 22 | 2,2 | 2,1 |
| 40 | 100 | 0,04 | 4,3 | 9,76 | 19 | 1,5 | 1,9 |
| 40 | 200 | 0,08 | 4,4 | 5,14 | 23 | 2,2 | 2,1 |

The table summarizes the obtained values of average flux density, standard deviation, uniformity coefficient, and selected field gradient parameters for different measurement configurations. The summary illustrates the impact of two key parameters – the distance between the coils *d* and the supply current *I* – on the level and uniformity of the generated field. Based on these data, it can be observed that smaller distances between the coils (10–20 mm) contribute to higher flux density values, which is beneficial for achieving the required field intensity for stimulating magnetostrictive samples. At the same time, in some cases (e.g. for *d*=20 mm and *I*=100 mA), the uniformity coefficient can reach even 6–7%, indicating moderate uniformity.

Increasing the current from 100 mA to 200 mA allows for higher flux density values, however in some cases, it may cause a slight deterioration in uniformity (an increase from approximately 4% to 5–6%).

The field gradient coefficients in the X and Y directions remain at a low level (around 1–2 μT/mm), which favors relative uniformity in the examined area.

For longer distances between the coils (30–40 mm), the magnetic flux density values decrease, which is natural due to the spread of field lines over a larger volume. Nevertheless, at a current of 200 mA, it is still possible to achieve flux density at the level of 0,08–0,11 mT, with a uniformity coefficient of 3–5%.

Figure 4 shows the graph of the uniformity coefficient $U_B$ as a function of the distance between the coils for a coil supply current of 200 mA. The green line refers to the 5% uniformity threshold considered good, and the red line to the 2% uniformity threshold considered very good.

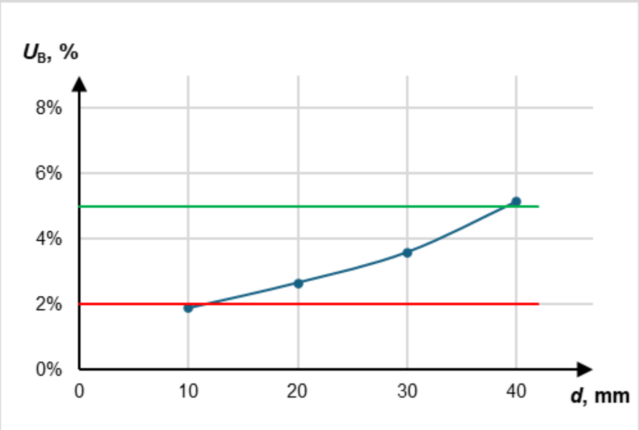


Fig. 4. Magnetic field uniformity for *I*=200 mA


**Summary**

The main objective of the measurements was to present and evaluate the conducted measurements clearly confirmed that the oval coils of the developed design can generate magnetic fields of the assumed intensity in a relatively small area (50×5×1 mm). Summarizing the conducted studies, it was shown that smaller distances between the coils favor achieving higher magnetic flux density values. Doubling the supply current allows for a double increase in flux density values. The analysis of the uniformity coefficient for most configurations revealed that it oscillates in the range of 2–7%, which qualifies the results as good or moderate in terms of uniformity. Such a level of uniformity is usually sufficient for magnetostriction studies, especially with a small measurement volume. Low field gradients proved beneficial for the stability and repeatability of measurements using the SAMR method. Additionally, the use of oval coils, which maintain relatively compact dimensions, allows for their effective placement inside a solenoid generating a longitudinal field, enabling multi-axis sample stimulation.

The results demonstrate that the described coil system is an effective solution for generating a transverse magnetic field in a small space, necessary for magnetostriction studies using the SAMR method. In further research, we will focus on optimizing the winding distribution and analyzing thermal effects at higher currents.



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