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DESIGNING THE CONTROLLED GENERATOR OF A HOMOGENOUS MAGNETIC FIELD

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Abstract: *The paper describes a design of a generator of a homogenous magnetic field by two pairs of Helmholtz coils and related calculations. The paper presents software that performs the calculation, as well as the proof of results using two magnetometers. Simulated results completely correspond to the experimental results. Therefore, the presented software can be used for designing the generator of the homogenous magnetic field of different magnetic field strengths, as well as different dimensions. The presented generator enables an easy positioning of a magnetic element into the generated homogenous magnetic field.*

Keywords: *Helmholtz coils, solenoid, coil, magnetic field generator.*

1. INTRODUCTION

A controlled generator of a homogenous magnetic field produces a magnetic field of high homogeneity in the axis direction along which magnetically sensitive elements are installed [1]. High homogeneity is achieved along the axis between a pair of the Helmholtz coils [1-3]. This enables an easy positioning of magnetic elements into a homogenous field. These magnetic elements are analyzed with the additional tools from the aspect of change of electromagnetic performances under the influence of the homogenous magnetic field [4]. Homogeneity of the magnetic field along the axis of coils may be increased by adding more pairs of the Helmholtz coils [3]. The homogenous magnetic field enables considering the change of other physical characteristics (such as impedance, electrical resistance, pressure, etc.) depending on the change of the magnetic field [5, 7].

2. THEORETICAL BACKGROUND

2.1. Field along the solenoid axis

Let us assume that the solenoid consists of a large number of coils of a thin conductor which is tightly and evenly winded on a cylinder of a diameter r and length L (Fig. 1) [1, 2]. If the coil consists of a large number of N turns, then N*dx*/L is the number of turns on the element of a length *dx* of a solenoid axis.

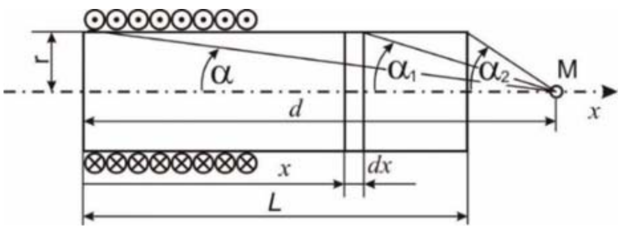


Figure 1. A solenoid with induction in point M.

If one presents a current in a solenoid, made of a group of turns on the element *dx*, it may be treated as a helical current contour where the value of current is *(NI/L)dx*, and the complete solenoid could be considered as a series of equivalent helical current contour with mutual distance *dx*. Since in solenoid axis points the elementary inductions by certain current contours have only axial component, we may add them algebraically, so the total induction in point M is [1]:

$$B = \int dB = \mu_0 \frac{NI}{2L} \int dx \frac{\sin^3\alpha}{r}, \qquad (1)$$

where x is a distance of elementary current contour from the left solenoid end, and *d* is a distance from the point M, where the following relations are valid: $d - x = ctg\alpha$ and $dx = (r/\sin^3\alpha)d\alpha$. If one counts an integral in the interval from α_1 to α_2, the next equation is satisfied:

$$B = \mu_0 \frac{NI}{2L} \int_{\alpha_1}^{\alpha_2} \sin\alpha \, d\alpha = \mu_0 \frac{NI}{2L} (\cos\alpha_1 - \cos\alpha_2). \qquad (2)$$

Observing the point M in the center and on the edge of the solenoid, we get the expressions for induction in the center of the solenoid:

$$\alpha_2 = \pi - \alpha_1 \Rightarrow B = \mu_0 \frac{NI}{2L} 2\cos\alpha_1 = \mu_0 \frac{NI}{2L} \frac{1}{\sqrt{1+(r/L)^2}}, \quad (3)$$

whereby, if L is much larger than r, it follows: $B = \mu_0 NI/L$, and according to the same principle, when $\alpha_2 = \pi/2$, the induction at the solenoid end is: $B = \mu_0 NI/2L$, i.e., twice lower regarding the solenoid center.

2.2. Field along the coil axis

The coil may be observed as a certain number of solenoids winded to each other, where the diameter of each following solenoid increases by the thickness of a wire regarding the previous one (in case of ideal contours) *(Fig.2 a)* [2].

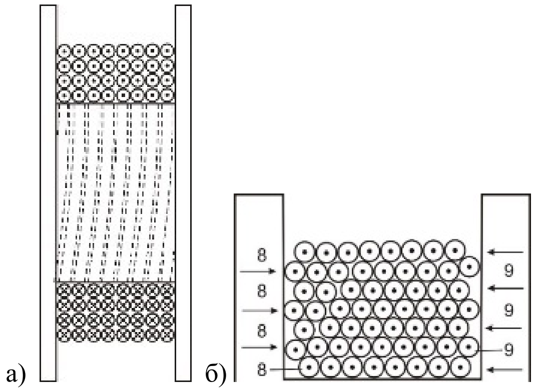


Figure 2. Wiring into a coil: a) ideal contours, b) real contours.

For thinner cross sections of lacquer isolated wire, it is difficult to ideally arrange each following row of wire precisely one onto another, so that the coil in each following row (solenoid) in the circular transducer falls into grooves between two previous windings (*Fig. 2 b*)) [2]. In that case, the increase in the diameter of each following solenoid in the coil is determined as a relation to the thickness of coils and the number of winded solenoids, which is a lower value than the total wire thickness (with isolation). For thicker cross sections of the wire and precisely dimensioned width of the coil frame, it is possible to achieve that each row of coils has an identical number of windings. However, if that condition is not fulfilled, each second row of coils usually has an identical number of windings, and the neighboring ones differ for one winding (*Fig. 2 b*). Therefore, the field in the solenoid axis is calculated according to the formula (2), and the field in the coil axis is calculated as an algebraic sum of all individual results.

2.3. Field along the axis of the pair of coils (Helmholtz coils system)

If one applies the previously description on a pair of coils where L is significantly smaller regarding r, and if they are arranged at a mutual distance a, and if fulfilled a condition that a = r, the magnetic field between these coils will be approximately homogenous along the axis x [2,4]. This coils system is known as “Helmholtz coils”, according to the scientist who constructed them. In case (a > r) or (a < r) the homogeneity of the field is lost, and the field lines are convex or concave, respectively (Fig. 3).

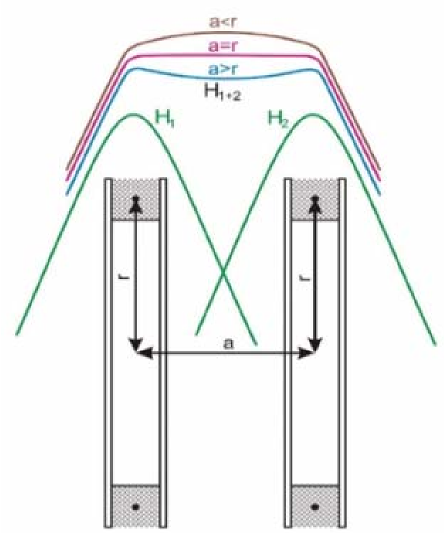


Figure 3. Helmholtz coils for different relations of the parameters a and r.

3. CALCULATION OF FIELD ALONG THE PAIR OF COILS

Parameters for the calculation of the field in a point along the x-axis of the pair of coils:

$H = H_1 + H_2 = \frac{NI}{2L}(\cos\alpha_1 - \cos\alpha_2 + \cos\beta_1 - \cos\beta_2)$

$\alpha_1 = \mathrm{arctg}(a/x)$, за $0 < x < c$

$\alpha_2 = \pi - \mathrm{arctg}(a/(L-x))$, за $0 < x < L$

$\alpha_2 = \pi/2$, за $x = L$

$\beta_1 = \pi - \mathrm{arctg}(a/(b-x))$, за $0 < x < b$

$\beta_1 = \mathrm{arctg}(a/(x-b))$, за $b < x < c$

$\beta_1 = \pi/2$, за $x = b$

$\beta_2 = \pi - \mathrm{arctg}(a/(c-x))$ за $x < c$

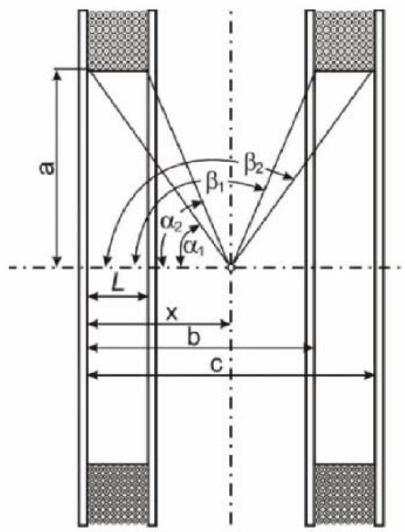


Figure 4. Helmholtz coils with the parameters for the calculation

Figure 4. shows the parameters for calculation of the field in the axis of coils, with individual cases of the position of the parameter x.

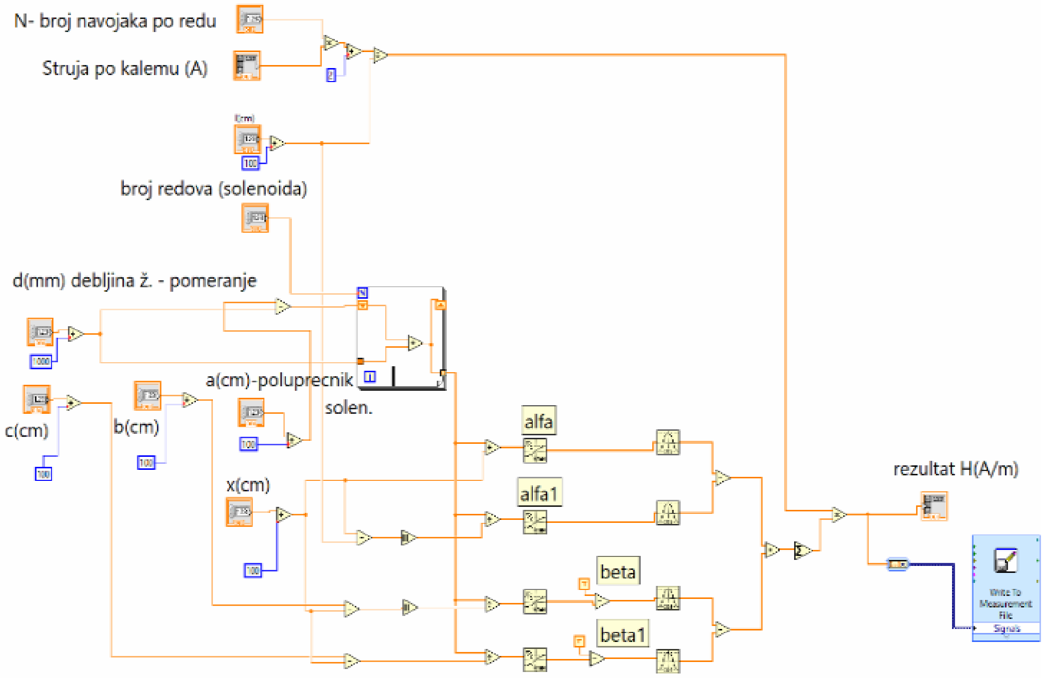


Figure 5. A block diagram of the “G” software for relation L<x<b

A block diagram of the “G” software that is performed in the “Labview” software package for the case, i.e. L<x<b is shown in Fig 5. When the value x is out of these limits, it is also necessary to adjust the software code by creating the sub-software for each case shown in Fig 4. Based on geometry and data on the thickness of the wire we determine the number of turns along the solenoid, as well as several rows (solenoids) in the coil. Using the “movement” parameter, close to the value of the thickness of the wire “d”, we define the change of the parameter “a” while performing each software loop (“FOR loop”) in “G” software, and several solenoids define how many software loops will be performed. The software code is started, after entering the parameters in the front panel of the program code, for calculating the field in the axis of the Helmholtz coils (Fig. 6). The set parameters in the Front panel (Fig. 6) are executed in the background through "G software" (Fig. 5). The results obtained from the front panel (Fig. 6) are shown in the diagrams in Figures 9 to 11.

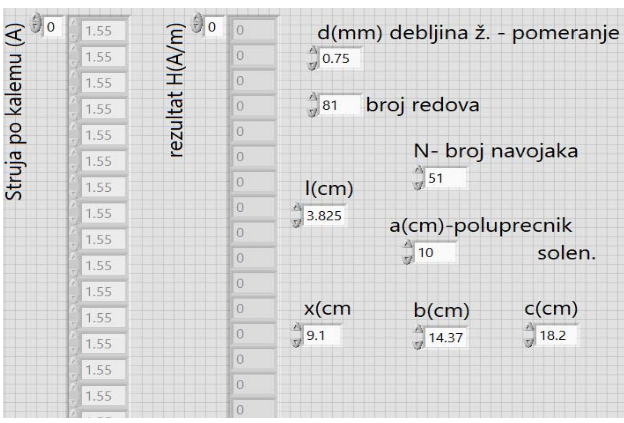
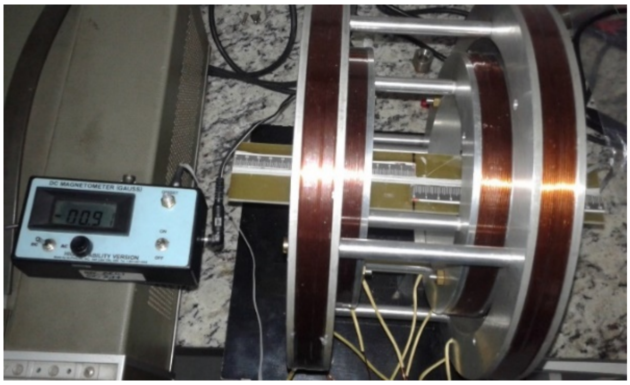


Figure 6. The Front panel of the software for the calculation of the magnetic field

4. TESTING HOMOGENEITY OF SIMULATED AND MEASURED VALUES OF MAGNETIC FIELD GENERATOR

By applying the two pairs of Helmholtz coils, the homogeneity between the coils is increased (Fig. 7).



Small coils	Large coils
x = 5.75 cm ***L***= 2 cm **a** = 8.5 cm **b** = 9.5 cm **c** = 11.5 cm **N** = 377 **d** = 0.95 **number of rows** = 21 R_{Small}= 5.5 Ω×2	**x** = 7.75 cm ***L***= 2 cm **a** = 13 cm **b** = 13.5 cm **c** = 15.5 cm **N** = 367 **d** = 0.95 **number of rows** = 21 R_{Large} = 7.7 Ω×2

Figure 7. The generator of the homogenous magnetic field made of two pairs of Helmholtz coils with coils parameters

Testing the homogeneity of the generator of the magnetic field from Figure 7 is realized by two magnetometers: *AlphaLab Inc* (Fig. 8 a) and *Metrolab* (Fig. 8 b). For a precious movement of a sensor, a slider with a brake has been designed (Fig. 8 c).

Figure 8. Equipment for testing homogeneity of the magnetic field, magnetometers: a) “AlphaLab Inc.” and b) “Metrolab” and c) slider with brake

The results of testing the homogeneity of the generator of the homogenous magnetic field from Fig. 7 are shown in Figures 9 – 11.

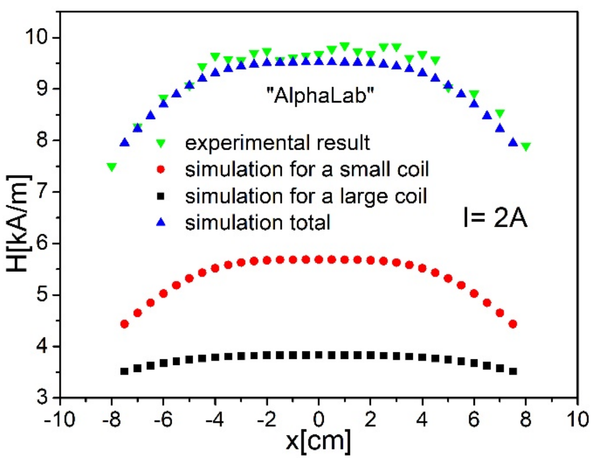


Figure 9. Testing the homogeneity of the generator of the magnetic field with the “AlphaLab Inc.” instrument

Fig. 9. shows the diagrams obtained by the experimental results and calculated values of the magnetic field along the x-axis which has been measured by the “*AlphaLab Inc”* instrument, while Fig. 10 shows the results obtained by the “*Metrolab”* instrument.

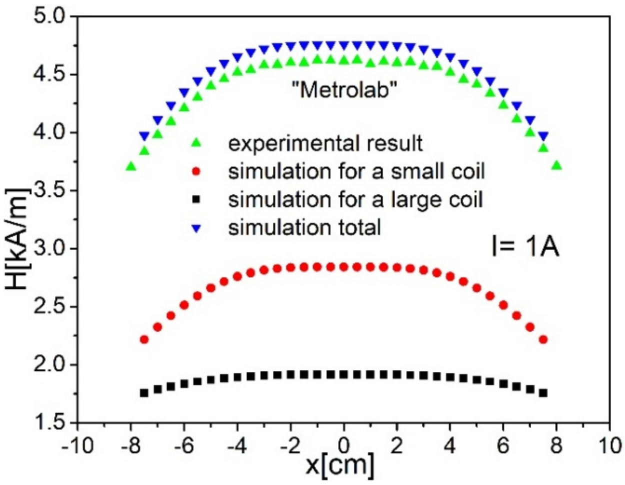


Figure 10. Testing the homogeneity of the generator of the magnetic field with the “Metrolab” instrument.

The magnetic field is extremely homogeneous in a length of 6 cm in the axis of the coils (from -3 cm to +3 cm) (Fig. 11). The maximum deviation of the results obtained by the "AlphaLab" instrument is: +4% (at +3cm), while this value for the results measured by the "Metrolab" instrument is: -3.6% (at +3cm). It is important to note that the measurement error was significantly reduced by using a slider that accurately move the sensor along the axis of the coils. The value of the calculated magnetic field in the x-axis of the coils is extremely close to the values of the arithmetic mean of the results obtained with two different magnetometers.

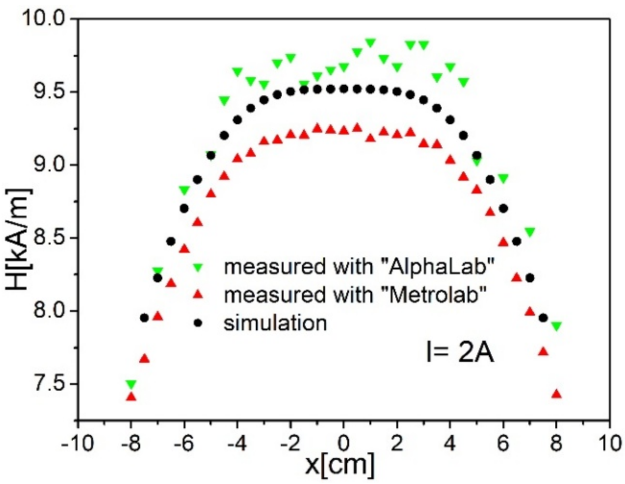


Figure 11. Comparison of the simulated result with experimental results obtained with various instruments.

One pair of the Helmholtz coils can be set at an angle 90^{o} to the second pair (Fig. 12), and in that way, it is possible to test the magnetocrystalline anisotropy of the magnetic element [3].

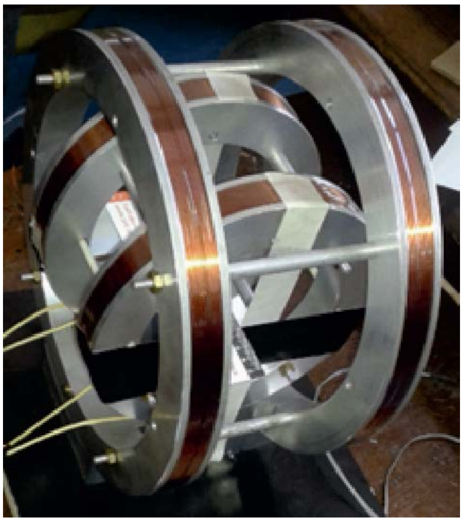


Figure 12. Arranging coils for testing the magnetocrystalline anisotropy of the magnetic element.

5. CONCLUSION

By applying two pairs of Helmholtz coils to one axis we achieve a remarkable homogeneity of the magnetic field between the coils arranged along the central axis. The simulated result of the magnetic field obtained by the “Labview” software package corresponds to a real value of the magnetic field that is generated by coils with a *dc* currency flow. The described method can be applied for the design and calculation of the coils with various dimensions, depending on the required intensity of the magnetic field of high homogeneity.

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