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Calibration of Magnetic Field Sensors up to 10 kHz Based on 50 Hz Helmholtz Coils

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Abstract **– Helmholtz coils (HC) are used to develop uniform magnetic fields for a variety of research applications. Helmholtz coils can be easily constructed and the fields easily calculated. This makes them especially useful in calibrating sensors and numerous other low-frequency magnetic-field testing applications. Such a calibration system with Helmholtz coils can be found in ICMET, operating at a frequency of 50 Hz. Recently, the issue was raised for calibration of certain measuring devices up to 10 kHz frequencies needed for measurement in industrial applications such as induction hardening of metal parts. The first part of the paper presents theoretical analysis on the volume confining the space where the magnetic field components have a predetermined deviation (a 2% threshold) from the center of the classical Helmholtz system followed by a comparison with a 3D FEM simulation and measurement of HC field. The second part describes the parameters identification and the resonant power supply used to significantly reduce the excitation output required for the Helmholtz coil system at these frequencies.**

Keywords – Helmholtz coils, parameters, resonant supply, FEM model, uniform field volume

I. INTRODUCTION

Precise measurement of the magnetic fields generated by electrical and electronic equipment is a requirement imposed by international standards. In some cases, it includes functional measurements; in other cases there are imposed safety measures for persons or operators. Periodic calibration of the equipment and sensors for magnetic field measurement is imposed by the laboratory quality assurance system. However, the cost of such calibration is substantial because, even abroad, there are few laboratories accredited for this kind of measurements.

Such a calibration system with Helmholtz coils can be found in ICMET, operating at frequencies of 50 Hz and the respective measurement was accredited in 2007 by DKD (Deutscher Kalibrierdienst) [1].

The paper presents a theoretical analysis on a classical Helmholtz system, determining the region confined by a predetermined deviation of the magnetic field components relative to the magnetic field value in the center of the Helmholtz system. Also related to the theoretical elements, there are determined the dependence of this volume (with field values of predetermined deviation) to the distance between the two coils of the Helmholtz system. There are also indicated metrological references and recommendations related to problems encountered when using a single Helmholtz system located in the environmental magnetic field or in the presence of spurious components of magnetic field.

The Helmholtz system analysis [2-4] is extended to the use of simulation software based on the finite element method. By implementing the three-dimensional geometric model of the Helmholtz system in the Ansys Maxwell virtual environment, there are obtained the magnetic field values for a pair of rectangular coils in Helmholtz configuration carrying electric current, computed in the region of space confined by the Helmholtz system. The results of the numerical simulation determine the dimenions of the region of field uniformity expressed relative to the magnetic field value computed in the center of the HC system. Based on the analytical and numerical calculations, there is presented the design of the calibration system with Helmholtz coils found at ICMET Craiova [5].

Regarding the Helmholtz systems, there were raised recently demands for calibrating certain measuring devices operating on frequencies up to 10 kHz, needed for magnetic measurements in industrial applications such as induction hardening of metal parts. The paper describes the parameters identification and the resonant power supply employed in order to significantly reduce the excitation output required for the Helmholtz coil system at these frequencies.

II. THEORETICAL ASPECTS OF HELMHOLTZ SYSTEMS

For the computation of the field produced by the Helmholtz system, there were considered the contributions all the eight current segments constituting the sides of the coil pair. In order to achieve the uniformity condition, there were imposed the well-known conditions for gradient annulment in the geometric centre of the system. If there are considered the coils sides as segments of length a, carrying an electric current of intensity I, and the coils located at distance d/2, there yields the relationship for determining the magnetic field induction generated by one coil [6-8]:

$$B(z) = \frac{2\mu_0}{\pi} Ia^2 \left(\frac{1}{\left[a^2 + (z - d/2)^2\right]\sqrt{2a^2 + (z-d/2)^2}} + \frac{1}{\left[a^2 + (z + d/2)^2\right]\sqrt{2a^2 + (z+d/2)^2}} \right) \quad (1)$$

For the considered Helmholtz system, the length of the coil side is a = 1 m. In order to calculate the deviation of the magnetic flux density from the geometric center on the -z...0...+z axis of the coordinate system there was considered an electric current I = 1 A, and the magnetic induction results in a dependence on just two parameters z and d:

$$B(z,d) = \frac{2\mu_0}{\pi} F(z,d) \quad (2)$$

In Fig. 1 there is plotted the above mentioned function, determining the relative deviation of the magnetic flux density values *B(z,d)*, considering as standard value the magnetic induction B_H in the geometric center of a system fulfilling the Helmholtz condition for square coils:

$$\frac{d}{2} = 0.5445a \quad (3)$$

$$\Delta B = \frac{B_H - B(z,d)}{B_H} = \frac{F_H - F(z,d)}{F_H} = 1 - \frac{F(z,d)}{F_H} \quad (4)$$

In Fig. 2 there was illustrated the deviation of the *F(z,d)* function compared to its value in the geometric center *z=0*, considering the distance *d/2* as function parameter:

$$F(z,d) - F(z=0,d) \quad (5)$$

These representations are useful when there is concerned a particular workspace, considering a preset deviation value in the magnetic field relative to its central value. In Fig. 6 there is illustrated a detailed view of the previous representation. It is obvious that for smaller distances between the two HC, the magnetic field representation displays a bulge, whereas for larger distances between coils – there are two bulges, indicating larger field gradients. Also, there is noticed that the highest precision is achieved while fulfilling the Helmholtz condition – the distance between coils being 0.5445 times the coil side 1 m.

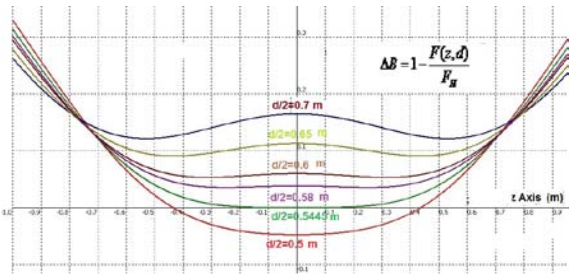


Fig. 1. The Helmholtz coils system magnetic field deviation relative to its value in the geometric center

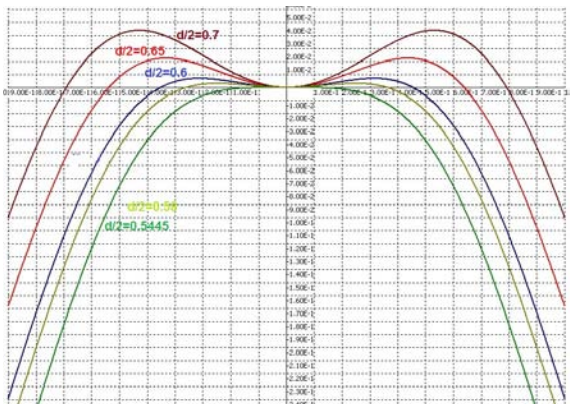


Fig. 2. Deviation of the F(z,d) function relative to its value in the geometric center

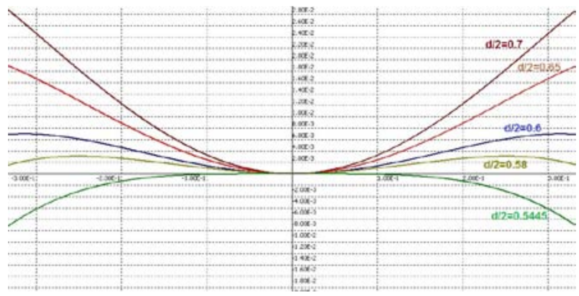


Fig. 3. Detailed view of the deviation of the F(z,d) function relative to its value in the geometric center

Therefore, as it is illustrated in the detailed view in Fig. 3, the longitudinal distance for which field uniformity is attained is approximately 200 mm, for the Helmholtz condition.

III. NUMERICAL SIMULATION RESULTS

The Helmholtz system analysis is extended to the use of simulation software based on the finite element method [9-12]. There was implemented in the virtual environment the geometric model of the HC system, each coil being comprised of a single turn. The coil side is a = 1 m, and the distance between coils is 0.5445 m. The system geometry is illustrated in Fig. 4. The coils are marked in purple, and the current excitation – entering and exiting the coils, is marked with red arrows.

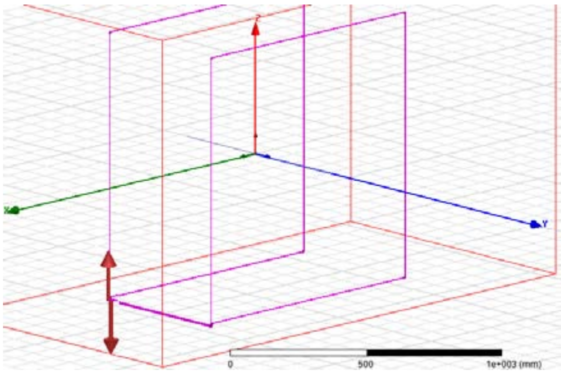


Fig. 4. Geometry of the Helmholtz rectangular coil system

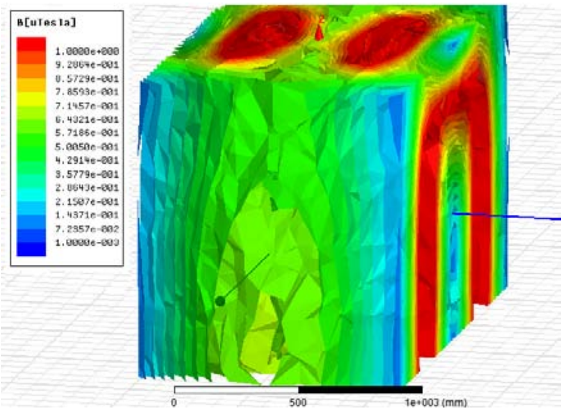


Fig. 5. The magnetic induction generated by the Helmholtz system in the analyzed region

The analyzed region is delimited by a rectangular box surrounding the coils. In Fig. 5 there is illustrated the magnetic field generated by the pair of rectangular coils in Helmholtz configuration carrying an electric current I = 1 A. The electric current excitation is applied on the edges of the coil pair, located in the left afore side of the system, as detailed in Fig. 4.

In order to obtain a better view of the field distribution in the analyzed region, and to determine the uniform field region, there are illustrated, in Fig. 6 – Fig. 8, sections of the region in the longitudinal plane (on the coil axis), transversal plane and horizontal plane, respectively.

Since the area of interest is located on the coils axis – the distance between the centers of the two coils, the magnetic induction is also computed on the respective axis. Fig. 9 illustrates such a representation. Thus, there is obtained the distance of field uniformity of almost 200 mm on the longitudinal axis, corresponding to the theoretical calculations.

By extending the view and achieving better accuracy in expressing the field uniformity, the region of interest is the one determined by uniform magnetic field relative to the field value in the geometric center of the HC system.

In order to determine the respective region, there is computed the normalized difference of the magnetic induction values relative to the standard value the magnetic induction in the geometric center [13, 14].

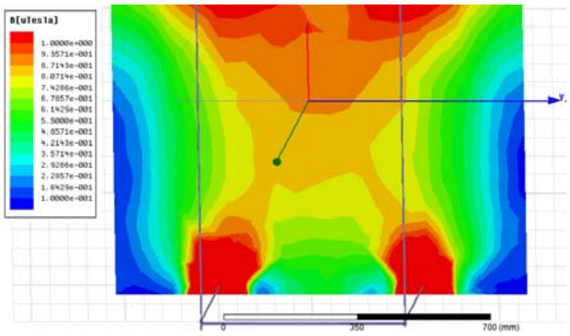


Fig. 6. The longitudinal plane section of the HC field domain

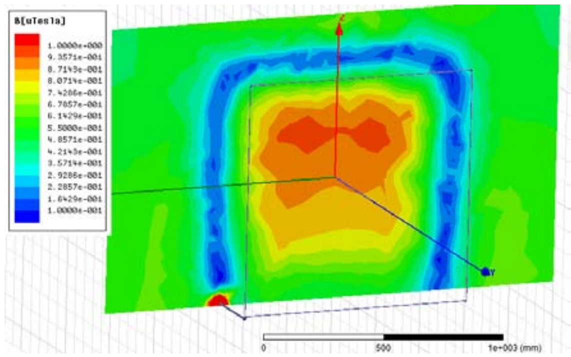


Fig. 7. The transversal plane section of the HC field domain

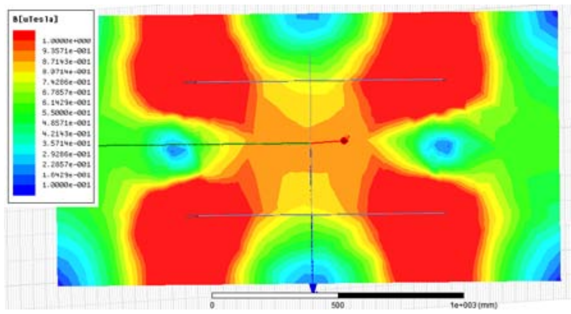


Fig. 8. The horizontal plane section of the HC field domain

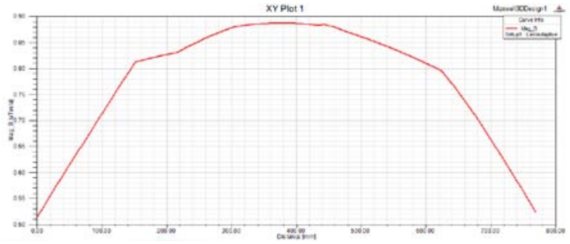


Fig. 9. The magnetic induction computed in the centerline of the Helmholtz system

Based on the magnetic field values obtained in Fig. 6 – Fig. 8, there is computed the deviation of magnetic field relative to the value in the center of the HC system (also considered as the center of the coordinate system). The magnetic field in the center of the HC system is B_0= 0.888 μT. The relative deviation is computed with relationship:

$$B_{rel}(x,y,z) = \frac{|B(x,y,z) - B_0(0,0,0)|}{B_0(0,0,0)} * 100\ [\%] \quad (6)$$

The purpose is to determine the region where the magnetic field deviation relative to the center value is less than 2%. In order to obtain a better view of the field distribution in the analyzed region, and to determine the uniform field region, there are illustrated in Fig. 10 – Fig. 12, sections of the region in the longitudinal plane (on the coil pair axis), transversal plane and horizontal plane, respectively.

Therefore, the illustrations describe the space defined by field uniformity – a deviation less than 2% relative to the center field value. As it is noticed in Fig. 10, on the longitudinal axis (OY), field uniformity is attained on a distance of 180 mm, slightly lower than the distance of uniformity of 200 mm obtained from the analytical calculations and illustrated in Fig. 3.

Regarding the transversal and horizontal plane sections illustrated in Fig. 11 and Fig. 12, respectively, field uniformity on the transversal axis (OX) is achieved for 300 mm, whereas for the vertical axis (OZ) the distance of uniformity is significantly lower, of 100 mm.

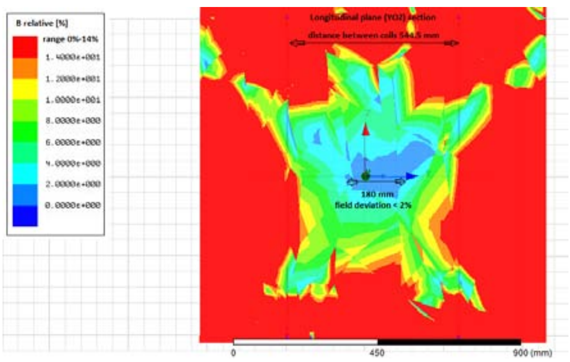


Fig. 10. Field uniformity in the longitudinal plane HC section

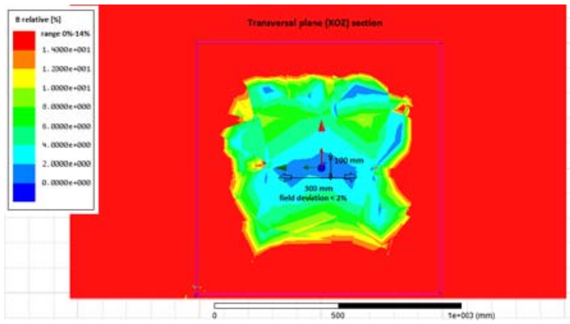


Fig. 11. Field uniformity in the transversal plane HC section

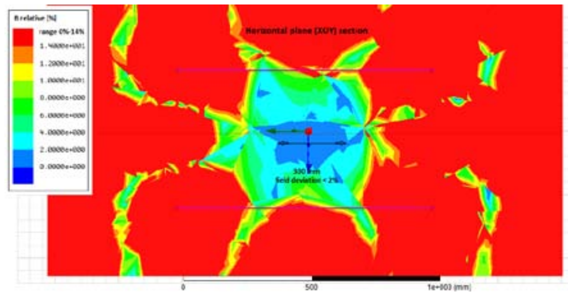


Fig. 12. Field uniformity in the horizontal plane HC section

IV. HELMHOLTZ COILS DESIGN

Our HC with rectangular geometry (Fig. 13), designed initially for the calibration of industrial magnetic probes only at 50 Hz frequency, was very convenient for construction and installation. A square HC produces a volume of nearly uniform magnetic field greater than a circular HC of comparable dimensions [2].

The performance is maintained up to a certain frequency limit. The frequency limitation is a function of the coil's parameters, radius, number of turns, type of connection (series or parallel of the two coils and finally the feed configuration (balanced or unbalanced with respect to ground).

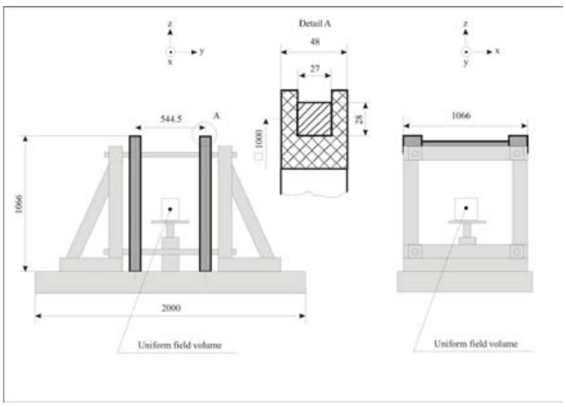


Fig. 13. Design of Helmholtz coil

An unique VNA (Vector Network Analyzer) device is used for identification of all circuit parameters (Fig. 14) by impedance measurements and transfer characteristics

[15]. From first resonance frequency of the coils system, the parasitic capacitance C_p is determined. Table I contain L, C_p, f_r values and Table II the AC coils resistance for different frquencies.

Fig. 14. HC equivalent circuit

The frequency characteristic of HC is given in Fig. 15. The resonant frequency is 15.6 kHz, which shows that the maximum working frequency of the HC calibration system must be less than 10 kHz, frequency until the system remains inductive.

Table 1. Measured parameter of HC system.

Parameter	Value
f_r	15.6 kHz
L	2 x 77 mH/coil
C_p	0.675 nF

Table 2. R_{ac} and Q function of frequency.

Frequency (Hz)	R_{ac} (Ω)	Q
50.44	4.15	5.85
502.95	4.85	50.01
994.13	7.37	65.15

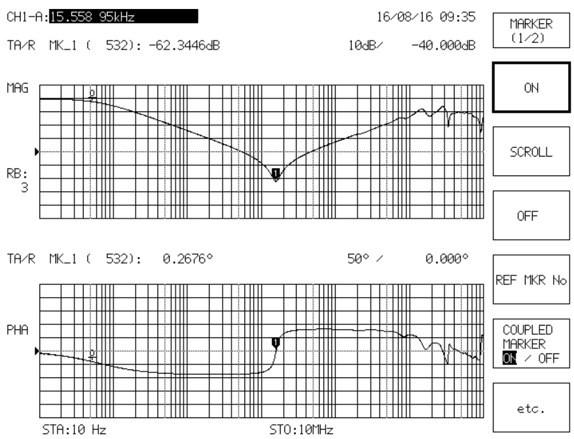
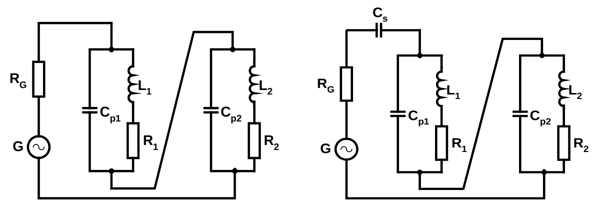


Fig. 15. Frequency characteristic of HC system

V. DRIVING HIGH FREQUENCY HELMHOLTZ COILS USING RESONANCE TECHNIQUE

The direct drive is used only for 50 Hz. The resonance method is advantageous at higher frequencies in order to obtain the lowest driving power [5]. In principle, serial or parallel resonance can be used. Both can be used with serially or parallel HC coils. LTSpice simulation and validation experiments were done in series assembly to be able to use the system as it is, both the 50 Hz and the high frequency, Fig. 16. Fig. 17 shows a simulation example at the frequency of 500 Hz, which takes into account the increase of coil resistance in alternating currents compared to the value at 50 Hz (17%).



(a) (b)

Fig. 16. Circuits used for simulations:
a) series coils; b) series resonance of series coils

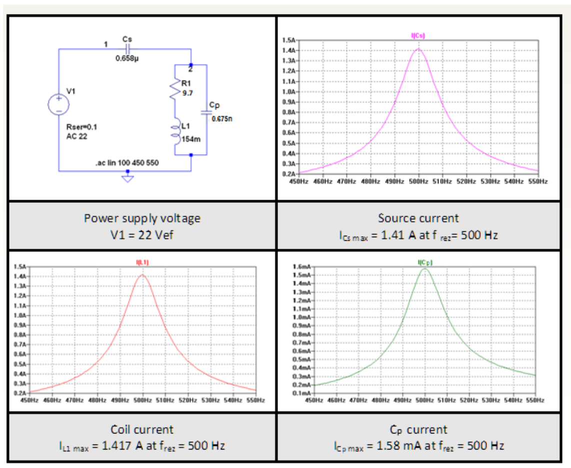


Fig.17. Example of simulation result

VI. EXPERIMENTS AND CALIBRATIONS

The measuring instrument used is the EFA 1 transfer standard [16] a magnetic field analyser with internal triaxial B sensor which was previously calibrated at PTB Germany. This device measures in the range from 5 Hz to 32 kHz (3 dB). EFA1 was so arranged that the field sensor was placed in the origin of the HC coordinate system.

For field sensor exact positioning, the anti-HC mounting is used. An anti-HC is the same HC, except the current in the two coils flows in opposite directions.At the point (y = 0, z = 0), the magnetic field must be equal to zero. In our experiment for I_L = 0.4 A, the correction is 9 µT.

A self-developed software is used to check uniformity of magnetic field produced by the HC using the transfer standard. The results are shown in Fig. 18.

In order to verify the results obtained, the measurements contained in Table III in the series resonant scheme were made except for the 50 Hz frequency. As is seen, voltage across the coils at higher frequencies represent a limiting factor (e.g. 9.1 V/turn at 5 kHz).

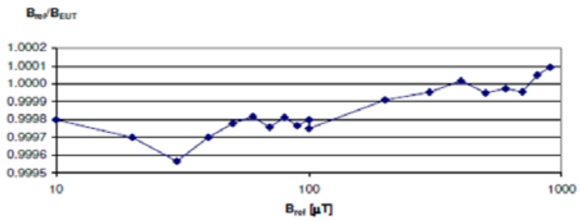


Fig. 18. Calibration result: ratio EFA 1 / EFA 300

Table 3. Measured values.

f [Hz]	50	673	1213	2460	5230
I_L [A]	0,4	0,4	0,4	0,4	0,2
B [µT]	103	103	103	103	52
U_L [V]	21	281	515	1004	1100

VII. CONCLUSIONS

The paper determines the magnetic field generated by a Helmholtz coils (HC) system fulfilling the Helmholtz condition, and studies its uniformity. The analytical calculation of the field uniformity yields a longitudinal distance of approximately 200 mm on the coils axis. However, numerical calculations employing FEM software Ansys Maxwell determines a field uniformity area of the following dimensions: 180 mm on the coils axis (longitudinal axis OY), 300 mm on the transversal axis (OX), and 100 mm on the vertical axis (OZ), respectively. The field uniformity was determined as relative deviation from the magnetic field in the center of the HC system. There was imposed a deviation threshold of 2%.

It is noticed that the vertical dimension of the field uniformity region is lower than the other dimensions – this is due the wires connecting the two HC, which were carrying currents of opposite directions. As illustrated in Fig. 4, the excitation (electric current) was applied in the left coil, and the current is leaving the circuit also in the left hand side of the geometry, after having passed the left coil, the wire connecting it to the second one, the right coil, and the wire returning to the left hand side. The two wires – the one connecting the coils and the returning wire – are parallel, the distance between them is 5 mm, whereas the distance to the center of the HC system is approximately 500 mm. This small distance between the wires determines a variation between the tangent components of the magnetic field generated by the electrical current passing through the wires in opposite directions, which further determines a lower vertical dimension of the field uniformity region [17].

By knowing the spatial distribution of field deviation relative to the center value, a field correction can be applied for sensors exceeding the uniformity area. The experimenter can apply the correction by performing the field integration from the system center to the longitudinal extremity.

The paper refers to the use of ICMET's HC low frequency coils (50 Hz) for frequencies up to 5 (10) kHz using series resonance circuits taking into account as limiting factors the maximum allowed coil voltage and coils self - resonance frequency. Identification of HC parameters is done seamlessly with a vector network analyzer (VNA). Measurements comparison with FEM modeling and circuit simulation give good results.

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