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CALIBRATION OF MAGNETIC FIELD METERS AT 60 Hz USING A HELMHOLTZ COIL: CONSTRUCTIVE ASPECTS AND CALCULATION OF ASSOCIATED UNCERTAINTIES

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Abstract: This paper describes the construction of a Helmholtz coil to be used as a magnetic field generator during the calibration of magnetic field sensors. A magnetic field meter was calibrated using the coil to test its efficiency. The obtained results were then compared to the meter's calibration sheet.

Keywords: Calibration, Uncertainty, Magnetic fields, Magnetic field measurement, Coils.

1. BASIC INFORMATION

LACTEC routinely executes measurements of low frequency magnetic fields in industrial environments and power system installations, requiring its instrumentation to be always calibrated and working properly.

LACTEC is thus forced to send its instrumentation to be calibrated overseas every 2 years, as such service is not offered in Brazil. This process takes approximately 3 months, due to transportation, bureaucratic paperwork and the calibration itself.

The main purpose of building a Helmholtz coil is to make it possible to do in-house calibration of magnetic field meters, eliminating the costs of sending these sensors to be calibrated abroad.

The Helmholtz coil is an appropriate tool to generate a uniform magnetic field (with known direction) in a region of space. This uniform field then can be used to calibrate magnetic field meters or to test the immunity of other equipment to LF magnetic fields.

The so called "Helmholtz coil" is in fact a system composed by two coils parallel to each other, as shown in Figure 1.

According to Helmholtz's theory [1], the magnetic field along the x-axis, at the system's geometrical center, will be uniform as long as the number of loops of each of the two coils is the same and the following relationships are true:

$$r = r1 = r2 \tag{1}$$

$$r = d = 2d_1 = 2d_2 \tag{2}$$

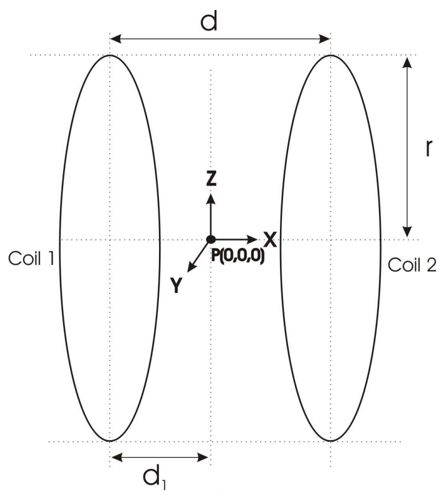

Figure 1 - Set of Helmholtz Coils

The magnetic field on the x-axis may be calculated through the equation:

$$B_x = \frac{\mu_0 . n . i}{2.r} \left\{ \left[1 + \left(\frac{1}{2} - \frac{x}{r} \right)^2 \right]^{-\frac{3}{2}} + \left[1 + \left(\frac{1}{2} + \frac{x}{r} \right)^2 \right]^{-\frac{3}{2}} \right\} \tag{3}$$

Where: **i** is the current through the coils;
n is the number of loops of each coil;
$\mathbf{\mu_0}$ is the air relative permitivity.

If the origin, where the magnetic field meter to be calibrated will be placed, is defined as x = 0, equation (3) will have the following form:

$$B_x = \frac{\mu_0 . n . i . (1{,}25)^{-\frac{3}{2}}}{r} = \frac{0{,}7155 . \mu_0 . n . i .}{r} \tag{4}$$

2. CONSTRUCTION OF THE HELMHOLTZ COIL

The Helmholtz coil built at LACTEC is composed of two coils of 230 loops each, made of copper wires (22 AWG) with maximum current capacity of 1 A, enough for the generation of magnetic fields with magnitude of up to 400 μT.

The loops are placed on a circular aluminum frame, built in a way as to reduce induced currents that may interfere on the calibration process of the magnetic field.

A uniform magnetic field can then be generated in a cylindrical area with 8 cm of radius and 15 cm of height, limiting the maximum size of the meter that may be calibrated.

Figure 1 shows the Helmholtz Coil Framework, built at LACTEC.

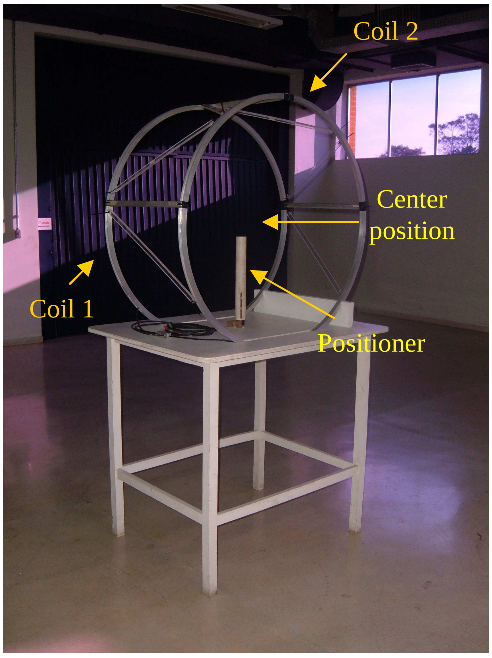

Figure 2 – Helmholtz Coil Framework

Besides the main coils of 230 loops each this Helmholtz coil has two auxiliary coils of 23 loops each. They can be used to compensate extra-system magnetic fields that may interfere on the calibration process. Currently, the calibration system is used in an area of low magnetic field dispensing the use of the compensation coils.

Figure 3 shows a graph, obtained through computational simulation, representing the surface of the axial magnetic field at position x = 0, at the yz plane. Only the central region is shown, where the magnetic field is uniform.

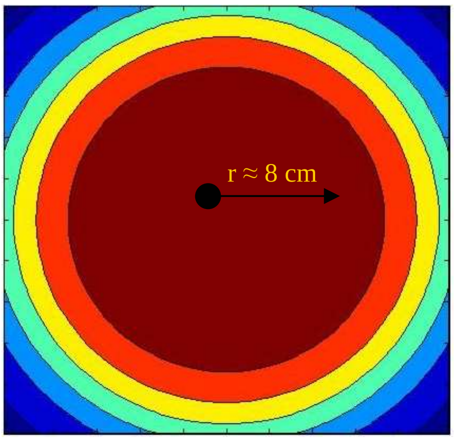

Figure 3 – Magnetic field in the center of the coil (yz axis)

To calibrate magnetic field meters, the main coils (made of 230 loops each) are connected in series to a traceable AC current standard.

The meter to be calibrated must be placed in the central region of the coil (see Figure 2). The measuring axis to be calibrated must be aligned with the Helmholtz coil x-axis.

Figure 4 shows a simplified diagram representing the calibration process.

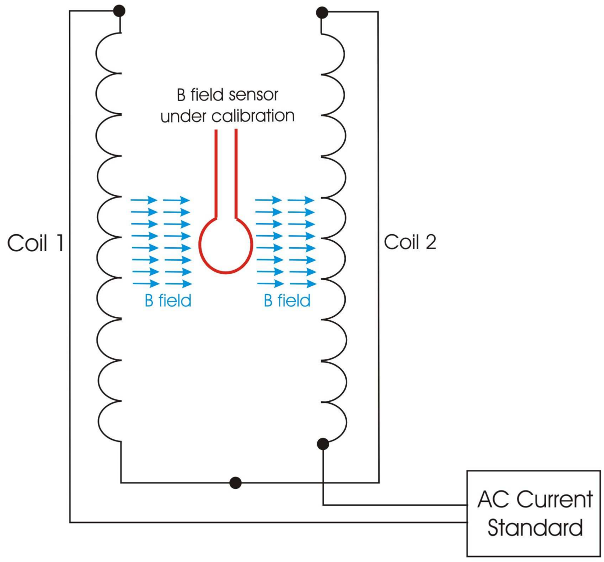

Figure 4 – Simplified diagram of the calibration process

During the calibration, the presence of ferromagnetic materials near the Helmholtz coil must be prevented, as they may distort the generated magnetic field.

3. UNCERTAINTY CALCULATION

The value of the magnetic field generated inside the Helmholtz coil is subject to the following uncertainty components:

a) Current: variations of the current applied to the coils influence the magnetic field generated inside it. The current value uncertainty depends directly on the AC current standard uncertainty;

b) Dimensional components: the physical dimensions of the coil components interfere on the field generation. There are uncertainties on the coils radius (**r**), the distance between them (**d**) and their alignment. The coils are made of several layers of copper, so there is also the uncertainty associated with the position of each coil to the object to be calibrated. A coordinate measuring machine (CMM) with 0,2 mm associated uncertainty was used to determine the physical dimensions of the coil, figure 5;

c) Loops: the number of loops in each coil may be an uncertainty factor in the calibration process, if this number is not exactly known. The number of loops of the LACTEC Helmholtz coil was accurately determined, making the uncertainty contribution zero.

Figure 5 – Coil dimensional measurement using the CMM arm.

In equation (4) the number 0,7155, with four significant digits, represents approximately an error of 0,006 % or 60 ppm, which is too low to be considered. The following equation allows the determination of error [2]:

$$\varepsilon = \frac{\Delta B_x}{B_x} = -0{,}2.\left(\frac{\Delta r}{r1} + \frac{\Delta r}{r2}\right) - 0{,}6.\frac{\Delta d}{d} + \frac{\Delta i}{i} + \frac{\Delta n}{n} \qquad (5)$$

The systematic error of the magnetic field may be calculated through (5), its value being +0,07 % solely due to constructive aspects.

The calculation of magnetic field value uncertainty is presented below:

$$\mu^2\left(\frac{\Delta B_x}{B_x}\right) = \left(\frac{\partial \frac{\Delta B_x}{B_x}}{\partial \frac{\Delta r_1}{r}}\right)^2 .\mu^2\left(\frac{\Delta r_1}{r}\right) + \left(\frac{\partial \frac{\Delta B_x}{B_x}}{\partial \frac{\Delta r_2}{r}}\right)^2 .\mu^2\left(\frac{\Delta r_2}{r}\right) +$$
$$+ \left(\frac{\partial \frac{\Delta B_x}{B_x}}{\partial \frac{\Delta d}{d}}\right)^2 .\mu^2\left(\frac{\Delta d}{d}\right) + \left(\frac{\partial \frac{\Delta B_x}{B_x}}{\partial \frac{\Delta i}{i}}\right)^2 .\mu^2\left(\frac{\Delta i}{i}\right) + \left(\frac{\partial \frac{\Delta B_x}{B_x}}{\partial \frac{\Delta n}{n}}\right)^2 .\mu^2\left(\frac{\Delta n}{n}\right) \qquad (6)$$

The solution of equations (5) and (6) shows it is possible to use the Helmholtz coil as a magnetic field source for the calibration of magnetic field meters.

As an example, the results obtained after the calibration of a magnetic field sensor owned by LACTEC, using three distinct configurations, are shown below. Only the axial component of the magnetic field was considered. Calibration of omnidirectional meters will be presented eventually in another paper.

Table 1, Table 2 and Table 3 show the results of the calibrations made using the Helmholtz coil built at LACTEC.

Table 1 – EFA-300 magnetic field meter (using internal meter) calibration results

Helmholtz coil generated field	Meter under calibration		Measured error	Calibrator uncertainty	Measurement uncertainty (k=2)	TUR
	Measurement	Error limit				
μT	μT	μT	μT	μT	μT	
98,46	98,37	3,93	-0,09	0,63	1,3	3,6
88,62	88,93	3,56	0,32	0,56	1,1	3,6
78,77	79,28	3,17	0,51	0,50	1,0	3,7
68,92	69,14	2,77	0,22	0,44	0,9	3,6
59,08	59,19	2,37	0,12	0,38	0,8	3,6
49,23	49,27	1,97	0,04	0,32	0,6	3,6
39,38	39,43	1,58	0,05	0,25	0,5	3,6
29,54	29,59	1,18	0,05	0,19	0,4	3,6
19,69	19,76	0,79	0,06	0,12	0,2	3,7
15,75	15,81	0,63	0,05	0,10	0,2	3,7
11,82	11,84	0,47	0,03	0,07	0,2	3,6
7,88	7,91	0,32	0,04	0,05	0,1	3,6
3,94	3,94	0,16	0,00	0,03	0,1	3,6

Table 2 - EFA-300 magnetic field meter (using 100 cm3 external meter) calibration results

Helmholtz coil generated field	Meter under calibration		Measured error	Calibrator uncertainty	Measurement uncertainty (k=2)	TUR
	Measurement	Error limit				
μT	μT	μT	μT	μT	μT	
98,46	97,44	3,90	-1,02	0,63	1,3	3,6
88,62	87,98	3,52	-0,64	0,56	1,1	3,6
78,77	78,12	3,12	-0,65	0,50	1,0	3,6
68,92	68,23	2,73	-0,69	0,44	0,9	3,6
59,08	58,53	2,34	-0,55	0,38	0,8	3,6
49,23	48,74	1,95	-0,49	0,32	0,6	3,6
39,38	39,04	1,56	-0,35	0,25	0,5	3,6
29,54	29,24	1,17	-0,30	0,19	0,4	3,6
19,69	19,51	0,78	-0,18	0,12	0,2	3,6
15,75	15,62	0,62	-0,14	0,10	0,2	3,6
11,82	11,71	0,47	-0,11	0,07	0,2	3,6
7,88	7,82	0,31	-0,05	0,05	0,1	3,6
3,94	3,89	0,16	-0,05	0,03	0,1	3,5

Table 3- EFA-300 magnetic field meter (using 3 cm external meter) calibration results

Helmholtz coil generated field	Meter under calibration		Measured error	Calibrator uncertainty	Measurement uncertainty (k=2)	TUR
	Measurement	Error limit				
µT	µT	µT	µT	µT	µT	
98,46	97,57	3,90	-0,89	0,63	1,3	3,6
88,62	88,19	3,53	-0,42	0,56	1,1	3,6
78,77	78,33	3,13	-0,44	0,50	1,0	3,6
68,92	68,57	2,74	-0,36	0,44	0,9	3,6
59,08	58,65	2,35	-0,42	0,38	0,8	3,6
49,23	48,43	1,94	-0,80	0,32	0,6	3,5
39,38	39,12	1,56	-0,26	0,25	0,5	3,6
29,54	29,30	1,17	-0,24	0,19	0,4	3,6
19,69	19,54	0,78	-0,16	0,12	0,2	3,6
15,75	15,62	0,62	-0,13	0,10	0,2	3,6
11,82	11,71	0,47	-0,11	0,07	0,2	3,6
7,88	7,82	0,31	-0,06	0,05	0,1	3,6

Observing the obtained results, some conclusions may be taken:

- The measurement errors are in the nominal specifications of the calibrated magnetic field meters;
- The uncertainty of LACTEC's calibration process is compatible with the European laboratory process.
- In all the cases, the TUR indicates it is possible to use the Helmholtz coil as a magnetic field standard for the calibration of magnetic field meters.

4. CONCLUSION

The Helmholtz coil built at LACTEC is perfectly capable of being used in the calibration of the magnetic meters used by the Institute, as long as the maximum allowed meter size is observed.

The uncertainties associated with the calibration process are compatible with state-of-the-art magnetic field measurement.

The use of this coil may even benefit other Brazilian institutes that need their equipment to be properly calibrated.

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