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A method for calculating the magnetic field produced by a coil of any shape

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Abstract

This work deals with the design of coils to obtain a desired magnetic field in the axial direction. A computer program has been developed to implement the obtained equations and assist the design. Practical results are given to illustrate the accuracy of theoretical predictions with measured magnetic field curves. © 2001 Published by Elsevier Science B.V.

Keywords: Any shape coil; Magnetic field; Theoretical calculation

1. Introduction

One of the main problems we find when performing magnetic measurements is the low efficiency of field producing systems [1,2], for example, to obtain homogeneous magnetic fields in reduced spaces big coils are required [3–5]. Big coils count, among its problems, the need of high voltages to drive appreciable currents, and its high cost and weight due to the huge quantity of copper wire needed to manufacture them.

In this paper, we will describe our work to avoid some of these problems. Earlier, we have studied the possibility of obtaining the field produced by a current line of finite length. From this result we can obtain the magnetic field produced by a spire of polygonal section in a point as the sum of that produced by each one of their sides in this point. The field produced by a coil in a point is obtained as the sum of the field produced by each spire in that point.

In the particular case of circular coils, an approach has been made that consists of considering each circular spire as a polygon of enough number of sides. The error estimated this way is based on the difference between the magnetic field obtained for a spire in several points at the axis and its exact value (from the known analytic expression of the magnetic field produced by a circular spire in any point of its axis). If this error is higher than a defined limit, then it is necessary to increase the number of sides of the polygon.

2. Theoretical results

To obtain the magnetic field produced by an electrical current, it is necessary to use the Biot and Savart‘s law [2]:

$$H=\frac{I}{4\pi}\oint\frac{\mathrm{d}l\wedge(r_2-r_1)}{|r_2-r_1|^3} \tag{1}$$

By integrating this expression for a current line of finite length, such as the one shown in Fig. 1 the following theoretical expression results:

$$H_X=0 \tag{2a}$$

$$\begin{aligned}H_Y&=-\frac{zI}{4\pi}\int_{-b}^{b}\frac{\mathrm{d}x_0}{[\sqrt{(x-x_0)^2+(y-a)^2+z^2}]^3}\\&=-\frac{zI}{4\pi[(a-y)^2+z^2]}\left[\frac{b-x}{\sqrt{(b-x)^2+(a-y)^2+z^2}}\right.\\&\qquad\left.+\frac{b+x}{\sqrt{(b+x)^2+(a-y)^2+z^2}}\right]\end{aligned} \tag{2b}$$

$$\begin{aligned}H_Z&=\frac{(y-a)I}{4\pi}\int_{-b}^{b}\frac{\mathrm{d}x}{\left[\sqrt{(x-x_0)^2+(y-a)^2+z^2}\right]^3}\\&=-\frac{(a-y)I}{4\pi[(a-y)^2+z^2]}\end{aligned}$$

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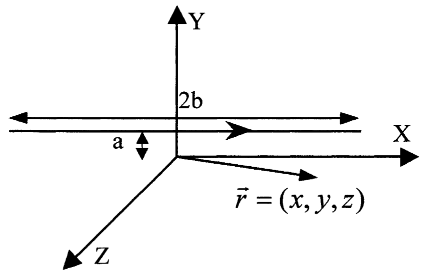

Fig. 1. Spatial arrangement of the current line of finite length for theoretical calculations.

$$\times \left[\frac{b-x}{\sqrt{(b-x)^2+(a-y)^2+z^2}} + \frac{b+x}{\sqrt{(b+x)^2+(a-y)^2+z^2}} \right] \quad (2c)$$

where x, y, and z are the Cartesian coordinates of the point were the magnetic field is calculated. Any disposition of the line in space can be reduced to the solution given by rotating and/or translating the reference system.

Once this problem is solved, the process to obtain the magnetic field produced for a closed current path of any polygonal shape reduces to adding the different magnetic fields produced for each of the straight paths. Further, a coil of polygonal section produces a magnetic field given by the addition of its windings. For circular or curved section coils, we may approximate them by a polygon of a high enough number of sides.

3. Experimental results

To evaluate quantitatively the presented calculation method and the implemented computer program, we set up a configuration of spires as a solenoid coil of certain longitude to obtain a uniform field (dispersion <1%) in an area as wide as possible. The theoretical predictions for the best coil topology configuration show that it is necessary

- to have a variable number of spires by unit of longitude along the coil. This number of spires is bigger at the ends of the coil.

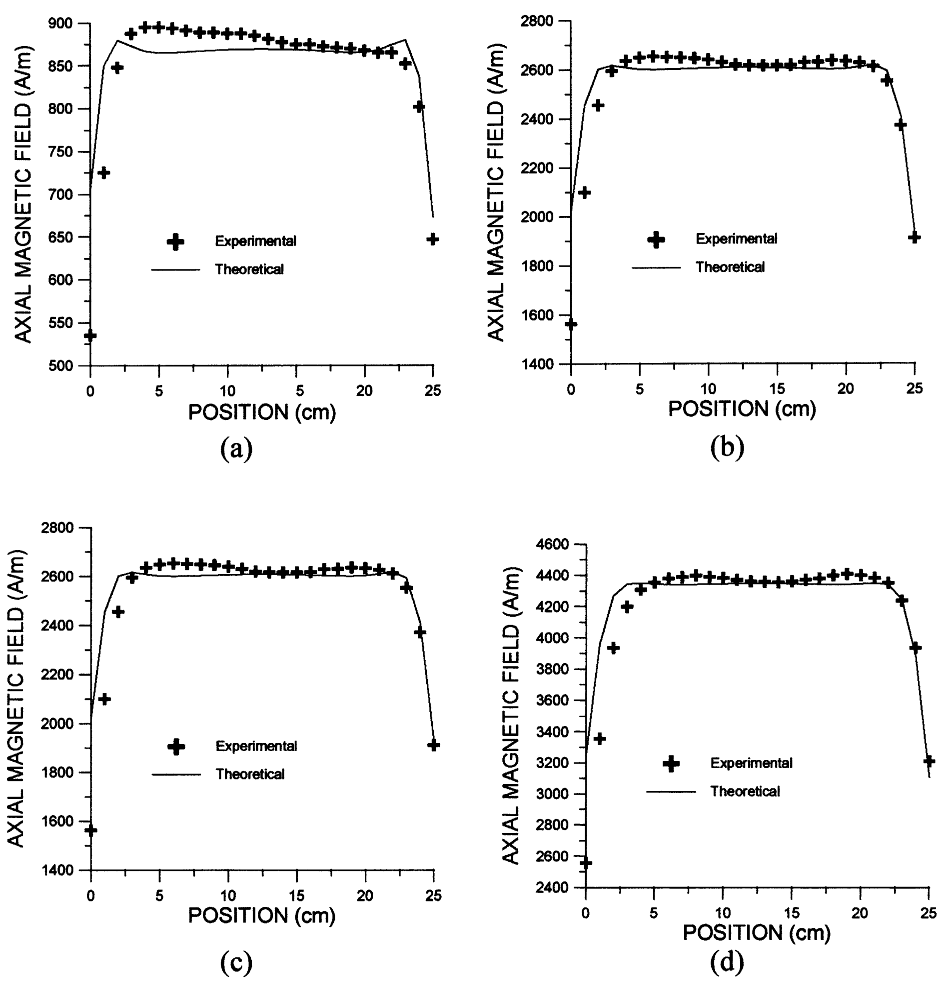

Fig. 2. Theoretical predictions and experimental calibration for four coils of the same length depending on the number of layers of spires: (a) one layer; (b) two layers; (c) three layers; (d) four layers.

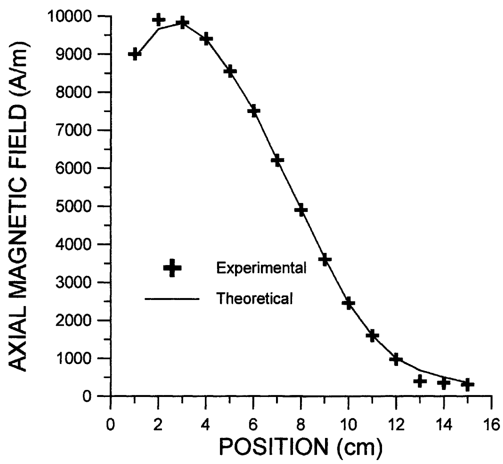

Fig. 3. Theoretical predictions and experimental calibration for the coil that produces a linearly variable magnetic field along the axis which depends on the distance to the border.

- that the total coil length must be slightly larger that the region where the uniform field is wanted.

By using these predictions, we have built four solenoidal coils. In Fig. 2 the theoretical results can be compared with the curves of magnetic field calibration in different coils.

We have even designed and built a coil that produces a linearly variable magnetic field along the axis which depends on the distance to the border. The result was a step-like distribution of spires. In Fig. 3 shows the theoretical results and the calibration curve for this coil.

4. Conclusions

A computer program has been developed that allows us to obtain the magnetic field created by a polygonal section (regular or irregular) or circular coil, or to obtain the proper distribution of spires for the coil in function of the wanted magnetic field distribution.

The design of coils using this method can allow a reduction in the number of spires, size, and self-induction of the coils. This optimization in the design of coils can make a reduction of cost in the systems of continuous magnetic field production and even more for the systems of alternating magnetic fields production due to the additional benefit of the reduction in the self-induction of coils.

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