Magnetic Field Measurement of a Planar Coil Using Magnetic Resonance Imaging Methods

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Abstract. *A new method for mapping and imaging of the magnetic field of planar electromagnetic coil, placed into the homogenous magnetic field of an NMR imager, is proposed. First attempts of electromagnetic planar coil computation and testing on an NMR 0,2 T imager were accomplished. In our experiments a homogeneous phantom (reference medium) was used - a container filled with water - as a medium. The resultant image represents the magnetic field distribution in the homogeneous phantom. A standard gradient echo imaging method, susceptible to magnetic field homogeneity, was used for detection. An image acquired by this method is actually a projection of the sample properties onto the homogeneous phantom. The goal of the paper is to map and image the magnetic field deformation using NMR imaging methods.*

Keywords: magnetic field, magnetic resonance imaging, electrical phantom, meander coil

1. Introduction

Nuclear Magnetic Resonance (NMR) measurement and imaging of proton density of biological and physical structures is a routine investigating procedure. Another case is when an object that generates a weak magnetic field is inserted into a stationary homogeneous magnetic field resulting in deformation of the basic stationary magnetic field. If the space in the vicinity of this object is filled with a water containing substance, we are able to image this object. The acquired image represents a modulation of the basic magnetic field by the weak field of the coil.

First attempt of a direct measurement of the magnetic field created in living tissue by a simple wire fed by a current was reported in [1]. A method utilizing the divergence in gradient strength that occurs in the vicinity of a thin current-carrying copper wire was introduced in [2]. Using pulsed gradient spin-echo NMR sequence, in vitro micro images of a sample, a solution of polyethylene oxide in water, were presented. A simple experiment with thin, pulsed electrical current– carrying wire and imaging of a magnetic field using a plastic sphere filled with agarose gel as phantom, was published in [3]. First attempt of the indirect susceptibility mapping of thin-layer samples using phantoms was described in [4].

In this paper we propose an electromagnetic planar coil supplied by small and stabilised DC current. Computation of the magnetic field of the planar coil serves for comparison of theoretical results with experimental.

2. Subject and Methods

We suppose that the conductor position is on the x-axis in the rectangular complex coordinate system (**i**x, **j**y, **k**z) and the diameter of the conductor is neglected.
According to Fig. 1, we suppose one conductor limited by two points (P, Q), lengths of 2L, with the left - right symmetry. Conductor is fed by currents +I. The basic magnetic field B_0 of the NMR imager is parallel with the z-axis. The task is to calculate the $B_z(x,y,z)$ component of the magnetic field near the conductor.

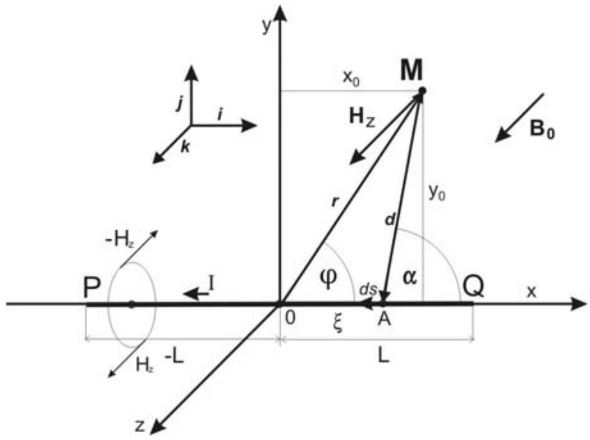

Fig. 1. Basic configuration of the limited length conductor $\overline{PQ}$ placed into the x – axis.

The formula for magnetic field in the point $M(x_0,y_0)$ is supposing that $z_0 = 0$. For computation of the magnetic field $B_z = \mu_0 H_z$ the Biot-Savart law in vector form was used [5].

$$\mathbf{H} = \frac{I}{4\pi}\oint \frac{d\mathbf{s}\times\mathbf{d}}{d^3} \tag{1}$$

From the physical interpretation the magnetic field is line-symmetry in compliance with x -axis, and symmetric according to the yz – plane. The calculation is limited to the first quadrant of the xy – plane. Following the Fig. 1 and formula (1) we can write:

$$d\mathbf{s}\times\mathbf{d} = ds\, d\, \sin(\alpha) = d\xi\, d\, \sin(\alpha) \tag{2}$$

Using formula (1) we get the basic expression as follows

$$\mathbf{H} = \mathbf{k}\frac{I}{4\pi}\int_{-L}^{L}\frac{\sin\alpha}{d^2}\,d\xi \tag{3}$$

Considering Fig.1 : $\sin\alpha = \frac{r}{d}\sin\varphi$, $d^2 = r^2 + \xi^2 - 2r\xi\cos\varphi$, $r\sin\varphi = y$, $r\cos\varphi = x$

In the complex coordinate system (**i**x, **j**y, **k**z) we get the final formula for magnetic field **H** in the integral form

$$\mathbf{H} = \mathbf{k}\frac{Iy}{4\pi}\int_{-L}^{L}\frac{d\xi}{\sqrt{\left(x^2+y^2+\xi^2-2\xi x\right)^3}} \tag{4}$$

After integration of (4) we get the final general formula for magnetic field calculation

$$H_z = \frac{I}{4\pi y}\left[\frac{L-x}{\sqrt{\left(x^2+y^2+L^2-2Lx\right)^3}} + \frac{L+x}{\sqrt{\left(x^2+y^2+L^2+2Lx\right)^3}}\right] \tag{5}$$

As a mathematical and physical model a flat meander rectangular coil was designed and magnetic field using formula (5) for every wire was calculated. The resultant plots of magnetic field relative values are depicted in Fig. 2.

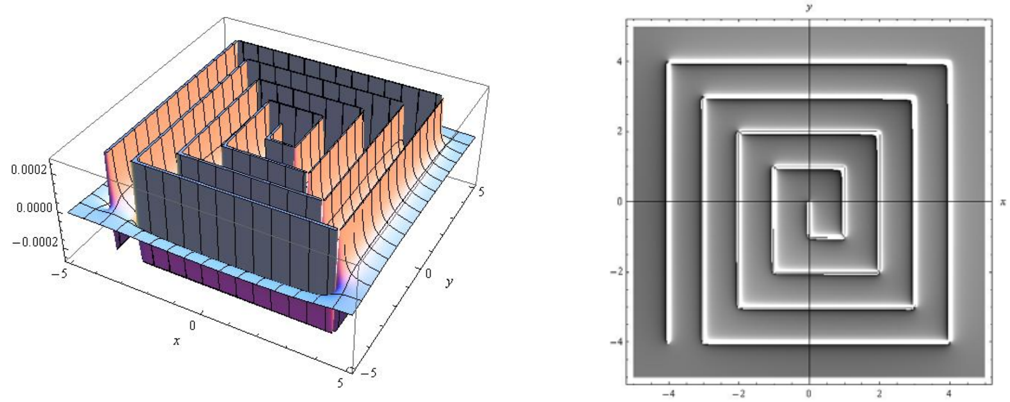

Fig. 2. Calculated magnetic field H_z (x,y) of the planar meander rectangular coil, limited plot-range.
Left: 3D-plot of relative values. Right: Density-plot of relative values.

3. Experimental Results

As a physical model, a planar meander rectangular coil was realized on a thin plate. The coil was placed between two rectangular holders – homogeneous phantom filled with 0,1 wt% solution of $CuSO_4$ in distilled water, see Fig.3.

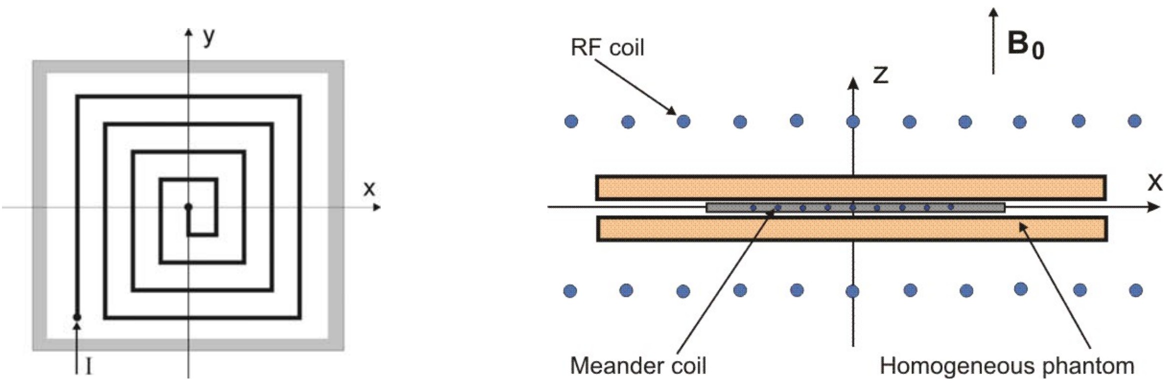

Fig. 3. Left: Meander planar coil design, dimensions 60 x 60 mm, realized on a printed board.
Right: RF coil, active measuring volume (homogeneous phantom) and meander planar coil.

An NMR imager (ESAOTE Opera), permanent magnet 0,2 T with vertical orientation of the basic magnetic field B_0 was used. Feeding current I = 30 mA was applied to the meander coil creating a planar source of a weak magnetic field in the shape of a meander. The "gradient-echo" NMR sequence (Fig. 4) was selected for the measurement [6]. A special feature of the sequence is its sensitivity to basic magnetic field inhomogeneities.

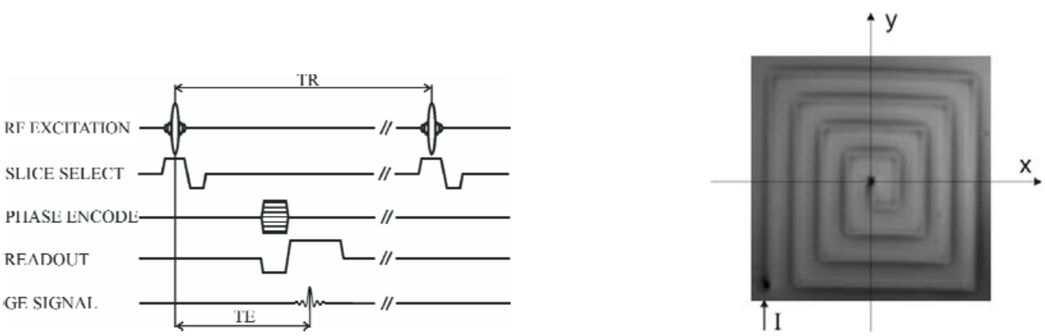

Fig. 4. Left: Time diagram of the NMR sequence for the gradient-echo signal detection. TE - echo time of 18 ms, TR – repetition time of 300 ms. Right: NMR image of the magnetic field distribution of a meander planar coil (60 x 60 mm), number of measured voxels 150 x 150.

4. Results and discussion

The single meander coil served for verification of this methodology, for the adjustment of basic parameters of the imaging sequence: time intervals TE and TR, number of averages, and for testing of a reference environment – $CuSO_4$ doped water in connection with relaxation times of the measuring sequence. It is evident that imaging of the magnetic field of the electromagnetic coil can be performed only if the vector of the static magnetic field $B_0 = B_z$ is perpendicular to the phantom plain. Other orientations caused significant blurring of the image edges in the x- and y-axis directions due to strong basic magnetic field B_0.

5. Conclusions

A new method for mapping and imaging of the magnetic field of planar electromagnetic coil placed into the homogenous magnetic field of an NMR imager is proposed. The method is based on a projection of magnetic field of the electromagnetic coil into a homogeneous planar phantom and subsequent NMR imaging using a gradient-echo sequence. The method was tested using a single planar coil – meander fed by electric currents and generating weak magnetic field.

Electromagnetic coil can serve as a special phantom and additional tool for measurement and imaging quality testing using NMR imaging methods. The advantages of such an electromagnetic phantoms are: universality, stability, repeatability, simple modification of basic parameters and precision. They are suitable for S/N ratio testing and very useful for imaging pulse sequences adjusting and examination. The first results showed the feasibility of the method and some of possibilities offered in this field of research.

Acknowledgements

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