Design and Optimization of a Planar Gradient Coil System for a Mobile Magnetic Resonance Device

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Abstract

This paper presents the computation and optimization of a surface gradient coil system for usage in a mobile MR tomography. Here the principle planar gradient coil design required by a MR Mobile Universal Surface Explorer (called MOUSE) is demonstrated. The analytical calculation of the z-components of the x-/z-gradient field is introduced. A numerical optimization process based on stochastic genetic algorithms is applied to the field problem in order to fulfill and optimize the system's requirements concerning gradient field strength and linearity. The computed solutions are compared to measurements of an experimental prototype.

Introduction

The design of the unilateral Mobile Universal Surface Explorer (MOUSE) requires a planar arrangement of a suitable surface gradient coil system. The measuring device of this MR system resides below the NMR specimen, the specimen is placed onto the MOUSE [1]. The C-core design of the main NdFeB magnet which produces the B_0-field distribution causes a naturally occuring static y-gradient along the penetration depth of the B_0-field. Therefore planar coil arrangements must be found only for the generation of the G_x and G_z gradients.

Theory of planar gradient coil systems

The principle design of a planar z-gradient coil system is a twofold array of symmetric current loops which face each other. Several long wire pairs with different coil winding numbers form current loops and produce a z-directed field. Each current wire *i* is located at an optimal position b_i/d_i on the surface. The z-gradient can be calculated analytically by application of Ampere's law which yields to the following equation:

$$B_z^{(i)}(y,z)=\frac{\mu_0 n_i I}{2\pi}\left\{\frac{y+b_i}{(y+b_i)^2+(z-d_i)^2}-\frac{y+b_i}{(y+b_i)^2+(z+d_i)^2}\right\}$$

The x-gradient system is arranged in a planar and symmetric fourfold array of current loops. The field distribution of the x-gradient is more complicated and requires the solution of Biot-Savart's law in order to receive the $B_z(x,y,z)$-component of a closed rectangular loop:

$$\vec{B}(\vec{r})=\frac{\mu_0 I}{4\pi}\int_C \frac{d\vec{r}'\times\vec{R}}{|\vec{R}|^3},\ \vec{R}=\vec{r}-\vec{r}'$$

$$B_z^{(i)}(x,y,z)=\frac{\mu_0 I\cdot y}{2\pi}\left[\underbrace{\frac{x-x_0}{\left[y^2+(z-z_i)^2\right]\cdot\sqrt{(x-x_0)^2+y^2+(z-z_i)^2}}}_{I.}\right.$$

$$\left.\underbrace{-\frac{x-x_1}{\left[y^2+(z-z_i)^2\right]\cdot\sqrt{(x-x_1)^2+y^2+(z-z_i)^2}}}_{IV.}\right]$$

These are the z-components of the gradient field in the 1st and 4th coil quadrant. Substitution of z_i by $-z_i$ delivers B_z-components in 2nd and 3rd coil quadrant. The introduced formulas for x- and z-gradients are valid only for one current loop. The linearity of both equations submits the calculation of the total flux density in the following way:

$$B_{x/z}^{Ges}(\vec{r})=\sum_{i=1}^{N_{x/z}} B_{x,z}^{(i)}(\vec{r})$$

The gradient field strengths can be obtained from the equations:

$$G_x^{Ges}(\vec{r})=\frac{\partial B_z^{Ges}(\vec{r})}{\partial x},\quad G_z^{Ges}(y,z)=\frac{\partial B_z^{Ges}(y,z)}{\partial z}$$

Optimization strategy

A suitable object-oriented numerical optimization process has been developed in order to handle the amount of accumulating optimization data [2],[3]. A genetic strategy based on the Elitest model is used to find the number of coil windings n_i, their location z_i as well as their length $|x_0-x_1|$ and the impressed current I within the predefined Field of View (FOV) by minimization of the object function:

$$\varepsilon=\iiint_{FOV}\left|G_x^{Ges}(\vec{r})-G_x^{desired}(\vec{r})\right|\cdot W(\vec{r})dV$$

Optimization results

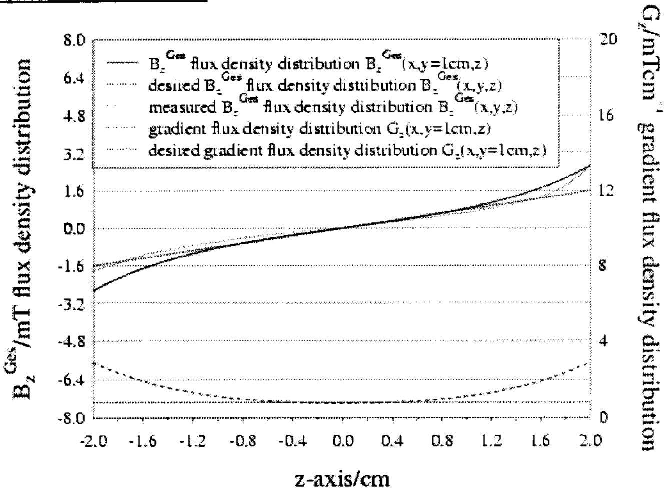

Figure 1. Comparison of flux density distribution of the analytically optimized solution and measurements of the built prototype for a penetration depth of y=1cm.

Fig. 1 shows the flux density distribution of the G_z-coil system after 2000 iteration steps. The desired field gradient has been predetermined as G_z=0.1mT/cm. After 2000 parameter variations the resulting flux density nearly fits the desired one. Finally the optimizer calculated N=2 coil pairs, their locations as well as the number of coil windings n_i for a current of about I=20A. Reference measurements of a built prototype verify the optimization results.

Conclusions

In this paper a planar gradient coil system and the system's basic descriptive analytical formulas have been introduced. The knowledge of the analytical gradient field distribution motivates the efficient application of a stochastic optimization tool. The correspondence of theory and measurements confirms this approach for the design of a planar gradient coil system.

References

1. H. Popella, *Compel*, 20(1), pp. 269-278, 2001
2. H. Popella, *Object-Oriented Genetic Algorithms for Two-Dimensional Design Optimization of the Magnetic Circuit of a Mobile Magnetic Resonance Device*, ISEM, Tokyo, 2001.