Design Methodology for Arbitrary Shaped Gradient Coils for MRI

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Introduction

In magnetic resonance imaging (MRI), spatial encoding is generated by employing a set of gradient coils which produce a magnetic field where the z-component varies linearly along the x, y, and z directions, respectively. The efficiency of a gradient coil can be quantified by a particular parameter or combination of a number of parameters for a particular coil. These parameters include gradient strength per unit current, inductance, resistance, the homogeneity of the gradient field region, or the extent of shielding. Mostly, all the gradient coil designs assume either cylindrical geometry or a pair of coils of planar geometry [1]. In terms of solution techniques, other than direct analytical solution, the design problem is reduced to solving a system of linear equations with final optimization being performed by the use of procedures such as simulated annealing (SA) [2].

In this presentation, a new gradient coil design method is described. The central idea is to use the minimum number of parameters to define uniquely a complicated three dimensional gradient coil pattern. The desired coil pattern is achieved by geometric mapping techniques as follows. Firstly, a two dimensional wire pattern is defined uniquely by chosen contour lines of a two dimensional function. Secondly, an arbitrary shaped three dimensional coil can then be obtained directly by using a geometric mapping function that transforms the two dimensional wire patterns to the desired three dimensional wire patterns. The shape of the resultant three dimensional coils is dependent on the mapping function. The field and gradient distribution are directly calculated by using the Biot-Savart law based on the mapped discrete three dimensional wire patterns. The inductance is calculated in a similar manner. A hybrid optimization procedure which includes a non-linear least-square (NLLS) method [3] and SA are employed to achieve the optimum of the specified coil's parameter set.

Theory

The basic philosophy for the design of a gradient coil is that any possible gradient coil geometry can be realized by purely numerical calculation of the fields generated by a set of wires, together with an algorithm for the placement of wires, to achieve the desired property of the gradient field. The method developed herein is best illustrated using the following example.

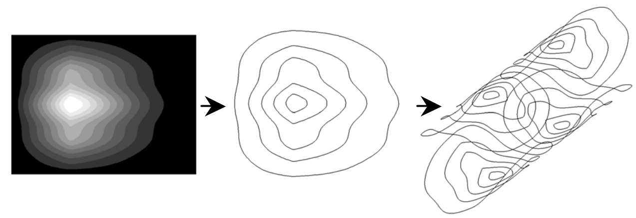
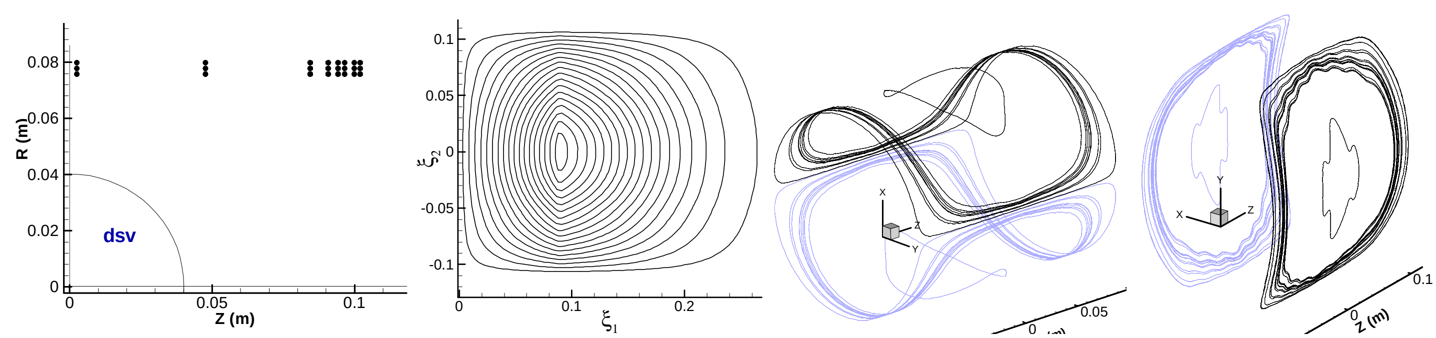


Figure 1. Graphical representation of the design methodology.

Define, as per Figure 1, a two dimensional function in the domain $\mathbb{R}^2 : [a_1, a_2] \times [b_1, b_2]$ as $\Psi(\xi_1, \xi_2) = \sum_{i=0}^{n} \alpha_i \beta_i (\xi_1, \xi_2)$,where $a_1 \le \xi_1 \le a_2$ and $b_1 \le \xi_2 \le b_2$. Here, $\boldsymbol{\alpha}$ are the coefficients and $\boldsymbol{\beta}$ is the basis function that forms the desired functional distribution in the domain If a number m of wire loops are chosen, a set of two dimensional wires pattern $\mathbf{W}^{(2D)}_{(\xi_1,\xi_2)}$ can be found based on the contours lines $\mathbf{W}^{(2D)}_{(\xi_1,\xi_2)} = \left\{ W_j^{(2D)} = \left\{ (\xi_1, \xi_2)_k, k = 1, 2, \ldots, q_j \mid \Psi(\xi_1, \xi_2)_k = J_j \right\}, j = 1, 2, \ldots m \right\}$. k represents the number of discrete points on the wire loop. This two dimensional wires pattern $\mathbf{W}^{(2D)}_{(\xi_1,\xi_2)}$ is mapped to a three dimensional coil pattern by a geometric transformation function Ω employing the following relationship $\mathbf{W}^{(3D)}_{(x',y',z')} = \left\{ W_j^{(3D)} = \left\{ (x', y', z')_k = \Omega\left[\boldsymbol{\gamma\lambda}\left((\xi_1, \xi_2)_k \in W_j^{(2D)} \right) \right], k = 1, 2, \ldots, q_j \right\}, j = 1, 2, \ldots, m \right\}$. Where $\boldsymbol{\lambda}$ are the basis function of the geometric shape and $\boldsymbol{\gamma} = \{\gamma_1, \gamma_2, \ldots, \gamma_s\}$ is the set of coefficient parameters of the shape function Ω to form the desired three dimensional geometry, for example, a cylinder, a hyper-surface, etc. The parameter set $\mathbf{p} = \{p_1, p_2, \ldots, p_{l=n+m+s}\} = \{\alpha_1, \alpha_2, \ldots, \alpha_n\} \cup \{\delta_1, \delta_2, \ldots, \delta_m\} \cup \{\gamma_1, \gamma_2, \ldots, \gamma_s\}$ gives complete control of the arbitrary shape of the three dimensional gradient coil patterns $\mathbf{W}^{(3D)}_{(x',y',z')}$. The optimization process designed is to find the best set $\mathbf{p}$ such that the coil's performance satisfies the desired specified requirement (or requirements). To achieve the goal of an optimum targeted performance for a gradient coil, the NLLS method and the SA are used together to give the most advantageous way to search for the optimum design.

Results

Based on the design methodology described in the previous section, the numerical optimization has been implemented in C-code and all the results of the computations discussed throughout this section were performed on a Pentium 4, 2GHz DELL laptop computer. To illustrate the flexibility of the method, the algorithm was used to design some unconventional coils pattern as well as conventional gradient coil set. The results are demonstrated in figure 2. These results were chosen to highlight the advantages of this new approach, which have demonstrated that this approach has the ability to design a number of gradient coils having different geometric architectures including a conventional gradient coil set, multilayer gradient coils, a novel openable cylindrical Z gradient coil, and a curved biplanar Z gradient coil. These applications illustrate the flexibility of the method.



Multilayer Z gradient | Transverse gradient | Openable Z gradient | Curved Z open gradient

Figure 2.

Reference

1. Turner R. (1993). Magn. Reson. Imag. 11:903–920
2. Crozier S, Doddrell DM. (1993). J. Magn. Reson. A103:354-357
3. Zhao H, Crozier S, Doddrell DM. (2000). Med. Phys. 27:599