Parametrical Optimization of a PatLoc Gradient Coil

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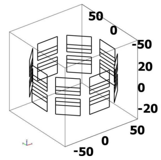
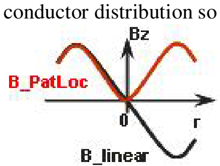
Introduction

In the most MRI gradient coil designs, the gradient strength linearity and switching rate are optimized. Nonetheless, in the practical settings of human imaging the speed of MRI pulse sequences is often limited by the peripheral nerve stimulation rather than by technological constraints. Commonly used gradient coils generate unidirectional gradients over the *region of interest* (ROI) along the spatial coordinates x, y and z. The concept of PatLoc gradients (parallel acquisition technique using localized gradients) overcomes the constraint of neuronal stimulation by using multiple local field profiles (Fig.1) [1], which can be optimized both to the underlying anatomy and minimal stimulation. The goal of this study is to optimize the curvilinear magnetic field distribution of the cylindrical multipolar PatLoc gradient coil. The most gradient coil design approaches are based on the target field method [2]. Because the linearly changing field can be expressed by the first-order polynomials, this method is especially suitable for the design of unidirectional gradient coils. When designing a PatLoc gradient coil, the magnetic field should ideally be changed linearly along the radial direction with a possibly sharp turnover at the centre, which cannot be expressed using few polynomial terms. Thus, the standard target field method, where the harmonic series expansion is used to express the spatial distribution of the magnetic field is not efficient anymore. In this paper, we present a simple iterative optimization method in order to design a PatLoc gradient coil of a predefined basic layout. A residual function between the ideal field and the physical field distribution over the ROI is minimized by the least square optimization method. The optimization procedure includes calculation of the magnetic field using the Biot-Savart method, the determination of the optimal number of conductors, and the corresponding positions. In order to use the continuous optimization method to optimize the layout of discrete conductors, the continuation method is used to transform the integral design variable to bounded continuous design variable. The optimal solution still maintains the discrete conductor distribution so that the optimized gradient coil can be fabricated directly without any further post-processing.





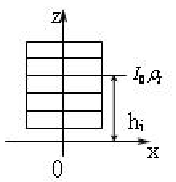


Figure 1. PatLoc coil, ideal PatLoc magnetic field distribution, and design variables of GSC.

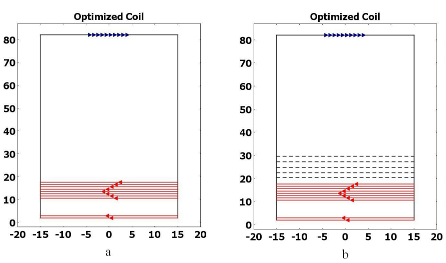


Figure 2. Optimized unidirectional PatLoc unit coil. The dash lines are the deleted conductors after optimization. a) and b) the optimal solution with initial 10 and 15 GSC.

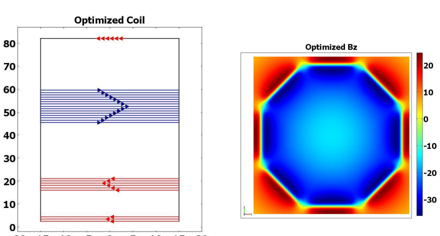


Figure 3. Optimized two-direction PatLoc unit coil and magnetic field Bz (mT). The blue and and red lines are the optimized conductors.

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Optimization method

The optimization of the PatLoc coil is inherently a discrete problem which only the conductors parallel to the x-y plane contribute to the magnetic field B_z. In a general setting the coil optimization consists of a determination whether there is a conductor or not for all the possible positions. In order to use the continuous optimization method instead of integer programming, a relaxation of the design variables leads to a description of a conductor by using continuously varying variables. The approach outlined above is known as the *ground structure approach* [3] in the design of truss type mechanical structures. This means that for an initially chosen large enough number of conductors and corresponding positions, the optimal structure is found as a subset of all the elements of the initially chosen set of coils. The optimization model used has nonlinear least square format:

$$Obj1 = \int_{ROI} \left[\sum_{i=1}^{k} B_z(I_0, \rho_i, h_i) - (G_x X + b)\right]^2 d\Omega \quad (1)$$

where B_z is the space magnetic distribution, I_0 is the current density pass through the *ground structure conductors* (GSC), ρ_i and h_i are the continuous design variables and the space design variables for GSC, G_x and b are the slope and intercept of target linear gradient field, i=1,…,k is the number of GSC. In this paper, we assume that the current density of the ground structure conductor has fixed value. In order to recover the discrete property of conductors, the second objective is chosen as:

$$Obj2 = \begin{cases} \sum_{j=1}^{k} \left[\rho_j(1-\rho_j)\right]^2 & \text{unidirectional current} \\ \sum_{j=1}^{k} \left[\rho_j(1-\rho_j)(1+\rho_j)\right]^2 & \text{bi-directional currents} \end{cases} \quad (2)$$

so that intermediate value of the ρ_j is penalized when the Obj2 is minimized. During the optimization, the position of the conductor on the top (82mm) is fixed. Here the "unidirectional current" means that the electrical current passes through the ground structure conductor has same direction (In Fig.2, the currents flow from right to left); the "bi-directional currents" means that the electrical current is allowed to passes through the ground structure conductor in both directions (In Fig.3, the currents flow from left to right are marked as blue line and from right to left as red line, respectively). The shape of all the conductors is limited to a straight line. For a conductor located at z=0 plane and parallel to the y axis, the analytical solution can be obtained easily using the Biot-Savart method. Translation and rotation operators can be used then to obtain the distribution of B_z induced by the whole PatLoc coil. Because there are bounded and linear constraints among ground structure conductors, the optimization software SNOPT [4] was used to implement the constrained nonlinear least square optimization. Sensitivities to design parameter variations can be calculated analytically, allowing for an efficient optimization implementation.

Numerical results

Numerical examples demonstrate that the most of the continuous design variables ρ_i will converge to the ideal discrete values. For all the numerical examples presented in this paper, the current of 16A and the gradient G_x is 40mT/M were used. The distance of the coils away from centre is 45 mm and the ROI along the z axis is 4 mm. For the unidirectional current case, the optimal distribution of ground structure conductors is shown in Fig.2. One of the advantages of the ground structure approach is that one can choose relatively large number of GSC as initial guess and the optimal solution which does not depend on the choice of the initial guess is obtained automatically. The optimal solution for the bi-directional case is shown in Fig.3. The value of the Obj1 is merely half when compared with the unidirectional current case. The gain in field profile fidelity stems from the more flexible choice of the direction of electric current and the optimal distribution of ground structure conductors in both directions.

References

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