Discrete Design Method of a Transverse Gradient Coil for Magnetic Resonance Imaging

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Introduction

In this work we describe a discrete gradient coil design method that does not include some of the essential steps of continuous current based minimum energy design methods. The key concept is that all characteristics of a transverse gradient, such as coil inductance, spatial distribution of the magnetic field, coil resistance, and slew rate of the coil, are expressed through the set of z-intercepts where the coil current pattern intersects the cardinal axes, for example Z_i along $\phi=0$ and $\phi=\pi$ for an X-gradient. We illustrate the advantages of the discrete design method with the example of a whole body gradient.

Method

Conventional methods of shielded gradient coil design [1,2] include two important steps: 1) find the continuous current distributions on the primary and shield coils that provides the required field quality characteristics such as gradient strength at the isocenter of the coil, gradient field linearity and uniformity within the Field-of-View (FoV), minimum coil inductance, and good shielding. In the case of finite length coils the current density is represented by a finite length series expansion; 2) discretize the continuous current distribution with an integer number of turns to match the power amplifier current-voltage characteristics. Constraints can be built into the analytical formalism [2] to achieve these goals. Depending on the size of the FoV, the size of the coil, and the field quality characteristics it often happens that the coil turns on the primary coil are most concentrated along the lines $\phi=0$ and $\phi=\pi$. The spacing between the turns centroids along these lines determines the allowed conductor widths and positions. Regions with smallest spacing have the highest power density. Power density or turns density is an important factor for short coils with relatively large FoV. We propose a method of shielded transverse gradient design that provides direct control of turns density. Suppose one wants to design a gradient coil that has $N_{P,S}$ number of turns in each of four quadrants on the primary/shield coil. Our method starts with a "pre-discretized" primary coil that carries current $\mathbf{I}$ and is determined by the set of z-intercepts, $\left\{Z_n^{(in)}, Z_n^{(f)}\right\},\ 1 \le n \le N_P$ of the coil turns along $\phi=0$ as shown in Fig.1. The shield coil can be introduced by using the shielding conditions [1,2] or by using a corresponding set of z-intercepts. We show, using the results of [3], that the intercept positions completely determine the current paths $\varphi = \Phi_n(z)$ due to the predefined azimuthal sin(ϕ) topology of the z-component of the current flow. These are expressed in terms of the Error-function

$$\Phi_n(z) = \arccos\left\{\frac{n-1/2}{N_{P/S}} Q(z_{eye})/Q(z)\right\}, \quad Q(z) = \sum_{n=1}^{N_{P/S}}\left\{erf(\frac{z-Z_n^{(in)}}{2\sqrt{\beta}}) + erf(\frac{z+Z_n^{(in)}}{2\sqrt{\beta}}) - erf(\frac{z-Z_n^{(f)}}{2\sqrt{\beta}}) - erf(\frac{z+Z_n^{(f)}}{2\sqrt{\beta}})\right\} \quad (1)$$

In this equation z_{eye} is the root of the equation $Q'(z_{eye}) = 0$ and β is a small parameter that is introduced for the purpose of current centroid smoothness. All characteristics of the coil can be expressed through the set of z-intercepts. By numerical methods, the positions $\left\{Z_i^{(in)}, Z_i^{(f)}\right\}$ (thus the conductor width) are varied to achieve the required or target characteristics of the coil. In this variation we monitor the coil inductance, magnetic field behavior, and coil resistance. The intercepts $\left\{Z_i^{(in)}, Z_i^{(f)}\right\}$ on both the primary coil and the shield coil can also be varied to balance the net thrust force exerted on the gradient by the magnet's field. The minimization conditions of Turner [2] are necessary but not sufficient in terms of minimization conditions with respect to the z-intercepts. Variation of the functional to be minimized with respect to the intercepts requires the additional step of calculating the variation of the current density with respect to the intercepts.

Results and Discussion

We have compared a finite length transverse whole body gradient coil designed by continuous current method with sinusoidal series expansion [2], after discretization, with a coil that was designed using our discrete method. The coils have identical radii and lengths conductor thickness, and the same number of turns. The conductor width for the primary coil is set to the minimum centroid distance minus 1 mm and is held constant for each turn. The gradient strength at isocenter is G_X=40mT/m with ~2% non-linearity and ~-25% non-uniformity of the gradient strength over 50cm(X/Y-direction)X40cm(Z-direction). The Table 1 below shows a comparison of the characteristics of the two coils. The coil performance using the z-intercept method is improved in this example, with 18% lower resistance.

Conclusion

We describe an analytical/numerical approach that eliminates some essential steps of [1,2] by using a "pre-discretized" coil from the start of the design process. Conceptually the Turner method [2] of coil design and our discrete method differ in the function description of current density, where the variables are now the points of intersection of the current with a chosen line on the surface of the cylinder. Both methods completely describe current paths that will generate the desired magnetic field. For a self-shielded coil either the shielding conditions [1,2] can be used or a separate set of z-intercepts for the shield coil can be introduced. The discrete method allows one to design a self-shielded coil with genuinely finite length avoiding truncation/appodization errors of discretization. The discrete design approach can be applied to gradient coils with 3D topology, symmetric unshielded and asymmetric shielded insert gradient coils, and resistive shim coils.

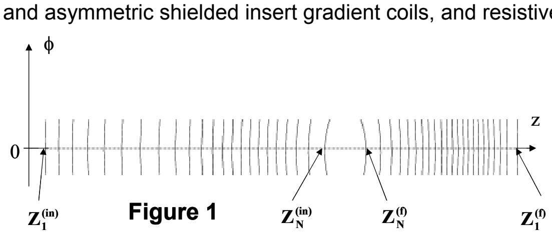

Figure 1

Table 1

Property	Prior Coil	New coil
Sensitivity [μT/m/A]	71.6	74.6
Inductance [μH]	673.0	653.3
Smallest centroid separation [mm]	5.3	5.75
Conductor width/thickness [mm] on Primary coil	4.3/4.9	4.75/4.9
Conductor width/thickness [mm] on Shield coil	18/2.1	19.1/2.1
Resistance (P/S) [mΩ]	100/45	83/36
Non-linearity at x=0.25m	+1.0%	+1.7%
Non-uniformity at z=0.2m	-24.6%	-24.6%
Residual eddy current effect range	0.4%	0.2%

References

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