Z-intercept Method for Improved SUSHI Gradient Solutions

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Introduction

Good solutions to the SUSHI shielding equation, motivated by the desire for ultra-short gradients, often have current reversals and have been investigated previously using continuous current density solutions. In this work we show that a discrete coil design method can be applied to solve the SUSHI problem, with *a priori* use of current reversals on the primary coil. A key is that all characteristics of a transverse gradient are expressed through the set of z-intercepts where the current patterns intersect the cardinal axis φ=0. We illustrate the method with an X-gradient design having reduced turns density and improved magnetic performance.

Method

Most of the methods of a shielded gradient coil design include two important steps: 1) find the continuous current distributions on the primary and shield coils that provide the required field quality characteristics (gradient strength at the isocenter of the coil, gradient field linearity and uniformity within the imaging volume (***IV***)), minimum coil inductance, and good shielding; 2) the continuous current distributions are discretized with an integer number of turns to match the power amplifier current/voltage characteristics. Constraints can be built into the analytical formalism [1] to achieve these goals. Depending on the size of the ***IV***, the size of the coil, and the field quality characteristics it often happens that the turns on the primary coil are most concentrated along the lines $\phi=0\ (\pi)$ as shown in Figure 1. The spacing between the centroids along these lines determines the minimum conductor width and a position and value of highest power density (corresponding to the maximum heat) in the coil. A signature of a SUSHI-type solution [2] is that the current distribution on the primary coil has a negative lobe near its end that further aggravates the problem of power density. We apply the method [3] of a shielded transverse design that overcomes these issues. 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. The discrete method begins with a "pre-discretized" primary and shield coils that carries current $\mathbf{I}$ and is determined by the set of intercepts $\{Z_i^{(in)}, Z_i^{(f)}\},\ \ (1 \le i \le N)$ of the coil turns at $\phi=0$. For a SUSHI-type solution an additional set of z-intercepts is allowed for the reversed turns near the end of the primary coil to allow for additional self-shielding [2]. These positions completely determine all characteristics of the coil such as coil inductance, magnetic field, resistance of the coil, residual eddy currents, and the current paths on the primary and shield coils due to the predefined sin(φ) dependence for the z-component of the current flow. By numerical methods the z-intercept positions are varied until the required characteristics of the coil are obtained. In this variation each term of the following functional is monitored

$$W = \frac{L\mathbf{I}^2}{2} + \alpha_1 \sum_{IV} (B_z^{coil}(\mathbf{r}_i) - B_i)^2 + \alpha_2 \sum_{Lineofdefense} (B_z^{coil}(\mathbf{r}))^2 + \beta_1 \Re^{(P)} + \beta_2 \Re^{(S)} \qquad (1)$$

Here L is the coil inductance, B_Z^{Coil} is the gradient field produced by the coil, B_i are the desired values of the field inside the imaging volume, $\Re^{(P)} / \Re^{(S)}$ are the resistances of the primary/shield coil, and α_1, α_2, β_1, β_2 are weighting parameters. The shielding is introduced in terms of choosing constraints along the "line-of-defense" [4]. The level of shielding can be characterized in terms of the SUSHI error function [2]

$$\varepsilon_\varphi(k) = F_\varphi^{(S)}(k) + (R_P I_1'(kR_P))/(R_S I_1'(kR_S)) F_\varphi^{(P)}(k) \qquad (2)$$

Here $F_\varphi(k)$ is the Fourier transform of the φ-component of the current flow that is yet again expressed in terms of the z-intercepts.

Results and Discussion

We have compared an existing SUSHI transverse gradient coil [2] with a coil that was designed using our discrete method. The coils have similar geometry (same radii, similar lengths). For the newly designed coil the gradient strength at the isocenter is G_X=30mT/m, with ~5% nonlinearity, ~-30% nonuniformity of the gradient strength over a 45cm(in X/Y direction) X 40cm (in Z direction) ***IV***. The line-of-defense was chosen to be a cylindrical surface of radius 0.475m. The comparison of the SUSHI error-function (2) per unit current is illustrated in Figure 2. Table 1 below shows a comparison of the characteristics of the previous SUSHI coil [2] and that of the new coil. The SUSHI error-function has been reduced by about a factor of two in comparison with that of [2], indicating better shielding and lower residual eddy current effect. The spacing between the current path centroids is increased that makes the present design more practical. Also the field quality characteristics inside the imaging volume have been improved, especially the gradient strength non-uniformity. Importantly, the coil inductance has been reduced by 23% and the current required to produce a 30mT/m gradient strength is reduced by 10%. Combined together this reduces the stored magnetic energy by 31%. The discrete method reduces peak current density on the primary coil.

Conclusion

We propose a discrete coil design method for SUSHI type coils by using a "pre-discretized" coil from the start of the design. This method allows one to design a self-shielded coil with finite and ultra short length avoiding truncation/appodization errors.

Acknowledgments

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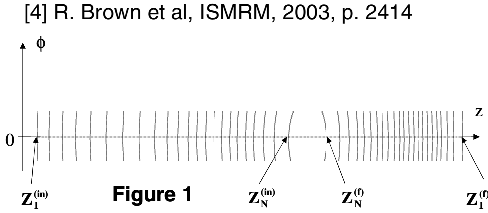

Figure 1

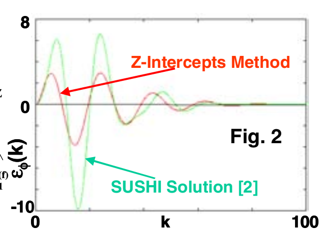

Fig. 2

Property	Coil [2]	New coil
Number of turns (P/S)	(23,11)/10	(23,8)/11
Electrical length P/S [mm]	1044/968	1106/1086
Inductance [μH]	1116.0	857.7
Current [A] for G=30mT/m	599.1	529.4
Minimum space between centroids [mm] (P/S)	2/13	4/15
Non-linearity at x=0.225m	-7.4%	+4.9%
Non-uniformity at z=0.2m	-38.5%	-30.4%
Residual eddy current effect	0.89%	0.37%