Should minimax|j| wire spreading be used for whole body gradient coils?

Michael S. Poole[1], Hector Sanchez Lopez[1], Stuart Crozier[1]

[1]School of Information Technology and Electrical Engineering, University of Queensland, Brisbane, QLD, Australia

Introduction

It has previously been demonstrated by experiment that, by spreading out the wires of gradient coils, it is possible to increase coil efficiency when limited by a minimum wire spacing and equilibrate the temperature in the coil [1]. It was thought that the benefits of wire spreading using the minimax$|j|$ coil design technique [2] would be less for whole-body gradient coils because of their large size and their performance is dominated by inductance. Previous studies have focussed on X-gradient coils, short coils, reduced radius asymmetric coils for head imaging and coils without active shielding. These studies demonstrated some of the more fundamental behaviours of the minimax$|j|$ coil design approach. In the present work we design whole-body, symmetric, actively-shielded X- and Z-gradient coils were designed with realistic limits for coil properties as a case study to determine whether the minimax$|j|$ wire spreading technique may be gainfully employed for gradient coils in whole-body MRI systems.

Methods

The minimax$|j|$ coil design method [2] was used to design X- and Z-gradient coils for whole-body systems. The coils of varied length were actively-shielded and designed with mixture of minimum stored magnetic energy (inductance), W, power dissipation (resistance), P, and maximum absolute current density, $\max|j| = \|j(\psi)\|_\infty$. Therefore the optimisation functional

$$U(\psi) = f(\psi) + \alpha e(\psi) + \beta W(\psi) + \gamma P(\psi) + \delta\|j(\psi)\|_\infty \quad (1)$$

given in Ref. [2] was minimised with respect to the variables that define the stream-function, ψ. An axisymmetric inverse boundary element method was used to parameterise the gradient coil current density [3] and Eq. 1 is minimised by a convex optimisation algorithm [2].

The coil efficiency, η, was maximised in the coil design process with the following constraints imposed: inductance, $L \leq 800\mu$H, resistance, $R \leq 0.2\Omega$, field error in the region of interest (ROI), $\Delta B_z \leq 5\%$, eddy current field in the ROI, $B_z^E \leq 0.1\%$, wire spacing, $ws \geq 6$mm. L and R were simulated with FASTHENRY [5]. The ROI was an oblate spheroid with 200 and 250 mm radii in the z and ρ dimensions respectively. The primary coil lengths were varied from 600 to 1600 mm with a radius of 344 mm. The active shield and the cryostat cold shield were 200 mm longer than the primary and had radii of 435 and 475 mm respectively.

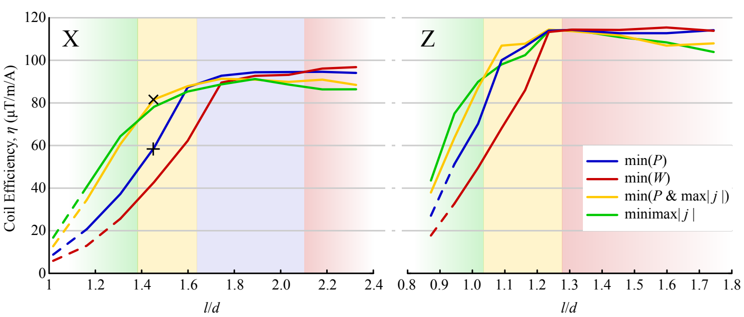

Figure 1: Gradient coil efficiency, η, as the length-to-diameter ratio, l/d, changes for X- (left) and Z-gradient coils (right). Coloured background indicates which type of optimisation produces the most efficient coil for that given length. + and × correspond to Fig 2 a) & b) respectively.

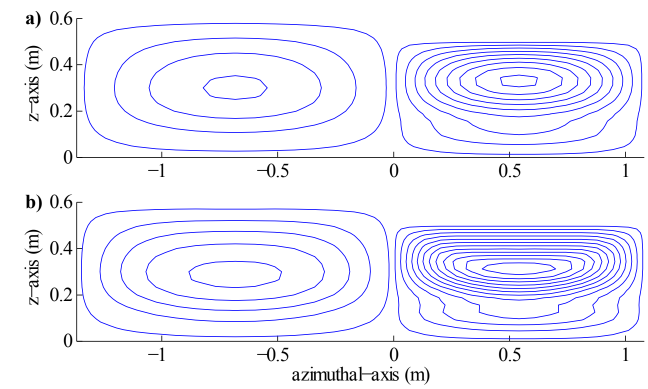

Figure 2: One quadrant of the X-gradient coil wire patterns; min(P) a) and min(P & max|j|) b). Primary coils appear right and active shields are on the left, $l/d = 1.45$ and only half of the wires are shown for clarity.

Results

Figure 1 shows the coil efficiency as the coil length is changed for both X- and Z-gradient coils and for the different optimisation weights. Min(P): $\beta = \delta = 0$, $\gamma = \gamma_P$. Min(W): $\gamma = \delta = 0$, $\beta = \beta_W$. Minimax$|j|$: $\beta = 0$, $\gamma = \gamma_P/10$, $\delta = \delta_J$. Min(P & max$|j|$): $\beta = 0$, $\gamma = \gamma_P/2$, $\delta = \delta_{JP}$. Figure 2 shows examples of wire patterns of X-gradient coils for the $l/d = 1.45$ min(P) and min(P & max$|j|$) cases.

Discussion and Conclusions

For the majority of whole-body X- and Z-gradient coils with sufficient length, the best scheme to use is either the standard min(P) or min(W) minimistaion, i.e. no minimax$|j|$ is needed, because the active constraint is the inductance of the coil. As the coils are made shorter, the minimum wire spacing takes over as the dominant constraint and the coil efficiency reduces dramatically. This happens at $l/d \sim 1.6$ to 1.7 for the X-gradients and $l/d \sim 1.1$ to 1.25 for the Z-gradient, for the given design constraints. In these short coils, it would be preferential to use some minimax$|j|$ weighted optimisation to ensure that both $L \leq 800\mu$H and $ws \geq 6$mm constraints are satisfied with maximum coil efficiency. This means that the minimax$|j|$ coil design technique can permit the design of shorter gradient coils than is currently possible with standard methods while maintaining good performance. Figure 2 shows a typical minimax$|j|$ effect on a short, shielded X-gradient coil where the efficiencies of the min(P) and min(P & max$|j|$) coils are 58.9 and 81.6 μT/m/A respectively. It is clear from this figure that the active shielding is a trivial addition to the optimisation and does not affect the minimax$|j|$ term since the current density is much lower on the shield than the primary.

References

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