Designing shim coils with minimax|j|

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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]. In this work we investigate what happens when the minimax$|j|$ method is applied to the design of shim coils. Shim coils upto and including third order were designed using continuous current density approaches with minimum power (a standard method) and minimum maximum current density. It is often the minimum wire spacing in a coil that constrains the strength of the field that it can generate with a given accuracy. Using the minimax$|j|$ method, the shim strength is always increased (between 22 and 92% in this study) for constant wire spacing compared to standard minimum power coils.

Methods

The minimax$|j|$ coil design method [2] was used to design upto third order shim coils for a whole-body system. The coils all had a length that was restricted to 1000 mm, a radius of 344 mm and were unshielded. A 10% error in the magnetic field they generate in an oblate spheroidal region (with radii of 500 and 400 mm) of interest was tolerated. Coils with minimum power, min(P), and minimum maximum current density, minimax$|j|$, were designed by solving

$$\min_{\psi \in \Psi} \{U(\psi) = f(\psi) + \gamma P(\psi) + \delta \|j(\psi)\|_\infty\} \quad (1)$$

with respect to the parameters that define the coil, ψ, where the terms are the same as in Ref. [2]. An axisymmetric inverse boundary element method was used to parameterise the shim coil current density [3]. In the azimuthal direction, the current density varies as $\sum_{m'=1}^{M} A_{m'} \cos(m(2m'-1)\phi)$ where m is the spherical harmonic degree of the shim field.

Results

Figure 2 shows the the wire-paths centres of the shim coils (with reduced numbers of turns to show the underlying pattern). Both the min(P) ($\delta = 0$) and minimax$|j|$ ($\gamma = 0$) coils are shown for qualitative comparison. The increase in efficiency of the minimax$|j|$ coils over the min(P) coils is presented in Fig. 1 for each shim coil. This was calculated by $(\eta_J w_J)/(\eta_P w_P) - 1$, where η_J is the efficiency of the minimax$|j|$ coil etc.

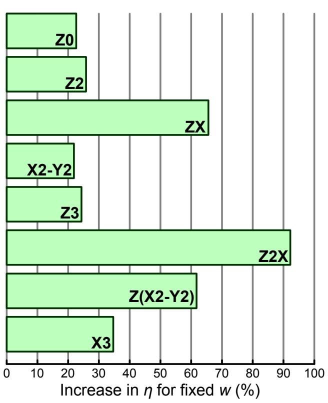

Figure 1: Increase in coil efficiency, η, for fixed wire spacing, w, achieved using the minimax$|j|$ method for each shim coil.

Discussion and Conclusions

Some fundamental patterns appear in the minimax$|j|$ shim coils. The Z0 reverts to a solenoid since for this length the homogeneity of 10% is easily achieved. Both X2-Y2 and X3 shims possess very square patterns with small meanders to ensure the field accuracy is 10%. The Z(X2-Y2) windings are not restricted by length and take on a hexagonal shape.
The results shown here represent the min(P) and minimax$|j|$ designs. It is also possible to design min(W) coils or any combination, but these solutions represent the most that the wires can be spread out for each case. The increase in efficiency for fixed wire spacing with minimax$|j|$ shown in Fig. 1, take positive values for all coils, varying from 22 to 92%. Zonal shims (Z0, Z2 and Z3) show low improvement whereas some tesseral shims show significant improvement where the restricted coil length impedes the coil return paths. Zonal coils have no return paths.
Necessarily, the resistance and/or inductance of the minimax$|j|$ coils is increased, but unlike gradient coils, they are not generally switched or require very large currents. This method allows the shim coil designer to chose from a wider range of coil performances. It is hoped that minimax$|j|$ coils will help improve the active shimming technique to achieve thinner linewidths in spectroscopy and less geometric distortion in fast imaging. This technique may also be useful for small bore systems and insert shim coils where thin flexible PCBs are used with wide tracks.

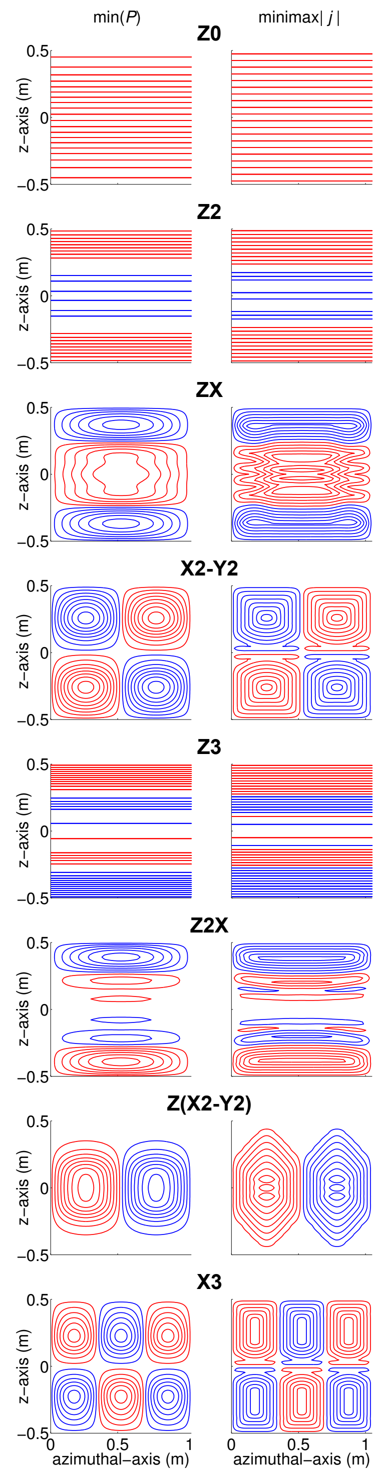

Figure 2: Wire paths of one half of the whole-body shim coils. Red indicates reversed current sense.

References

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