

Behaviour of Gradient Coils Designed With Varying Degrees of Minimised Maximum Current Density

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Introduction

The previously reported minimax current density coil design method [1] enables direct control over the maximum current density in a coil. This method is applicable to the design of low frequency coils such as gradient and shim coils. It is useful for two principal reasons: firstly a reduction in maximum current density reduces the peak temperature reached in the coil, and secondly it permits the design of the strongest possible magnetic field to be produced when limited by the size of the coil surface and the minimum wire size. In some cases the efficiency of a minimax $|j|$ (one designed with minimum maximum current density) coil can be double that of the next best minimum power design. Experiments have demonstrated qualitatively the reduction in peak temperature of minimax $|j|$ coils [2]. In this work we explore in more detail, and quantitatively, the behaviour of minimax $|j|$ coils. Results pertain to a short cylindrical X-gradient coil, but it is of course possible to repeat this investigation for other types of coil. To assess the gradient coil performance we use Biot-Savart simulation, inductance and resistance simulation and experimental and simulated heating results. To simulate the heating we use the recently proposed method of While et al. [3].

Methods

A range of gradient coils were designed by minimising the following optimisation functional:

$$U(\psi) = f(\psi) + \beta P(\psi) + \gamma \|j(\psi)\|_{\infty} \quad (1)$$

where f is the magnetic field error term and is the sum-of-squares of the difference between the target field and the field from the coil. P is the total amount of power dissipated by the gradient coil by Joule heating. j is the magnitude of the current density and $\|j\|_{\infty}$ is the maximum value of the current density, written here as the infinity-norm. β and γ are user-defined parameters used to trade-off minimisation of each term. The basis functions for this coil design were defined as the stream-function of the current density and have sinusoidal form in φ and are truncated sinusoids in z [4,5]. 10 harmonics were used in φ and 20 in z , giving a total of 200 basis functions. By using equation (1) with $\gamma = 0$ a usual $\min(P)$ coil is designed. Likewise by setting $\beta = 0$ we get a minimax $|j|$ coil. A range of coils between these two extrema were designed (maintaining a maximum field error of 5%) and tested. $\min(P)$ and minimax $|j|$ coils were constructed in such a way that the peak temperature could be measured experimentally using a thermal imaging camera (NEC F30). Temperature simulations were validated against measurements obtained from the $\min(P)$ and minimax $|j|$ coils and performed additionally for the intermediate coils to provide a quantitative prediction of their peak temperatures.

Results

Figure 1 a) shows a graph of the trade-off parameters, β and γ required to maintain 5% field accuracy. The appropriate figure-of-merit (FoM) with which to measure the performance of $\min(P)$ coils is η^2/R (where η is the coils efficiency and R is its resistance) since it gives a measure of the amount of magnetic field that can be generated, normalised to the amount of power dissipation. For minimax $|j|$ coils an appropriate FoM is ηw because this gives a measure of the amount of magnetic field that can be generated, normalised by the minimum spacing between wires, w . An equivalent FoM could be $\eta/\max(j)$. Figure 1 b) shows the behaviour of these two FoMs for the range of coils. Figure 2 shows the wire-paths for the coils in the range as well as their simulated temperature distribution and measured temperature for the $\min(P)$ and minimax $|j|$ coils. Fig 1 c) shows how the maximum temperature, $\max(T)$, varies with the total power dissipation of the coils.

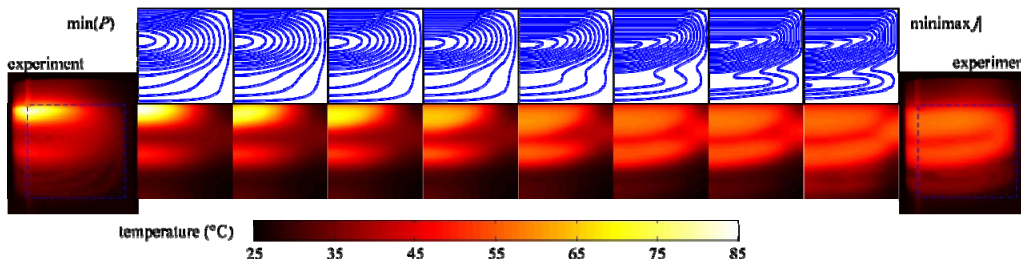


Figure 2. Top row: wire paths for one octant of the X-gradients ranging from $\min(P)$ at the left to minimax $|j|$ at the right. Bottom row: simulated temperature maps of the corresponding coil with experimental data at the far left and right.

Discussion and Conclusions

Minimum inductance and power are energy terms that are usually included in the design of gradient and shim coils and are well established and studied techniques [6]. They both have a natural regularising effect on the ill-posed field synthesis inverse problem that is “coil design” and are usually simply inverted because they are quadratic with respect to the solutions. $\|j\|_{\infty}$ is a new energy term that can be included in the design of gradient and shim coils and as such it is interesting to investigate its behaviour. Here, the behaviour of one type of coil was investigated for varying amounts of $\max|j|$ minimisation. It would also be interesting to study this approach with different types of coils, Z-gradients, shims and different geometries, short – long cylinders, planar coils etc. The return paths of these short cylindrical X-gradients are quite restricted and therefore the minimax $|j|$ technique has a considerable effect. The relationship between β and γ is non-linear but smooth and monotonic. Figs 2 a) and b) show that a small amount of one parameter can have a large impact on the design; i.e. a small amount of γ added to a $\min(P)$ coil significantly increases ηw (and decreases $\max(T)$) but has little effect on η^2/R (or P). Similarly, a small amount of β added to a minimax $|j|$ coil greatly reduces its power dissipation whilst maintaining low peak temperature.

References

- [1] M Poole et al. *J Phys D*, (2010) **43**, 095001 [2] M Poole et al. *Proc ISMRM*, (2010) **18**, 3943 [3] P While et al. *Concepts Magn Reson B*, (2010) **37B**, 146 [4] ZJJ Stekly *Proc ISMRM* (1985) **4**, 1121 [5] JW Carlson et al. *Magn Reson Med* (1992) **26**, 191 [6] R Turner *Magn Reson Imag* (1993) **11**, 903.

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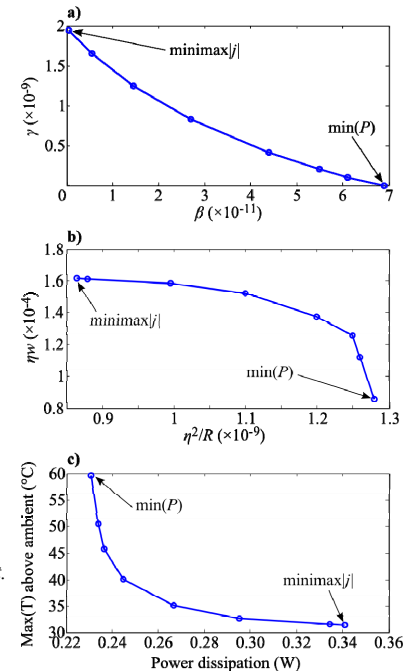


Figure 1. a) the trade-off parameters, β and γ , that ensure max field error = 5%, b) $\min(P)$ FoM against minimax $|j|$ FoM and c) maximum temperature, $\max(T)$, as function of total power, P , dissipation of the coils.