

Cool Gradient Coils Designed with Adaptive Regularisation

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Introduction Gradient coils can produce large amounts of heat when carrying hundreds of Ampères of current. The amount of current and duty cycle, the cooling efficiency and the winding pattern of gradient coils dictate the temperature of the coil. Excessive heating is known in some rare cases to cause failure of the gradients and elevated temperatures within the scanner [1] as well as thermal drifting of the background field due to the temperature dependence of the susceptibility of the passive shim pieces. Of particular concern are very short gradient coils that possess regions of high current density. We tackle this problem by developing a method that aims to minimise the maximum current-density of the wire-paths. A reduced maximum current density should lower the peak temperature given a particular coil geometry, operating currents and cooling provision. Using a boundary element method (BEM) [2] with a new regularisation term it is demonstrated that a significant reduction of the maximum current density magnitude can be achieved. This new regularisation term is dependant on a previous solution and is therefore called adaptive regularisation (AR). Basic heating simulations show a relative reduction in peak temperature between power-minimised (PM) and AR gradient coils.

Methods

The AR technique was incorporated into two BEMs, one based on triangular elements [2] and the other based on rotationally-symmetric elements [3]. Firstly, this method requires a PM gradient coil to be designed in the usual manner [4]. The AR matrix, \mathbf{A} , was then constructed by setting its off-diagonal matrix elements equal to $A_{pq} = \frac{1}{a_{mn1}} \frac{|\Delta\psi_{mn}|}{\Delta r_{mn}} \left(\frac{\mathbf{e}_{m1} \cdot \mathbf{e}_{n1}}{\|\mathbf{e}_{m1}\| \|\mathbf{e}_{n1}\|} \right)$ and the diagonal element are set equal to $A_{pp} = -\sum_q A_{pq}$, when node m and n are directly connected. $A_{pq} = 0$ for all other matrix elements. ψ is the previous solution, $|\Delta\psi_{mn}|/\Delta r_{mn}$ is the finite difference gradient of ψ between connected nodes m and n , a_{mn1} is the area of one of the triangles containing m and n and the vector \mathbf{e}_{m1} is the vector of the edge opposite the node m in that triangle. The weighted power minimisation term, $\beta\psi' \mathbf{R}\psi$, is replaced by $\beta_A \psi' \mathbf{R}\psi + \varepsilon\psi' \mathbf{A}\psi$ in the optimisation functional, where β_A is a greatly reduced (but not zero) PM weighting and ε is the weighting for the AR (ψ' is the transpose of the vector of stream-function values, ψ).

PM and AR cylindrical Z-gradient coils were designed using axially-symmetric boundary elements and cylindrical X-gradient coils were designed using triangular boundary elements. Their wire-tracks were generated based on a maximum track width of 20mm and a minimum track separation of 2mm and imported into COMSOL (COMSOL AB, Stockholm, Sweden). There, a 2D simulation was performed in which an electric current was passed through one quadrant of each coil sufficient to generate 2 mTm⁻¹. The copper tracks were assigned a thermal conductivity $k=400$ Wm⁻¹K⁻¹, density $\rho=8700$ kgm⁻³, heat capacity $C_p=385$ Jkg⁻¹K⁻¹ and electrical conductivity $\sigma=5.998 \times 10^7$ Sm⁻¹. The surrounding potting resin had $k=0.25$ Wm⁻¹K⁻¹, $\rho=1080$ kgm⁻³ and $C_p=1100$ Jkg⁻¹K⁻¹. It was assumed that heat was lost from the top surface via convection with a uniform transfer coefficient, $h=3400$ Wm⁻³K⁻¹.

Results

PM and AR Z-gradient coils were designed on short cylinders that possess the same degree of magnetic field linearity. Their stream-functions are shown in Fig. 1, their efficiencies (given $N = 10$ contour levels), η , were 266 and 229 $\mu\text{Tm}^{-1}\text{A}^{-1}$ and their minimum wire separations, $\min(\Delta w)$, were 5.8 and 8.0 mm for PM and AR respectively. Figure 2 shows temperature simulation results for the short, cylindrical a) PM and b) AR X-gradient coils with the direct current required for 2 mTm⁻¹, with 100% duty cycle. $\eta = 72.5$ and 69 $\mu\text{Tm}^{-1}\text{A}^{-1}$ and $\min(\Delta w) = 3.9$ and 6.0 mm for the PM and AR coils. Maximum temperatures were 362 and 332 K for PM and AR coils.

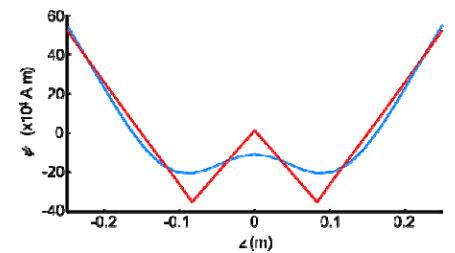


Figure 1. Stream-functions of a short cylindrical PM (blue) and AR (red) Z-gradient coil.

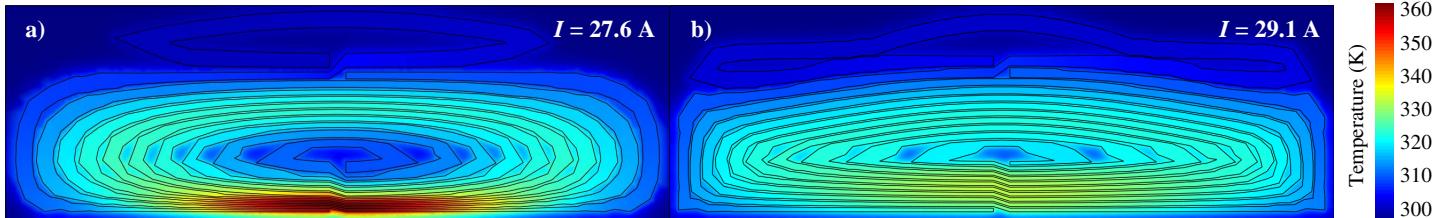


Figure 2. Temperature simulations of the short cylindrical a) PM and b) AR X-gradient coils with uniform convective cooling at $T_{\text{ambient}}=295$ K. Wire-paths are superimposed in black and the current, I , required to produce 2 mTm⁻¹ is displayed.

Discussion and Conclusions

Regions of high current density are clearly more spread in the AR coils. This appears, from the simulated results in Fig. 2, to reduce the intensity of “hot spots” of high temperature in the coils. Although realistic material properties were used in the simulation, the cooling is not realistic but is the same for both cases. An increase in inductance and resistance is observed in coils with reduced local heating. Another use of this method is to produce coils of maximum efficiency when limited primarily by the buildable wire separation. The PM and AR X-gradient coils would have an efficiency of 94 and 138 $\mu\text{Tm}^{-1}\text{A}^{-1}$ when constrained to 3mm wire separation and 13 and 20 contour levels were used. The AR method approximately minimises the maximum current density magnitude; a method that can obtain this solution with more accuracy is being sought. The method presented here is particularly effective at spreading the wires in coils with highly constricted geometry, with less benefit obtainable for long coils that easily accommodate return paths. It is interesting to observe that X-gradient coils naturally have $\psi \propto \cos \phi$, which causes the highest current densities to occur at $\phi = 0$. This region of high current density becomes spread when AR is performed and ψ no longer varies as $\cos \phi$. This leads to the unusual shape of the conductor paths shown in Fig. 2 b) that ensure linearity of the magnetic field to the same degree as the PM coil. AR is also applicable to the design of shim [5] and other field-generating coils.

References

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