AC Resistance Predictions vs Experimentally measured Values for a High Performance Head Gradient Coil

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Target audience: Engineers working on gradient coil development including design/analysis workflow and software prediction tools.

Purpose: Previously, the design of dedicated gradient subsystems for head imaging featured small-bore head gradients of about 30 to 35 cm inner diameter [1, 2]. More recent designs reported in [3] and [4] describe a larger, 42 cm inner gradient diameter; the former with a focus to insert the gradient coil into a whole body system (outer diameter = 67 cm), whereas the latter reported on a head gradient insertable into a proposed small-footprint head-only magnet, which is also the focus of this abstract. Besides meeting gradient performance criteria in terms of slew rate, amplitude, linearity, reduced forces [4], mechanical interaction [5], and eddy currents [6, 7] the gradient coil must also perform well in thermal management to ensure patient safety. We report finite element simulations performed to estimate the AC resistances induced in the gradient subsystem when pulsing each gradient axis individually. The predicted AC resistance values were compared to experimentally measured results from the first manufactured prototype (Figure 1), and good agreement was found.

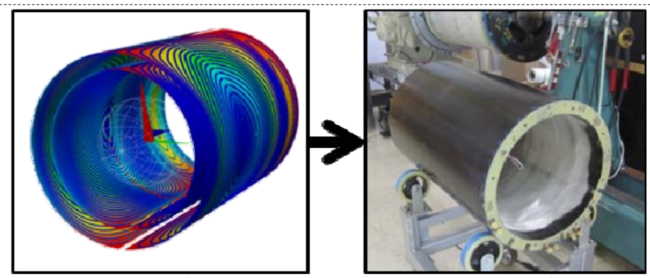

Figure 1: Pictures of the considered head gradient subsystem: from design to the first prototype.

Methods: The critical design parameters that influence AC resistance are the proximity of the coils and their elements, as well as the size and shape of the cross-sectional areas of each coil. Especially the latter can lead to higher AC resistance if the coil is modeled as a board due to relatively large conducting areas that support localized eddy current. To predict the AC resistance, the design was modeled in a finite element method (FEM) software [Maxwell3D, Ansys, Canonsburg, PA, USA]. Two different models were simulated. First an all-boarded design for X and Y axes was simulated (Figure 2) and second, wired primary coils of X and Y axes were modeled. In both cases, the Z coil was a wire model. The AC resistance model contained all three axes. Due to the different symmetry settings for each coil axis in 1/4th model, three simulations were performed in the frequency domain @1 kHz, where each axis was driven with a 10 A-peak sinusoidal wave. Additional mesh guidance by minimizing the ohmic losses helped to refine the mesh in coil regions where most losses are induced. The losses were extracted for each gradient coil loop and are normalized by $\left(I/\sqrt{2}\right)^2$ to represent the AC resistances given in ohms. In the experiments, the AC resistances were obtained from direct measurement of the voltage and current across each coil. A dynamic signal analyzer [Agilent 35670A] produced a sine sweep signal which was applied to the gradient coil. The voltages and currents were measured at the gradient coil terminal and across a resistive shunt, respectively.

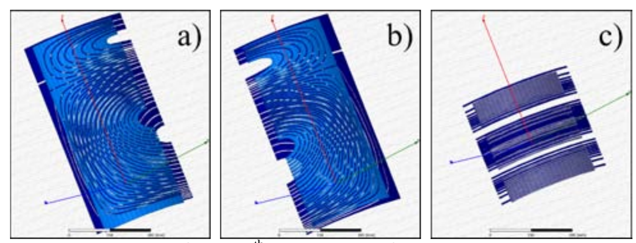

Figure 2: Pictures of the 1/4th FEM model of X (a), Y (b), and Z axis (c).

ACR	Experiments	Simulation	
	Board model	Board model	Wire model
X [Ω]	0.251	0.271	0.213
ε [%]		-8.0	15.1
Y [Ω]	0.234	0.241	0.189
ε [%]		-3.0	19.2
Z [Ω]	0.239	0.172	0.173
ε [%]		28.0	27.6

Table 1: Simulated and experimentally measured AC resistance values for board and wire models.

Results: The simulated and experimentally measured AC resistances are listed in Table 1. When comparing the board models in simulation and experiment to each other, relative errors of 8 % for X, 3 % for Y, and 28 % for Z coil were observed. An empirical scaling factor of 1.2 has been used to compensate for the meshing inaccuracies. The simulations could predict the AC losses for individual gradient coil excitation with reasonable accuracy for X and Y. Assuming that also in this setup the AC resistances are correctly estimated, the losses could be reduced when building a prototype coil out of wire as much as possible (Table 1, wire model).

Discussion and Conclusion: The comparison between measured AC resistances in the prototype gradient coil which uses boarded transverse coils and the simulated results on a boarded model showed reasonable accuracy. Further steps to improve the accuracy will include additional mesh layers inside the coil elements to improve the mesh accuracy, with an obvious cost in simulation time and memory. A next step is to transfer the predicted losses into a thermal analysis and compare simulated data with experimentally extracted temperatures. To conclude, the simulated AC loss predictions could be validated experimentally, verifying the capability of the finite element loss simulation to improve thermal performance of future gradient designs.

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References: [1] Alsop et al., MRM 35:875-886 (1996); [2] Tomasi et al., MRM 48: 707-714 (2002); [3] Green et al., Proc. Intl. Soc. Mag. Reson. Med. 16 (2008), #346; [4] Mathieu et al., Proc. Intl. Soc. Mag. Reson. Med. 20 (2012), #2588; [5] Graziani et al., Proc. Intl. Soc. Mag. Reson. Med. 20 (2012), #2585; [6] Lechner-Greite et al., Proc. Intl. Soc. Mag. Reson. Med. 20 (2012), #2604; [7] Lee et al., ESMRMB 29 (2012), #286;