Gradient induced heating on thin conducting surfaces: simulation and experiment

Chad Tyler Harris[1], William B. Handler[1], and Blaine A. Chronik[1,2]

[1]*Physics and Astronomy, Western University, London, Ontario, Canada,* [2]*Imaging Research Laboratories, Robarts Research Institute, London, Ontario, Canada*

Introduction: The time-varying magnetic fields generated by the gradient system during magnetic resonance imaging result in the induction of undesirable time-varying "eddy currents" in nearby conductive materials. When the nearby conductive materials are elements or components of devices or systems separate from the MRI system, not only can image artifacts occur, but the induced currents can also cause significant heating or mechanical vibrations on the device itself or some of its components [1, 2]. The ability to accurately model and predict the gradient induced eddy current over auxiliary devices would be extremely useful for their design and safety evaluations.

In this abstract, an integral method to calculate the eddy currents induced over arbitrary thin surfaces is described. The method is applied to predict the average heating rate of a small, thin, copper square, induced by a time-varying magnetic field and compared to experiment. The method is then extended to calculate the spatial distribution of the eddy current power deposition, and the spatially varying heating rate over the conducting surface. The spatially varying heating rate (with heat conduction between elements) is compared to the average heating rate.

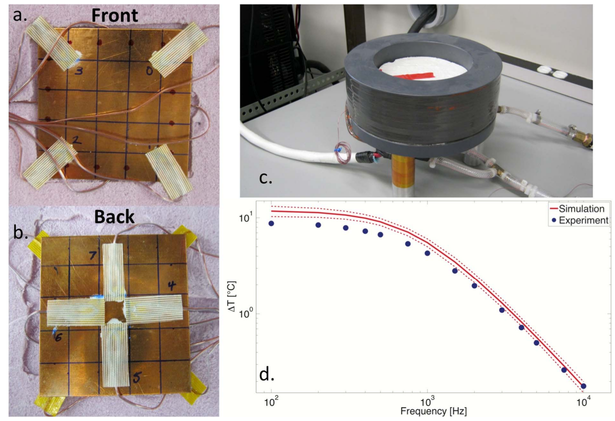

Figure 1. (a & b) Placement of the eight thermocouples used for temperature measurements. (c) Power solenoid used to produce the time-varying magnetic field. (d) Temperature rise vs. frequency for both the experiment (blue dots) and simulation (red line).

Methods: *Induced currents and power deposition:* Currents induced by time-varying magnetic fields can be calculated over thin conducting surfaces using an integral method [3]. To implement this method one must first discretize a surface geometry into a finite element mesh (triangles were used for the elements in this work). By defining a stream function over this surface, the induced current density can be approximated by a current basis set for each node of the mesh in a similar manner to the boundary element method for coil design [4]. Using this basis set, a time-varying field source, and the approach of [3], the unknown induced current density can be calculated. With the induced currents now known, the total power deposited in the surface can be found [4]. The total power can be integrated over time to find the total energy deposited into the surface and its average heating rate.

Instead of calculating the total power deposited into the surface, one can calculate the power deposited in each triangular element of the mesh. The formula for calculating the power deposited in element j is given by: $P_j = \frac{\rho}{t} A_j \sum_{n=1}^{3} \sum_{m=1}^{3} I_n \hat{J}_n \cdot \hat{J}_m I_m$, where ρ and t are the resistivity and thickness of the conductor respectively, A_j is the area of the triangular element, I_n is the stream function value for node n on triangular element j, and $\hat{J}_n$ is the current basis vector for node n on element j, calculated as the opposite edge vector divided by two times the element area. With the spatial distribution of the power deposited into the surface known, one can find the heating rate of the surface as a function of position.

Validation: A thin, square, copper plate (5.0 cm by 5.0 cm cross section, 0.53 ± 0.02 mm thickness) was centered within a custom-built thick solenoid electromagnet. Eight thermocouples (OMEGA® Type E) were placed at different positions distributed over the cross-section of the square (Figure 1 (a, b)). The magnet was driven with an AE Techron™ Power amplifier (model 7796) with a sinusoidal current waveform for multiple frequencies varying between 0.1 – 10 kHz. The electric field was used to calibrate the output at each frequency so as to produce a constant time-varying magnetic field dB/dt = 39 T/s. The solenoid was driven for 10 s with a 60 s buffer time placed both before and after the driving current was applied. The average temperature rise of the conductor over the heating duration (10 s) was extracted from the thermocouple data.

Simulation (Average heating rate): The copper plate from the experiment was represented as a triangular finite element mesh consisting of 3028 nodes and 5854 elements. The induced currents in the surface were calculated at a time step of 200 points per cycle. At each time point, the total power deposited into the entire surface was calculated. The deposited power was integrated over time to obtain the total energy deposited into the conducting structure, which was then converted into an average temperature rise. This process was repeated for each experimental frequency, with the current amplitude altered so as to produce a constant change in magnetic field with time of dB/dt = 39 T/s.

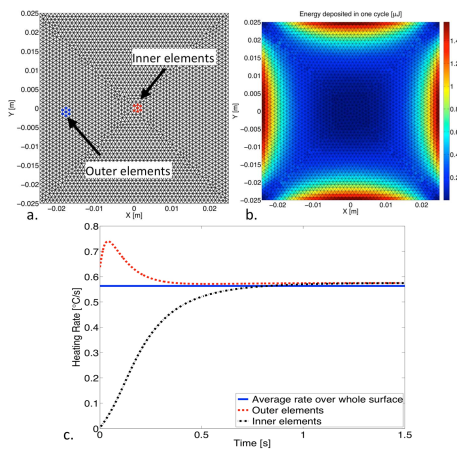

Figure 2. (a) Finite element mesh of the conducting square. The inner and outer elements used for heating rate calculations are shown. (b) Energy deposited into the conducting square over one cycle as a function of position. (c) Heating rate of the inner and outer elements as a function of time. Shown with the average heating rate of the square.

Simulation (Spatially varying heating rate): From the simulation we also know the spatial distribution of power. Using this information, the energy deposited into the surface over one switching cycle (in the steady state) as a function of position was found and subsequently converted to a rise in temperature. The model was extended to calculate the temperature rise over the heating duration on a cycle-by-cycle basis. After each cycle, heat transfer over the surface due to conduction between elements was included. The heating rate over a group of outer elements and inner elements (Figure 2 (a)) was found as a function of time and compared to each other and the average heating rate of the surface.

Results and Discussion: The average temperature rise predicted by the simulation and found by experiment is shown in Figure 1(d). The simulation was able to predict the heating rate within 30 % of the experimentally found values over the entire range of frequencies tested. The heating rate predicted by simulation was always larger than the experimental values, leading one to speculate that the simulation produces a worst-case heating scenario.

Figure 2 (b) displays the energy deposited into the conductor over one switching cycle as a function of position. Note how more energy is deposited near the edges of the conductor, with very little deposited at its center. Figure 2 (c) displays the heating rate over time for both the outer and inner elements along with the average heating rate of the conductor. The outer elements begin with a larger heating rate as is expected due to the larger amount of energy deposited in that area; however, due to heat conduction, the heating rate drops and reaches a steady state around the average heating rate. Conversely, the inner elements begin with a slower heating rate, due to the low amount of deposited energy in this area. Nevertheless, the heating rate increases due to conduction and reaches a steady state heating rate equal to the outer elements.

The methods described in this work allow the simulation of time-varying eddy currents on arbitrary conducting surfaces. It was used to model spatial variation in induced heating and validated by experiment. The method can be applied to any scenario in which induced eddy currents are important, including calculation of mechanical vibration, image distortion, and medical device heating.

References: **[1]** H. Graf, et al. *J Magn Reson Imaging*. **26**, 1328-1333 (2007). **[2]** H. Graf, et al. *J Magn Reson Imaging*. **23**, 585-590 (2006). **[3]** G.N. Peeren. *J Comput Phys*. **191**, 305-321 (2003). **[4]** M. Poole, R. Bowtell. *Concepts Magn. Reson. B*. **31B**, 162-175 (2007).