FDTD Analysis of transient eddy currents induced by gradient coil switching in MRI

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Synopsis: Most Magnetic Resonance Imaging (MRI) spatial encoding techniques employ low-frequency pulsed magnetic field gradients that undesirably induce multi-exponentially decaying eddy currents in nearby conducting structures of the MRI scanner. This is particularly problematic in superconducting system components. The eddy currents degrade the switching performance of the gradient system, distort the MRI image and introduce thermal loads in the cryostat. A recently proposed three-dimensional (3D), low-frequency Finite-Difference Time-Domain (FDTD) method in cylindrical coordinates (Trakic *et al.*, Cylindrical 3D FDTD algorithm for the computation of low frequency transient eddy currents in MRI, *ISMRM 2006*, submitted) is employed to analyse temporal eddy currents and manifest effects (e.g. B0-shift) induced by pulsed actively shielded symmetric/asymmetric transverse x-gradient head and whole body z-coils.

Methods: Analytical expressions involving cylindrical harmonics were used to define azimuthal and axial components of ideally distributed current densities for actively shielded symmetric and asymmetric transverse x-gradient coils with identical gradient field strengths of $10\ mTm^{-1}$. We initially consider 1cm-thick/0.65m-long conducting cold steel cylindrical cryostat and aluminium radiation shield walls as illustrated in Figure 1. The cryostat and radiation shields were assumed to be at temperatures of 300K and 80K. The grid resolution in both cases was: $\Delta r = 2mm$, $\Delta z = 5mm$ and $\Delta\phi = \pi/85$. The frequency and current rise time of the trapezoidal current excitation were 500 Hz and 250 μs, respectively. In order to avoid spurious oscillations an appropriately large scaling factor of 2.5e9 was chosen. With a safety coefficient of 0.95, the FDTD time step was around 5.85e-9s. In the second study, an unshielded z-gradient coil with a diameter of 0.69m and length of 1.28m was employed. A current of 100A was induced in the gradient coil with a trapezoidal amplitude modulation at 500Hz and 100 μs rise time. The grid resolution was: $\Delta r = 2.5mm$, $\Delta z = 10mm$ and $\Delta\phi = \pi/75$. The cryostat and radiation shield walls were 1.25cm in thickness with the same geometrical profile and material properties as in the x-gradient study, whereby the length of the cryostat wall was 1.4m.

Results: On a dual 3GHz/4GB RAM workstation, it took around 610MB of RAM and 26 hours to compute the transient eddy current problem in both the symmetric and asymmetric cases. Figure 2 illustrates the transient eddy current electric field at the inner surface of the cryostat and radiation shield walls in two different temporal representations for symmetric and asymmetric systems, respectively. In the first representation, the axial dimension is fixed at 0.25m while the azimuthal dimension is varied with time, while in the second representation the azimuthal dimension is fixed at 1.85 rad and the axial dimension is varied with time. Figure 3 illustrates the normalized spatial eddy current density plot at the inner surface of the cryostat and radiation shield walls for both x-gradient coil set-ups. Figure 4 shows the temporal B0-shift along the polar axis due to time-changing eddy currents induced in the cryostat and radiation shield walls. Figure 5 shows the transient azimuthal eddy current, eddy current free and total electric field at the inner cryostat wall as well as the eddy current induced B0-shift versus time and axial position in the z-gradient system, which is quite high in magnitude since the coil is not shielded and the surrounding conductors are quite thick in this simulation.

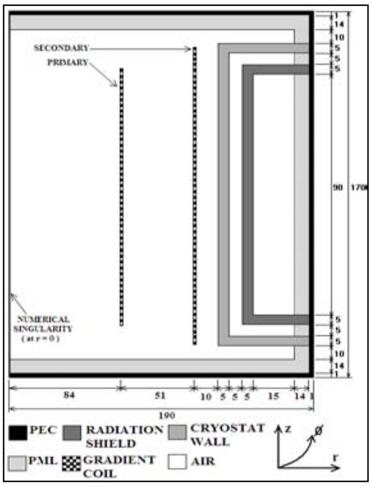

Figure 1 - FDTD Simulation set-up for the symmetric and asymmetric system

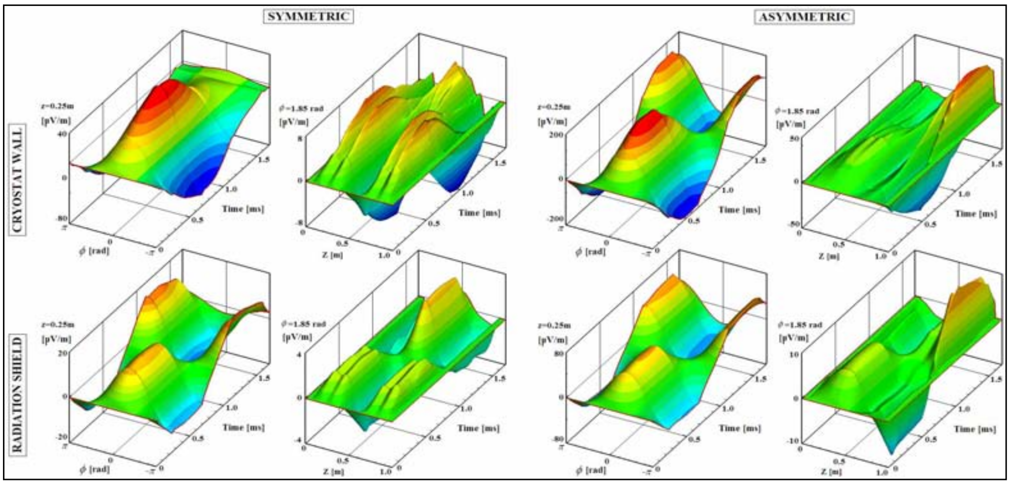

Figure 2 - Transient azimuthal eddy current electric field on the inner surface of the cryostat and radiation shield walls for symmetric and symmetric set-ups; $\phi - t$ (left) and $z - t$ (right) planar representations are illustrated

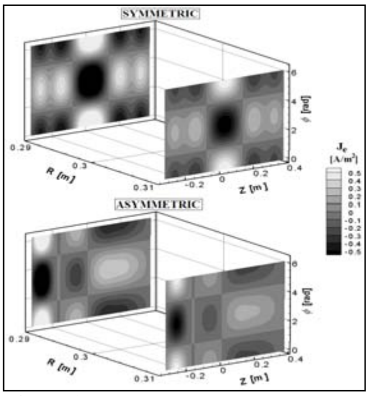

Figure 3 - Normalized spatial plot of the eddy current density at the inner surface of the cryostat and radiation shield wall for the symmetric (right) and asymmetric (left) system at t = 50 μs.

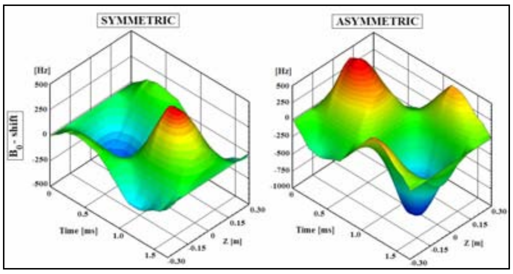

Figure 4 - B0-shift versus time and distance along the polar axis for the symmetric (left) and asymmetric (right) system

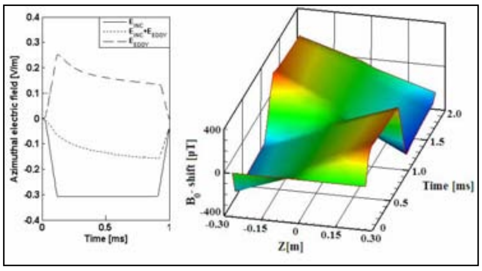

Figure 5 – Eddy current, eddy current free and total transient electric field at the cryostat (left) and B0 shift versus time (right) for the z-gradient system

Conclusion: In this paper we have demonstrated applications of the low frequency, cylindrical FDTD routine for the analysis of transient eddy currents and associated side effects when switching magnetic field gradients in MRI. A targeted application is the combined optimisation of gradient coils and magnet geometries as well as the preselection of initial pre-emphasis and B0 compensation waveforms.

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