Transient eddy current simulation of a uni-planar gradient set

S. M. Lechner[1,2], T. J. Hollis[3], H-J. Bungartz[2], B. C. Amm[4], G. Kudielka[1], and M. W. Vogel[1]
[1]GE Global Research Europe, Garching, Germany, [2]Technische Universität München, Garching, Germany, [3]GE Medical Systems, Oxford, United Kingdom, [4]GE Global Research, Niskayuna, New York, United States

Introduction:

Local gradients enable increased gradient strength and faster slew rates, which are both highly desirable to enable high-resolution and fast, real-time imaging(1). The planar gradient set presented in (2) illustrates one such gradient system, where all three gradient axes are incorporated into a uni-planar gradient set that is positioned within the magnet bore. Planar gradients present additional challenges in comparison with conventional gradient coils; additional eddy current sources such as the cooling tubes within the planar gradient set and the conductors of the built in cylindrical gradients can cause a strong distortion effect during their operation. Recently, a computer assisted magnetic resonance imaging (MRI) simulation technique has been introduced to support gradient coil design, which gives consideration to real hardware components in addition to the coils of the gradient (3). An important aspect of the simulation chain are the assessment techniques used to analyze and visualize the strength and timing behavior of the eddy currents. Transient finite element (FEM) simulations were used to characterize eddy currents by considering different materials and conducting structures, such as the cryostat, warm bore and cooling tubes.

Method and Materials:

The planar gradient set incorporates two sets of boards for each axis. Copper cooling tubes are added in between each plate to minimize the surface temperatures (2). As real experiments have shown that the z-gradient causes significant eddy currents, the z- planar gradient geometry is imported into the model from the original design CAD files. Eddy currents are unwanted currents induced in conducting structures, which cause undesired time dependent field disturbances. A general description is given for the example in (4), where the deformed eddy current terms $g(t)$ for constant, linear and higher orders are presented as a series of exponential decaying functions with the changing gradient waveform $G(t)$ over time:

$$g(t) = -\frac{dG}{dt} \otimes \sum_n \alpha_n e^{\frac{-t}{\tau}} \qquad [1]$$

The strength of the eddy current effects α is dependent on the strength of the gradient pulse, the conducting material resistivity and the geometry of the conducting structure as well as its distance from the gradient coil. The timing components τ are related to the aforementioned parameters and the frequency of the applied gradent waveform. For the transient FEM simulations the commercial software package Maxwell3D(5) is used. A single trapezoidal current pulse at a frequency and rise time of 1kHz and 100ms, respectively, has been used to excite the coil. Steady state simulations are applied at the end of the pulse to track the time decay of the induced eddy currents resulting in a total simulation period of 5ms. Firstly a simulation run is performed involving both the gradient coil and the conducting structure. Next, a reference simulation without the conducting structure is computed. The pure eddy current effect is obtained by subtracting the superposition field of reference and eddy current field response. As model complexity is a limiting factor in terms of simulation performance, symmetry boundary conditions are utilized so that all simulations are performed on 1/4 of the setup(3). The major eddy current sources are assumed to originate from the thermal shield and the warm bore. The presented coil also contains copper cooling tubes, which are positioned close to the imaging field of view and hence we also expect them to cause some eddy current effects. We investigated two different setup combinations: a) z-gradient and cylindrical shell representing the warm bore or the thermal shield with materials of stainless steel and aluminum, b) the z-gradient together with the copper cooling tubes aligned in z-direction (real model) and in x-direction (simulations). The decaying component after the pulse follows the exponential decay given in [1], which is determined by a linear least squares fitting routine, based on the simplex search method.

Results:

Fig.1a-c) show the implemented setup of the z-gradient coil together with the conducting shell and the time decaying curves of the B_z field at multiple positions: a) within the FOV of the gradient coil (at the positions that are usually used to determine the required gradient pre-emphasis) and b) close to the conducting shell, which is stainless steel in this case. Fig.1c) illustrates the configuration the z-gradient coil, including the closest cooling tubes to the coil. In this case, only the FOV volume points are considered. Tab.1 summarizes the resulting time constants and amplitudes for all three setups. As expected, the time decay behavior behaves consistently for all cases. The maximum amplitudes are obtained close to the shell, especially in regions, where the coil is placed closer to the shield due to the non-symmetric arrangement of the coil in y-direction. Interestingly, the strength of the eddy currents induced in the cooling tubes has a similar intensity to the eddy currents induced with the stainless steel bore tube, except the timing constant is shorter. If the cooling tubes were aligned in the x-direction, the eddy current effect would have been even stronger.

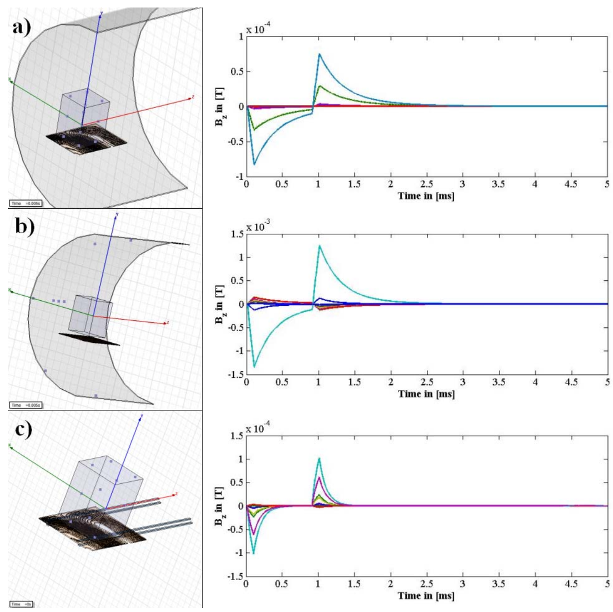

Fig.1a and b) illustrates the decaying eddy current curves at different points within the FOV region, which are located at the eight corners of the illustrated box, and additional points close to the simulated conducting shell. Fig.1c) shows the decaying eddy current curves at the FOV grid points, where copper cooling tubes have been simulated.

Material	α in [%]			τ in [ms[		
(σ - Conductivity in [S/m])	a)	b)	c)	a)	b)	c)
Stainless steel (σ=1.1e6)	0.25	68.9	-	0.39	0.28	-
Aluminum (σ=3.8e7)	0.02	10.24	-	10.04	9.91	-
Copper cooling tubes in z (σ=5.8e7)	-	-	0.24	-	-	0.10
Copper cooling tubes in x (σ=5.8e7)	-	-	1.13	-	-	0.10

Tab.1 summarizes the α, which is given in percent of the local field strength, and τ components of the presented setups.

Discussion and Conclusion:

With the presented work, we used the finite element simulation technique to analyze and visualize transient eddy currents induced in different components of the MR system. We demonstrated flexibility to combine material types, geometries and transient evaluations such that the spatially dependent eddy current time and amplitude behavior could be characterized. Furthermore, the characterization of transient eddy current effects is vital for their compensation and enables further optimization of gradient coils and detailed characterization of the design performance, without the expense of building and testing a physical prototype. While the possibility of considering different materials, geometries and pulses provides high flexibility within the simulation, the corresponding model complexity and adaptive meshing process currently results in a long simulation time. Eddy currents are frequency and skin depth bounded, which needs to be considered in the simulations. Applying efficient model representations such as symmetry together with parallelization approaches help to increase computational speed.

References: (1) Marinelli et al, 15th ISMRM, 2007 #926, (2) Aksel et al, Magn, Reson. Med. 58:134-43 (2007), (3) Lechner et al, 17th ISMRM, Honolulu, 2009 #3047, (4) Jehenson et al, JMR,90:264-278 (1990), (5) Maxwell3D12.0.1, Ansoft Corporation (LLC,2008)