Simulation of Magneto-mechanical Coupling in a 3T Head-only Magnet Design

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Introduction: In the design of high field (3T and up) head only imaging systems, the effect of eddy currents[1] on image quality can be significantly increased over those of conventional MR scanners due to the narrow bore of the magnet and increased peak gradient strength. A particular concern is magneto-mechanical coupling of the gradients to the magnet structure [2-3]. Lorentz forces, acting on eddy currents in the cylindrical conductive structures of the magnet, induce vibrations. The deformation of these surfaces cause localized changes of flux and additional currents to form. These motion induced currents can cause significant distortions of the gradient field, especially if a resonance condition is established. Here we present simulations (2D and 3D) for an asymmetric head-only gradient design and analyze the significant eddy current field enhancement due to magneto-mechanical resonance of a conducting cylinder.

Methods and Materials: Two actively shielded head-only gradients [4] were modeled using COMSOL (COMSOL, Inc. Burlington, MA). A two dimensional axisymmetric model was developed for the z-gradient, and a three dimensional model for the transverse gradient. The transverse coils are asymmetric about the z = 0 plane, but contain two planes of symmetry in the x and y directions. A quarter symmetry model was therefore used to reduce the time and memory requirements of the simulation. The models consist of a representation of the gradient coil winding pattern inside a conducting cylinder that is fixed at both ends. The 3.2 mm thick conducting surface was modeled as aluminum (conductivity of 3.0×10^7 S/m and Young's modulus of 69 GPa). The distance between the gradient coils and the conducting surface was 5 cm. For the 2D z-coil simulation, the wire positions of the gradient coils were explicitly specified. To avoid the level of mesh refinement needed to define the intricate finger-print winding pattern, the primary and shield transverse gradients were modeled as two cylindrical shells with continuous current densities corresponding to the prescribed wire layout. The gradient current amplitude was 620 A over a frequency range of 0–4 kHz. The steady state response to a continuous sinusoidal excitation was analyzed by calculating the gradient field strength at the centerline as a function of frequency. The simulation was carried out on an HP Z800 workstation operating on 8 cores at 2.67 GHz with 64 GB of memory. The total computation time was 12 min for the 2D model, and 15.7 hr for the 3D model.

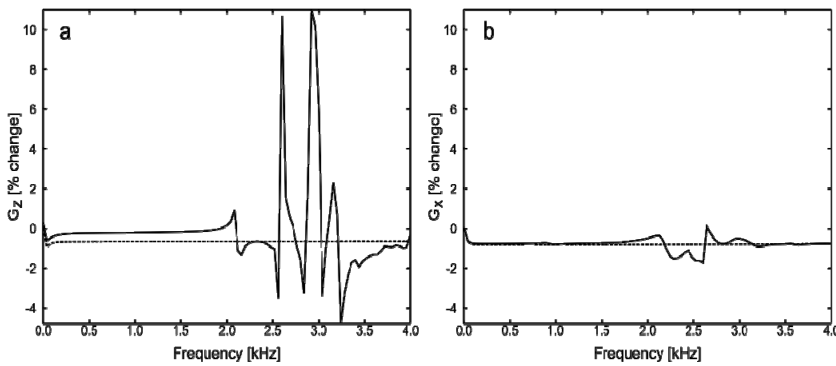

Fig. 1 The percent change in the peak gradient strength when compared to the DC amplitude for the longitudinal z-gradient (a), and a transverse x-gradient (b). Dashed lines represent the change in gradient strength without considering mechanical motion. The solid lines take into account eddy currents as well as magneto-mechanical coupling of the conducting cylinder.

Results: Magneto-mechanical resonance was observed for both the transverse and longitudinal gradient coils (Fig. 1) between 2 and 3.5 kHz. At resonance, the peak gradient strength changed by up to ~10% for the z-gradient when compared to the static case, and ~1.5% for the transverse coil. Significant deformation of the conducting cylinders was observed in both simulations, with peak displacements of 0.8 and 0.2 mm at resonance (Fig. 2).

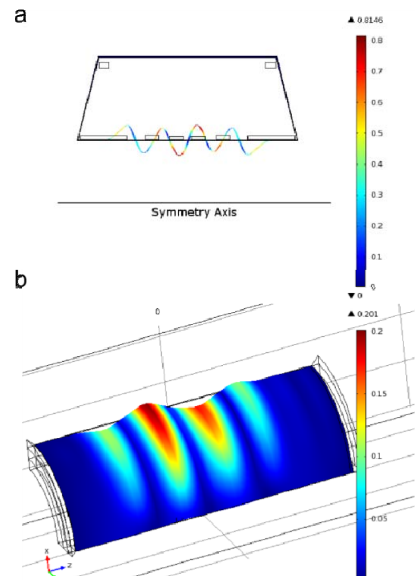

Fig 2. Deformation of the conducting cylinder for the z-gradient model (a), and transverse gradient model (b) showing peak displacements of 0.8 and 0.2 mm respectively.

Discussion and Conclusion: Magneto-mechanical coupling in a 3T head only magnet can contribute significantly to the gradient eddy current due to the close proximity of conducting surfaces to the gradient stack. Magnetomechanical effects such as magnetic damping and magnetic stiffening have been previously studied in the context outside of MRI, such as to characterize component vibration in the high magnetic field environment of a fusion reactor [5]. In this work we demonstrated results of fully coupled numerical analysis of magneto-mechanical interaction between the gradient coil and a conductive cylinder placed in the main magnetic field of a high field MRI scanner. We found that vibration-induced resonant interaction can greatly enhance the eddy current field in the imaging volume at kHz frequencies. Such enhancement can potentially be a significant image quality concern for high-field specialty scanners in which conductive cylinders are placed close to the imaging volume, and gradient waveforms can have substantial frequency content above 1 kHz due to higher slew rates available. Our work represents the first step towards developing modeling capabilities to simulate this complex phenomenon which is crucial for component level design optimization in a high performance scanner.

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