Accurate Vibroacoustic Simulations in High Performance Gradient Coils

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Target Audience: MR engineers with an interest in gradient coil acoustics.

Purpose: We present a new comprehensive modeling approach for understanding acoustic noise in MR gradient coils that includes previously neglected but essential factors in vibroacoustic analysis. We use this new approach to compare vibroacoustics in both head and body gradient coils.

Background: The conductors of MR gradient coils are subject to large Lorentz forces due to rapidly switched currents in the presence of the static magnetic field. These forces cause gradient coil conductor vibrations, which in turn generate displacement of the gradient coil and other structural support surfaces. The induced pressure variation in the surrounding air results in an acoustic pressure wave and sound radiation. The sound pressure levels (SPL) inside the gradient coil can exceed 100 dB, and these levels increase with field strength. The drive to higher gradient performance in both head and body gradient coils leads to increased concern about vibration and acoustics. We have found that prior analyses, which were based on simple analytical models of thin-walled cylinders or simplistic numerical analyses of shell vibration, neglected many essential effects. These turn out to be important for accurate prediction of the vibroacoustic phenomena occurring in MR systems. In this work, we introduce new vibroacoustic modeling features compared to previous literature, including: (1) comparison of a head gradient design [1] to a typical full-sized body gradient coil; (2) analysis with realistic wire patterns; (3) induction of motion-induced eddy currents in the gradient conductors; (4) full coupling of acoustic and structural modes; (5) inclusion of the patient bore tube and patient table support bridge; (6) full and realistically modeled effect of a volume of air outside the patient bore;. Using these new simulation tools, as well as corresponding experimental measurements, we were able to draw conclusions about high performance gradient coils that should provide guidance to investigators interested in maximizing imaging performance.

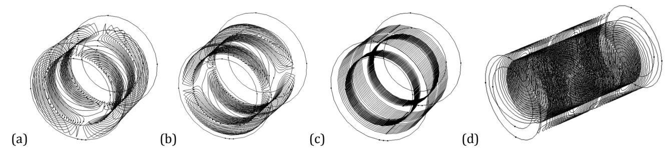

Fig. 1 Wire patterns for the head gradient: (a) *X*-, (b) *Y*-, (b) *Z*-gradient axes, (d) body gradient *X*- and *Y*-axes.

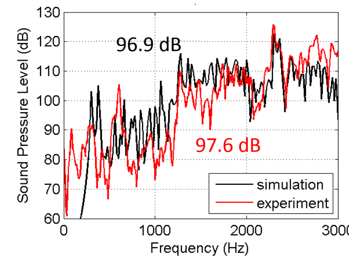

Fig. 2 Simulated vs experimental SPL at isocenter for the *X*-gradient coil at 3T/50A.

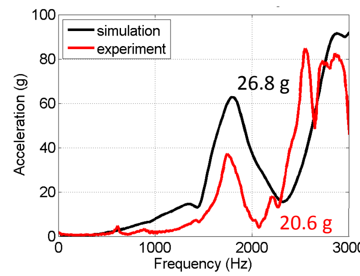

Fig. 3 Simulated vs experimental acceleration spectrum near the bore end (z = +16 cm) for the *X*-gradient coil at 3T/50 A.

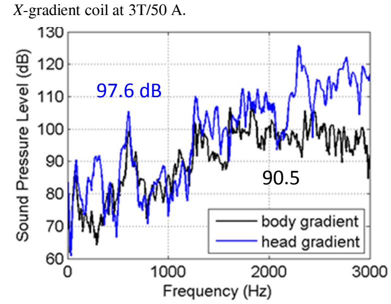

Fig. 4 Comparison between body *X*-gradient and head *X*-gradient SPL at isocenter (50A, 3T).

Methods: We chose to conduct realistic numerical modeling using the finite-element package COMSOL (COMSOL, Inc., Burlington, MA, USA). Our head gradient design was a novel folded shielded gradient design intended for human brain imaging [1]. The coil structure was modeled as a thick-walled epoxy cylinder (head gradient: inner/outer diameter 338/490 mm, length 450 mm; body gradient: inner/outer diameter 670/920 mm, length 1600 mm). Accurate conductor wire patterns were embedded in the structure to ensure a correct representation of the spatial excitation distribution for the analysis (Fig. 1). The effect of Lorentz damping due to vibration-induced eddy currents in the conductors was also modeled using copper wire of radius 3 mm. Epoxy was modeled as a linear elastic material (Young's modulus E = 10 GPa, density ρ = 1600 kg/m^3, Poisson's ratio ν = 0.4), whereas the air inside and outside the bore was modeled as a pressure acoustic fluid domain (speed of sound c = 343 m/s, ρ = 1.2 kg/m^3). The analysis included full coupling between acoustics and structural vibration. A cylindrically shaped bore duct of 60 cm diameter, as well as a planar bridge (patient table support) for the head gradient to sit on, were modeled with hard sound boundary wall conditions. A hemispherical air volume of radius 1 m was added to the analysis, flush with the patient bore end. A simulation domain of infinite size was mimicked using perfectly matched layers of 20 cm thickness. The analysis was carried out using a harmonic excitation with an AC current of amplitude 50 A over a frequency range of from 0-3000 Hz, which spans the frequency content of most RF pulse sequences. In the experiment, individual gradient axes were driven with a sinusoidal current waveform of 60 s sweep duration. SPL levels were measured using a Behringer ECM800 condenser microphone at various spatial positions in the bore. Vibration levels were characterized for the head gradient by making acceleration measurements using a single-axis Analog Devices ADX001-70Z accelerometer, sensitive to acceleration amplitudes of ± 70g. The accelerometer was positioned on the inner bore surface at various z-positions.

Results: SPL spectra show a very close match between simulation and experiment (head coil *X*-axis results shown in Fig. 2) with many similar features. The discrepancy in spectrally-averaged SPL at isocenter was only 1.6dB for the *X*-axis and 0.5dB for the *Y*-axis of the head gradient – similarly good matches between simulation and experiment were found for the body gradient. For the head *Z*-axis, the match was not as good (mean discrepancy 9.9 dB) – we speculate that the lack of realistic modeling of the hollow copper tubing used on the *Z*-axis is the reason for this larger discrepancy. Simulated and experimental acceleration spectra were reasonably well matched (Fig. 3), with average acceleration values of 26.8 g by simulation and 20.6 g by experiment at one typical accelerometer position. Fig 4 shows the experimental comparison between head and body *X*-gradient SPL spectra, measured at 50A peak current and 3T. Average SPL values were 90.5 dB (head) vs 97.6 dB (body). Spectral features between head and body gradients were found to be remarkably similar at low frequencies (0-1200 Hz), with the head gradient exhibiting higher SPL levels in the high frequency range (2000-3000 Hz). It should be noted however, that the head gradient was not yet lined with sound barrier material, which is expected to decrease its high frequency SPL levels substantially.

Discussion: Our simulation environment is the most complete developed to date for gradient coil vibroacoustic simulations. By accounting for a number of physical factors that have not previously been included, we have achieved a high level of match between simulation and experiment, giving us confidence that these simulation tools will accurately predict experimental acoustic and vibration levels under a wide variety of conditions. We have predicted average sound and vibration levels in head and body gradients, and have begun to use these tools to understand and suppress acoustic levels associated with novel high performance gradient coils.

Conclusion: A new framework for the comprehensive and realistic analysis in MR gradient coils has been proposed. Experiments show that both SPLs and acceleration levels are accurately predicted by our simulation framework.

References: [1]Wade TP, et al, Proc Intl Soc Mag Reson Med 22:4851 (2014)..

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