A Traveling-Wave Approach to Acoustic Noise Reduction in MR Gradient Coils

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

Purpose: We present a new wave-based framework for understanding acoustic noise in MR gradient coils, and propose two new concepts for acoustic noise reduction. Results of this wave-based coupled structural-acoustic modeling, as well as experimental measurements, demonstrate that the addition of an impedance matching "horn" and an absorbing end cap both act to decrease acoustic noise inside the gradient coil.

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 surfaces. The induced pressure variation of the air particles results in an acoustic pressure wave and sound radiation. The sound pressure levels (SPL) inside the gradient coil can reach levels well over 100 dB, especially at higher field strengths. High performance head gradient coils can further increase these levels. We sought to understand and reduce acoustic sound levels inside a novel head gradient design intended for use at ultra high field (7T).

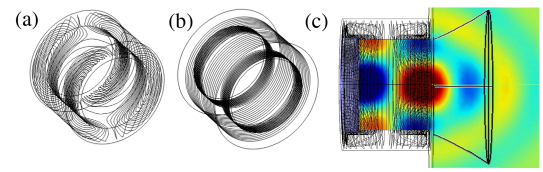

Fig. 1 Wire patterns (a) *x*- and *y*-, (b) *z*-gradient axes, (c) Traveling wave concept using a horn.

Methods: Existing theoretical analyses of gradient coil acoustics include the use of thin shell theory [1], as well as numerical analyses of more realistic thick-walled gradient cylinders [2]. We chose to conduct realistic numerical modeling using the finite-element package COMSOL (COMSOL, Inc., Burlington, MA, USA), with particular focus on a novel folded shielded gradient design intended for human brain imaging at 7T [3]. The coil structure was modeled as a thick-walled short epoxy cylinder (inner/outer diameter: 338/490 mm, length: 330 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 epoxy cylinder was modeled as a linear elastic material (E = 3.5 GPa, ρ = 1600 kg/m^3, ν = 0.4), whereas the air inside the bore was modeled as a pressure acoustic fluid domain (c = 343 m/s, ρ = 1.2 kg/m^3). The analysis included full coupling between acoustics and structural vibration. The effect of displacement damping due to vibration-induced eddy currents in the conductors was also modeled using copper wire of radius 3 mm. The analysis was carried out using a harmonic excitation with an AC current of amplitude 30 A over a frequency range of from 0–3000 Hz, which spans the frequency content of most RF pulse sequences. The cylindrical coil model used simply supported boundary conditions for the structural analysis [1]. In the experiment, the *X*-gradient was driven with a sinusoid of 60 s sweep duration. The SPL was measured using a Behringer ECM800 condenser microphone at 10 cm off isocenter along *x*, corresponding to the approximate location of a human subject's ear.

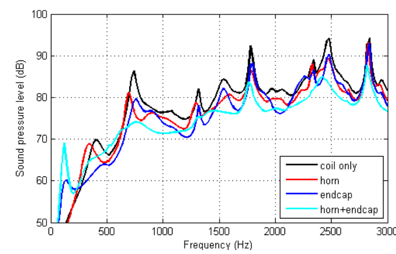

Fig. 2 Volume averaged SPL in simulation for all three gradient axes: original acoustic spectrum (black) and traveling-wave spectrum (blue: end cap, red: horn, cyan: end cap + horn).

Traveling-Wave Noise Reduction: We propose here the use of either a "horn" or an absorbing end cap, or both, inserted at the bore ends, to reduce acoustic sound levels inside the gradient bore. These concepts are founded on the acoustic transmission line characteristics of the gradient coil. The bore acts as a cylindrical waveguide with reflective bore ends due to the difference in acoustic impedance at this discontinuity with the outside free space air. The use of a horn, which "flares out" at one end of the gradient cylinder (Fig. 1c), acts to better match the characteristic acoustic impedance within the duct to the free space acoustic impedance. A traveling wave can then better carry sound energy from the interior of the resonator toward the outside world, thereby reducing the acoustic energy resonating inside the duct. An absorbing end cap, on the other hand, absorbs reflected energy at the impedance discontinuity. To study the horn concept in simulation, the horn was modeled with rigid walls, using a hemispherical volume of air in front of the horn. The horn shape was chosen to follow an exponential outline $r(z) = r_i \cdot e^{bz}$, which yields large impedance-matching bandwidth. The absorbing end cap was modeled with an absorption coefficient of 7 Np/m, using a thickness of 5 cm.

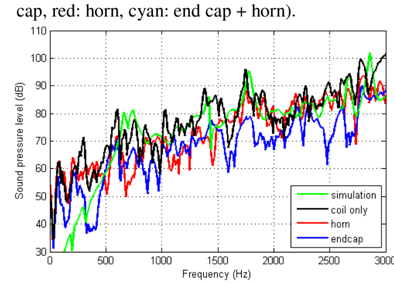

Fig. 3 Experimental results at ear position for stand-alone *X*-gradient coil and using horn and endcap noise reduction techniques.

Results: The simulated acoustic frequency responses for the unmodified gradient coil, with all three axes driven, are shown in black in Fig. 2; the acoustic pressure has been averaged over the bore volume at each frequency point. The linear volume-averaged SPL shows an average of 77 dB over the band of interest (0–3000 Hz). The simulated SPL spectrum with horn (b = 2, h = 10 cm) is shown in red, with end cap shown in blue, and with both shown in cyan. As a general result, both techniques serve to blunt all peaks in the acoustic spectrum. The maximum SPL at any frequency in the 3 kHz band is 94 dB and a maximal noise reduction of 8 dB and 10 dB is found at a frequency of 740 Hz for the horn and the end cap, respectively, with a noise reduction at this frequency of 13 dB for both. A mean reduction of 2 dB for horn and end cap, and 3 dB for both used in combination is found. Fig. 3 shows experimental measurements of SPL at a point +10cm right of center, for *X*-gradient excitation. The measured spectrum (black) is well approximated by simulation (green) and shows an average SPL of 76 dB. The horn (red) yields a mean and maximum noise reduction of 4 dB and 28 dB, while the end cap (blue) reduces noise by a mean and maximum of 9 dB and 27 dB, respectively.

Discussion: It may be practical to cap off the far end of a head gradient, while at the same time attaching a horn to the patient end, thus allowing for the combined sound reduction effect of both strategies. Future simulation work will incorporate more of the magnet and mechanical support / housing structures, as well as the human subject, into the analysis. We will also compare body gradient acoustics to head gradient acoustics. We expect that the wave-based approach combined with the simulation tools presented here will give us insight into new strategies to reduce gradient coil acoustics.

Conclusion: A new framework for analysis, and two new concepts for acoustic noise reduction in MR gradient coils, have been proposed. Experiments show that these two concepts lead to modest noise level reductions that are well predicted by our simulation framework.

References: [1]Li G, et al, MAGMA 22(6):353 (2009). [2]Yao GZ, et al, MAGMA 17(1):12 (2004). [3]Wade T, et al, Preliminary Evaluation of an Insertable Head Gradient. Proc ImagingNetworkOntario. Toronto (2013). [4]Edelstein WA, et al, Magn Res Imag 20(2):155 (2002).

Acknowledgement: Research support from NSERC, NIH P41 EB015891, the Lucas Foundation, and GE Healthcare.