Lorentz Damping and the Field Dependence of Gradient Coil Vibroacoustics

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Target Audience: MR engineers with an interest in gradient coil acoustics in Ultra High-Field (UHF) MRI.

Purpose: We present a new and comprehensive approach for modeling gradient-induced acoustics and vibration that accounts for previously neglected but essential Lorentz damping. We used this approach to study the dependence of acoustic noise and vibration levels on main field strength.

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 in surrounding air results in an acoustic pressure wave and sound radiation. The sound pressure levels (SPL) inside the gradient coil can exceed 100 dB, especially at higher field strengths. The drive to higher gradient performance leads to increased concern about vibration and acoustics, and there are fears that these safety concerns will be compounded at ultra-high main field strengths. In this work, we model the field strength dependence of gradient coils, including Lorentz damping. These results allow us to draw conclusions about the feasibility of high performance gradient coil operation at UHF strengths.

Theory: The vibrational motion of a gradient coil conductor in the static magnetic field induces an opposed eddy current, which therefore decreases the total force, leading to a form of structural damping that we refer to as "Lorentz damping". If the local displacements are small, each moving point in the solid conductor sees a constant magnetic field, and the induced eddy current density in the wire in A/m^2 is: $\vec{J}_{eddy}(\vec{r},t) = \sigma\left(\dot{\vec{u}}(\vec{r},t) \times \overrightarrow{B_0}(\vec{r})\right)$ [1], where σ is the conductivity of the wire and $\dot{u}(r,t)$ is the velocity of the wire. These eddy currents also induce a secondary Lorentz force (a counter-EMF). A section of the moving wire in the static magnetic field therefore experiences: $d\vec{F}(\vec{r},t) = d\overrightarrow{F_L}(\vec{r},t) + d\overrightarrow{F_{CL}}(\vec{r},t) = d\overrightarrow{F_L}(\vec{r},t) + l\,A\left(\vec{J}_{eddy}(\vec{r},t) \times \overrightarrow{B_0}(\vec{r})\right) = \quad d\overrightarrow{F_L}(\vec{r},t) + \sigma A\left(\left(\dot{\vec{u}}(\vec{r},t) \times \overrightarrow{B_0}(\vec{r})\right) \times \overrightarrow{B_0}(\vec{r})\right) dl$ [2] where $dF_L(r,t)$ is the incremental Lorentz Force induced by the externally applied currents in the static field B_0, dl is a scalar describing an incremental section of the conductor and A is the cross sectional area of the wire. For the case of MR gradient coils, the static B_0-field can be approximated as only having a z-component. The epoxy material can be treated as a linear elastic material. The equation of motion for an incremental section of a conductor can then be written as: $dm\,\ddot{\vec{u}}_i(\vec{r},t) + dl\,(\sigma A B_0(\vec{r})^2 + c)\dot{\vec{u}}_i(\vec{r},t) + k_i\,d\vec{u}_i(\vec{r},t) = d\vec{F}_L(\vec{r},t)$ [3] where dm is the mass of a conductor section dl, c is the damping coefficient of the material, and k is the elasticity of the surrounding material, related to the material's Young's modulus E and Poisson's ratio ν. It is clear from this equation that the Lorentz damping term depends quadratically on B_0, while the primary Lorentz force term depends only linearly on B_0. This leads to the prediction that SPLs will not linearly scale with field strength, and can in fact even decrease with field strength if the damping term becomes large enough.

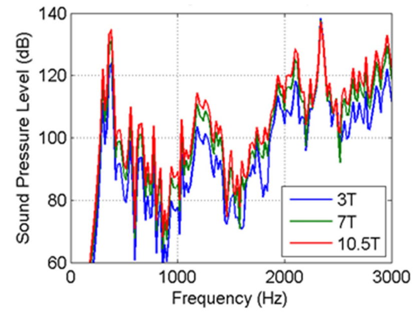

Fig. 2 SPL for four different field strengths without Lorentz damping term.

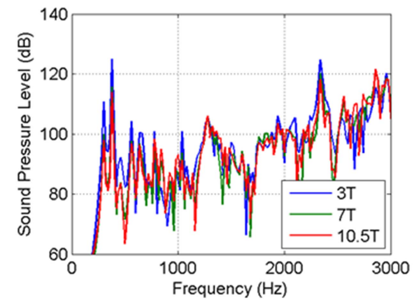

Fig. 3 SPL for four different field strengths including Lorentz damping term.

Methods: We conducted 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 high performance human brain imaging[1].The coil structure was modeled as a thick-walled short epoxy cylinder (inner/outer diameter: 338/490 mm, length: 450 mm). Accurate conductor wire patterns were embedded in the structure to ensure a correct representation of the spatial excitation distribution for the analysis. The epoxy cylinder was modeled as a linear elastic material (E = 13 GPa, density ρ = 1600 kg/m^3, ν = 0.4), whereas the air inside and outside the bore was modeled as a pressure acoustic fluid domain (speed of sound c_0 = 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 with flat bottom to represent patient table support, was modeled with hard sound 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 0-3000 Hz, which spans the frequency content of most pulse sequences. Three field strengths – 3T, 7T, and 10.5T – were modeled.

Results: Figs. 2 and 3 show the SPL spectra for the X-axis of the head gradient coil without and with the added Lorentz damping term, respectively. In the undamped case (Fig. 2), the spectrally averaged SPL values are 91.2 dB, 97.5 dB, and 100.8 dB, for 3T, 7T and 10.5T, respectively, confirming the expected linear scaling with main field strength, although some frequency points do not obey the linear relationship due to suspected structural-acoustic coupling. Fig. 3 shows the corresponding result when Lorentz damping is accounted for. Here we see that the field dependence of SPLs behaves quite differently. Spectrally averaged SPLs are 92.1 dB, 89.8 dB, and 90.5 dB for 3, 7, and 10.5 T, respectively. Simulated maximum acceleration values at 3T are > 400 g vs 85 g for undamped and damped cases, respectively. The experimentally measured value at 3T was 62 g; this is partial validation of our model conclusions, and suggests that Lorentz damping should not be neglected in vibroacoustic analysis of gradient coils.

Discussion: The amount of Lorentz damping depends on the conductor cross section as shown in Eq. [2]. The skin effect should be considered and may reduce the amount of damping, at higher frequencies. Experimental verification of these vibroacoustic field dependencies is ongoing.

Conclusion: We have presented a framework that accounts for Lorentz damping for the first time, in a comprehensive vibroacoustic gradient coil analysis, and we have used this framework to predict acoustic and vibration levels at ultra high field strengths. Overall, our analysis suggests that gradient acoustics and vibration / mechanical stress may be much more manageable at ultra high fields than previously thought.

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

Acknowledgement: Research support from NSERC, NIH (P41 EB015891 and 1 S10 RR026351-01Al) and GE Healthcare.