A FINITE-DIFFERENCE MODEL FOR THE ANALYSIS OF ACOUSTIC NOISE GENERATED BY GRADIENT COIL SWITCHING

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Introduction

A significant amount of acoustic noise can be generated during MRI data acquisition, which mainly comes from vibration of gradient coils [1]. The simulation of the process of production and propagation of the gradient switching induced noise is helpful to work toward reducing acoustic noise and design low-noise gradient coils. For this purpose, based on elastodynamics and aerodynamics theory, a force-vibration-noise model is established. Using the finite-difference method, the model accurately describes the noise variation in the cylindrical chamber. This abstract details the model development and simulation results of the acoustic problem in MRI; in addition, gradient coil design with minimized acoustic noise is also demonstrated.

Methods

Gradient switching function Gradient coils switch on and off during a scan for MRI data acquisition, subjecting them to large Lorentz forces that cause them to buckle. To model this, the trapezoidal pulse is used here as a switching function to simulate the process of coil vibration. Assuming the time interval between $t=0$ and the moment that the pulse begins to rise is t_1, the rise time is τ and the time taken from the moment that the pulse finishes rising to $t=T/2$ is t_2. Figure 1 shows an example of the switching function when $T=0.01s$, $t_1=t_2=0.002s$ and $\tau=0.001s$.

Acoustic modeling Considering deformation of gradient coils caused by Lorentz force a linear elastodynamic problem, the relation between force and deformation is able to be represented by the classic momentum equation of elastic body [2]:

$$\rho_c\left(\frac{\partial v_i}{\partial t} - f_i\right) = \sum_{j=1}^{3}\frac{\partial \sigma_{j,i}}{\partial x_i}, i = 1,2,3 \qquad [1]$$

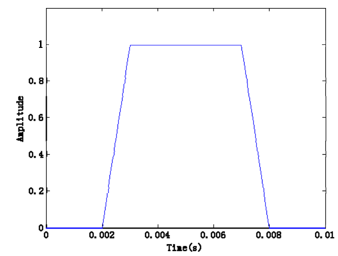


Fig. 1 Gradient switching function.

where v_i is velocity in three dimensions, f_i is the force subjected to the elastic body and $\sigma_{j,i}$ are the nine components of stress tensor. Subjecting the Lorentz force and stress tensor into [1] and simplifying the expression, we can obtain the following equation:

$$\rho_c \frac{\partial^2 u}{\partial t^2} = C\nabla^2 u + F \qquad [2]$$

where u is the coil deflection in radial direction, C is a constant determined by Young's modulus and Poisson ratio and F is a function related to the switching function. Additionally, the sound wave spread out in the air and it can be described using the sound pressure p:

$$\frac{\partial^2 p}{\partial t} = c_{air}\nabla^2 p \qquad [3]$$

where c_{air} is the isentropic sound speed. The sound wave is associated with the coil vibration by the inner wall boundary condition given by:

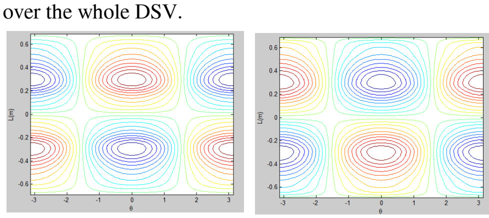
$$\frac{\partial p}{\partial r} = -\rho_{air}\frac{\partial^2 u}{\partial t^2} \quad \text{on} \quad r = R_a \qquad [4]$$

Finite difference based calculation of acoustic noise In our simulation, the current density in the coil space is discretized into mesh structures and approximated by finite difference form of stream function. The sound-related governing equations, which contain terms of second-order differential with respect to time, are also written in an explicit finite difference scheme. From the given initial condition, coil deformation and sound pressure over the simulated gradient switching period can be determined by a recursion process [3].

Gradient coils optimization for acoustic noise reduction Based on the acoustic model built in the work, the Tikhonov regularization is used for gradient coil optimization [4]. In the operation, a penalty function for sound pressure control is added to the regularization expression, and the designed gradient coils offers excellent magnetic field profiles and generates less acoustic noise.

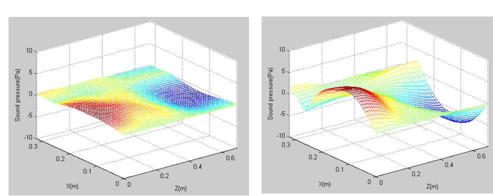
Results and discussion

The designed coils are shown in figure 2. The length of the coil L is 1.38m, the radius of primary coil is 0.32m and for shielding coil, it is 0.37m. The target area is a sphere with radius R = 0.225m. Figure 3 displays the distribution of sound pressure in the plane y = 0 at t = 2.01e-3s (left) and t = 2.50e-3s (right), presenting the propagation of the acoustic noise from the coil layer to the cylindrical chamber. It can be calculated that the average sound pressure level (SPL) at point (0.15m, 0, 0) is reduced to 77dB from 86dB after optimization. Figure 4 shows the gradient strength in the plane y = 0. It can be seen that the designed coils offer excellent linearity over the whole DSV.



(a) (b)

Fig.2 The designed cylindrical gradient coils. (a) Primary coil;(b) Shielding coil.



(a) (b)

Fig. 3 Distribution of sound pressure in the plane y = 0 at (a) t = 2.01e-3s and (b) t = 2.50e-3s.

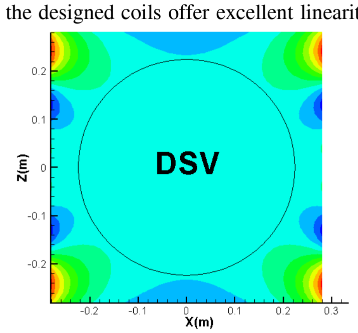


Fig. 4 The gradient field profile over the DSV. The target gradient strength G = 30mT/m.

Conclusions

We have established a finite difference model to analyze the acoustic noise generated by gradient coils in MRI. Using this acoustic model, the processes of production and propagation of acoustic noise have been simulated. With the help of this model, we have designed gradient coils with high performance and lower acoustic noise.

References

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