Acoustic Noise Suppression: Gradient Self-Help?

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Abstract

Recently, Tomasi and Ernst introduced a simple string model for understanding the vibrations of MRI gradient coils. [1] We build upon this simple foundation to provide a window into a particular method for active noise cancellation, where the pulse sequences that caused the problem may be designed to solve the problem. Previous work has focused on active and passive shielding to control eddy currents [2, 3] and on softening the gradient pulses [4]. More et al. [5] have noted that, because of the predictable harmonic behavior, the MR environment is ideal for general active noise control methods, such as earlier suggestions involving external microphone-controlled mounted plates [6] and active noise control focused on measuring and generating "anti-sound" [7]. Here, we consider the alternative possibility of augmenting the gradient pulse sequence itself to provide force/anti-force cancellations. We model the steady-state damped vibrations induced by the periodic application of one force followed by a second force. Motivated by this result, we investigate simple gradient-pulse steady-state experiments to search for sound suppression.

Theory

For a string of length L fixed at each end with tension T and mass density ρ, one can write the following expression for motion transverse to the length of the string

$$\ddot{y} = \upsilon^2 \frac{\partial^2 y}{\partial x^2} \qquad (1.1)$$

where $\upsilon = \sqrt{\frac{T}{\rho}}$. Solutions to this equation are of the form $y = A\sin(k\,x)\sin(\omega\,t)$. We can straightforwardly show that for a particular string disturbance at an initial time, a follow-up disturbance that is either a half-period later or otherwise 180^o out of phase, will completely cancel and quiet the string down for the mode of interest. For illustrative purposes consider the following steady-state problem, a one-dimensional driven damped simple harmonic oscillator can be used to model vibrational motion. The closed form solutions for such a system are easily found, and when the force is considered to be instantaneous and the time constant due to the damping small compared with the natural period of the spring resonance (that is to say, we are under-damped) the solution has the following form $x(t) \propto e^{-\frac{b|t|}{m}} \sin\left[t\sqrt{\frac{k}{m} - \left(\frac{b}{m}\right)^2}\right]$.

From this solution, a clear method for actively damping the motion of the mass presents itself. If one applies a second impulse force to the system with the same amplitude at a time corresponding to half a cycle from the initial impulse, the amplitude of the vibration is greatly reduced. The amount of the reduction is a function of only the damping coefficient b/m. When the amplitude of the second impulse is matched to account for the natural damping between the application of successive forces, it is possible to completely null the motion of the oscillator after the second pulse. Figure 1 displays a steady state result for a system driven by repeated impulse forces (blue) or a repeated drive and null pair of equal amplitude (red). While this is a simple example, it sheds a new light on the problem of designing MR pulse sequences with ancillary or reshaped gradient pulses. One may think of designing pulse sequences in which the gradient waveforms are chosen to achieve both the desired k-space coverage as well as actively damping a mode (or modes) of the gradient's vibration, much as one makes velocity or diffusion corrections.

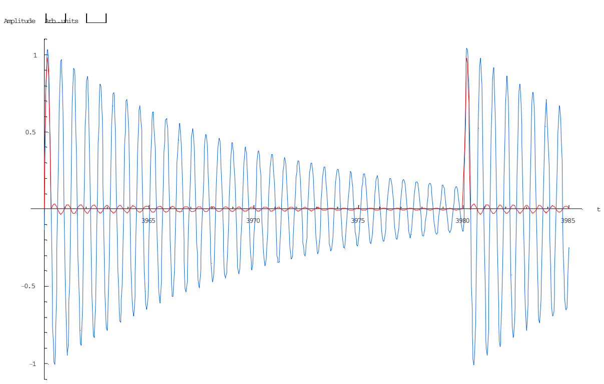

Figure 1: Steady state motion of free (blue) and actively damped (red) simple harmonic oscillator

Experimental Results

Motivated by the above simple modeling, we have investigated repeated pairs of gradient pulses for a given x, y, or z gradient (with no other RF or gradient fields present). A microphone was placed in the scanner room and its digital recording was Fourier analyzed. The scanner was a 1.5T Siemens Espree (Siemens Medical Solutions, Erlangen, Germany), and the gradient pulses had 100μs ramp-up and –down times, with a variable plateau. The separation time (TS) between the two pulses and the repeat time (TR) were variables (with range 0.1 – 10.0 ms). A first set of experiments involved trapezoids with 0.8ms plateau widths and variable heights for the second pulse (first pulse was fixed at 5 mT/m). It was easy to find cancellations of given frequencies, such as that of the first harmonic of the 1/TR frequency with the second pulse centered at TR/2 and its height equal to the negative of the first. But to better approximate the impulse modeling described previously, triangular pairs were then considered (zero plateau widths). With TR=10ms and TS varied over the TR interval, a noticeable change in the sound volume (which was confirmed by the time-series amplitudes) was heard for TS near 0.2ms and for the z-gradient. A naïve analysis would suggest the partial damping of the acoustic power pumped into the 2000-3000 Hz frequency range. No clear damping occurred for the very limited set of experiments we performed with x and y gradients, and a number of questions remain about which pulse shape and height and number are really optimal for damping. An optimized analysis for the full string model is tractable, and the above considerations make its results interesting and pertinent for an increasingly important problem, both for patient comfort and reducing signal errors in fMRI.

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