Acoustic noise reduction through pulse sequence design: timings, eddy-currents, fMRI

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Background and Methods: Guided by both spring and string ideas [1-3], we have previously investigated the manner in which sets of vibrational frequencies can be canceled by the appropriately designed gradient pulse. A picture of the cancellation of vibrations produced with a Lorentz impulsive force by an "anti-impulsive" follow-up force has emerged. This also provided a physical understanding of the oscillatory behavior observed in [4, 5] and showed the utility of studying the dominant frequencies in a string model [6] of the gradient system. The method suggests that properly designed sets of timings for the gradient pulse sequence can be used to attenuate important contributions to the acoustic spectrum. Successive convolutions of boxcars lead to a pattern of additional zeros in the frequency spectrum [3, 7]. With the appropriate timings, a boxcar can kill one frequency (and its harmonics), a trapezoid can kill two different frequencies, and the convolution of each additional boxcar with the original pulse can be used to cancel out one more frequency. The output acoustic power spectrum is $P(\omega) = |X(\omega)H(\omega)|^2$, which shows a direct relation between the output acoustic noise power spectrum and the gradient pulse spectrum.

Experimental Results and Discussion: We have analyzed in more detail the results from experiments performed on a 1.5T Siemens Espree system. Comparisons with our theoretical predictions are made for all measurements. For both scanners, acoustic noise from z gradient pulse trains with repetition time TR=10ms have been measured with a microphone placed in the scanner room and its digital recording Fourier analyzed. With variable ramp-up times t_r (the ramp-down times are always set equal to the ramp-up times) and a variable flat-top time t_{top}, the oscillations and zeros associated with the two frequencies at $1/t_r$, $1/(t_r + t_{top})$, and their harmonics are studied in more detail. Combinations of repeated trapezoidal pulses or new "quadratic" pulses obtained by convolving the trapezoid with a boxcar have been used to study further the cancellation of three fundamental frequencies and their harmonics. Additional studies are also made of pulse trains made up of a pair of trapezoids timed to cancel vibrations with three fundamental frequencies and their harmonics. Below we discuss results for the longitudinal gradient data that are representative of the success of our modeling and analysis. Corroborating results have been obtained for other gradient pulses and for transverse gradients.

The general rule for the frequencies that are nulled by a pulse made of convolutions of n individually timed boxcars is as follows. The frequencies $1/t_1$, $1/(t_1 + t_2)$, $1/(t_1 + t_2 + t_3)$, … $1/(t_1 + t_2 + \ldots + t_n)$ will be killed, where t_m is the time duration of the m^{th} boxcar. As caveats, the total time duration of the resultant pulse, which is $t_1 + t_2 + \ldots + t_n$, has to be limited. Another challenge is that the flat top of the resultant pulse, which is $\mathrm{MAX}\{0, 2\mathrm{MAX}(t_i) - \mathrm{SUM}(t_i)\}$, decreases with the number of convolutions. If data must be taken over the plateau of the read-out gradient pulse, this presents another trade-off issue.

It is important to disentangle frequency suppression due to impulse-anti-impulse cancellation from that due to a low-pass filter effect. When a boxcar gradient input excitation is used, the noise power spectrum is proportional to the square of a sinc function, which shows a general suppression of noise, especially for high-frequency components. As the width of the boxcar pulse increases, the suppression becomes more effective due to a well-known narrowing of the sinc profile. A trapezoidal gradient (the convolution of two boxcars) with fairly long ramp time reduces the noise significantly due to a "double" sinc effect in the power spectrum. A "quadratic" pulse (the convolution of three boxcars) has such severe high frequency suppression (three sinc factors in the spectrum) that its sound is spectacularly suppressed, but at the high cost of 3-4 ms pulse widths (coming from long ramp times) and short flat-top time.

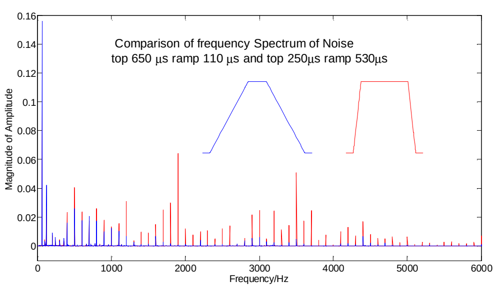

Figure 1. An illustration of both zeroing and low-pass filtering of the frequency spectra of noises with two different trapezoidal gradient pulses.

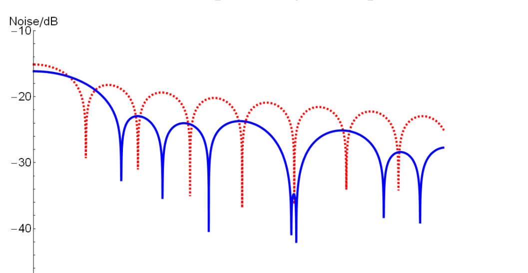

Figure 2. A comparison of simulation results of trapezoidal gradients as in Figure 1. Dash stands for red and solid for blue.

To show both zeroing and filtering, we compare two trapezoidal gradients with different ramp and flat-top time, while with the same height and area. In detail, one trapezoidal pulse is designed to kill frequency peaks at 1300 Hz and 1900 Hz and their harmonics, while the other one is just the regular one with short ramp-up and ramp-down time. Figure 1 shows the experimental comparison of the noise frequency spectra of them. The blue spectrum is the result of the zeroing of frequencies at 1300 Hz and 1900 Hz and their harmonics, as well as the suppression of frequencies above 2000 Hz. The red spectrum shows the zeroing of 1300 Hz and its harmonics, but much less higher-frequency suppression. There is a marked noise reduction between the regular and specially designed gradients. The noise difference was measured with a dB meter and is found to be relatively independent of the overall sound volume. The average difference was (9.2 ± 1.5) dB for four measurements. The measurements differed by changing the overall sound volume, and the volume change was such that the louder (quieter) sound ranged from 65 to 87 dB (57 to 78 dB). This is consistent with an estimated reduction of 7.5 dB based on a formula for the overall SPL (sound pressure level) over a series of peaks given in [8]. Figure 2 compares the dB levels found in simulation for the above two trapezoidal gradients (the overall scale is arbitrary). The color scheme follows Figure 1.

As a separate suppression mechanism, a "quadratic" pulse has such severe low-pass frequency suppression (three sinc factors in $X(\omega)$) that its sound is spectacularly suppressed for an additional 9.7 dB decrease, compared to the best of the trapezoid examples, but at the high cost of 3-4 ms pulse widths (coming from long ramp times) and short flat-top time.

Eddy-current-induced vibrations of cryostat inner bore and rf body coils are very important sources of acoustic noise [9]. We have found oscillatory behavior for the amplitudes for representative frequency peaks over the range of 300 Hz up to 5000 Hz. In a comparison with the extensive pathway discussion in [9], where, in particular, the main gradient sound source was eliminated through the use of a vacuum system, we have determined that all sources of the Lorentz-force-induced noise can be addressed with the pulse sequence cancellation mechanism discussed in this paper.

The interference of acoustic noise with fMRI experiments is especially of concern in probing auditory pathways and language in general. Since the dominant acoustic noise peaks are located in the range of tested audible frequencies between 1000 Hz and 2000Hz, the main scanner peaks have a corruptive influence on fMRI conclusions. Since our optimized pulse sequence cancellation mechanism is particularly effective in suppressing a given peak, we suggest that this may be an effective tool in reducing the effects of MR scanner noise on, for example, the auditory cortex activity studies in fMRI [10].

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