# Experimental Reduction of Acoustic Noise Through Cancellation of Impulsive Forces

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**Background and Motivation** A simple spring model has been used previously [1] to motivate and demonstrate an MRI acoustic noise cancellation mechanism that utilizes modifications of the gradient pulse sequence. The general idea is to create a follow-up impulsive force to cancel the vibration set up by an initial impulsive force. A more realistic model for impulsive forces is the forced damped vibrating string, which provides a physical basis for the experimental suppression of certain frequencies through the optimized variation of the length of a trapezoidal pulse (this experimental suppression has been noticed previously in [2]), and which is an embodiment of a general linear response description for the experiment (the relevance to a time-stationary linear system has been noted in [3]). The string model has been suggested previously [4] to describe the dominant frequency for the longitudinal and transverse gradient vibrational modes. Since the gradient vibrational frequency spectrum (i.e., the gradient frequency response function) is rich and broad with a number of important frequency peaks, the important question is the degree to which a sufficient number of these peaks can be suppressed so as to lead to noticeably less noise for the MRI patient.

**Methods and Model Guidelines** Using the forced damped string model as a guide, successive convolutions of boxcars are seen to lead to a pattern of additional zeros in the frequency spectrum. The pattern corresponds to the interference between the respective force impulses associated with turning the gradient on and off. 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. A different route that is verified by the modeling is to add a follow-up pulse whose ramp-up and ramp-down force impulses cancel the respective vibrations caused by the first gradient trapezoidal pulse. A pair of pulses can be added to this first pair to kill another frequency, and two more pairs can be added to these two pairs for yet another frequency zero, etc. Finally, to better understand the frequency spectrum, note that the output response y(t) of a linear time-invariant system to an arbitrary input excitation function x(t) is the convolution of x(t) with the system's impulse response function h(t): $y(t)=x(t)*h(t)$. The power spectrum is therefore $P(\omega) = |X(\omega)H(\omega)|^2$ in terms of the respective Fourier transforms. This shows a direct relation between the output acoustic noise power spectrum and the gradient pulse spectrum, and is useful for understanding and predicting the related experimental results.

**Experimental Results and Discussion** Through a variety of experiments we have been able to confirm the predicted cancellation of frequency peaks for all of the above pulse sequence configurations. We have also been able to observe the interplay between the excitation and response functions. The acoustic noise from x, y, or z gradient pulse trains with repeated time TR=10ms have been measured with a microphone placed in the scanner room (1.5T Siemens Espree, Erlangen, Germany) and its digital recording was Fourier analyzed. With variable ramp-up and equal ramp-down times Tra and a variable plateau Ttop, single trapezoid pulses have led to the expected oscillations and zeros associated with the two frequencies at 1/Tra, 1/(Tra + Ttop), and their harmonics. Combinations of repeated trapezoid pulses or new "quadratic" pulses obtained by convolving the trapezoid with a boxcar were also shown to be tunable so as to cancel three fundamental frequencies and their harmonics. Alternatively, a pulse train made up of a pair of trapezoids can be timed to cancel vibrations with three fundamental frequencies and their harmonics.

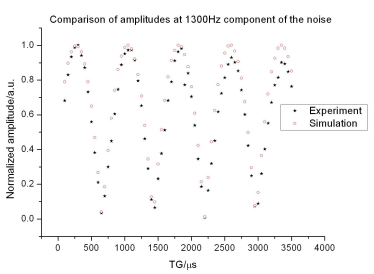


Fig. 1 Comparison of amplitudes at 1300Hz of noise for experiment results and simulation data.

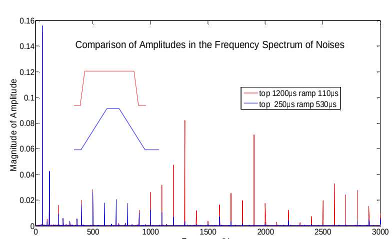


Fig. 2 Frequency spectrum of a trapezoidal gradient pulse with 530 μs ramp time and 250 μs plateau duration, while the insert picture shows their respective pulse shapes.

The main scanner resonance frequencies for longitudinal operation are found to be 1300Hz and 1900 Hz. To illustrate the effectiveness of the string simulation, consider the 1300Hz peak and a single trapezoidal pulse with variable flat-top time TG. In Fig. 1, we compare the simulation result $A=|\mathrm{Sin}(2\pi(TG+\tau)/T_0)|$ with TG = 1537μs and τ=109μs with the experiment data, for which TG = 1546μs and τ=110μs. The excellent fit (and the good agreement between 1/TG and 1300Hz) is within 1%, which also characterizes the size of the errors. In particular, we have the expected periodic zeroing of the peak and good agreement between the time shift τ and the ramp time, and agreement with the power spectrum formula proportional to (the square of) $\sin(\omega\tau/2)\sin(\omega(TG+\tau)/2)X(\omega)$. In all, the experiment results and their Fourier analysis are in excellent accord with the string model simulation. Finally, Fig. 2 shows the comparison of the amplitudes of two frequency spectra for different gradient pulse sequences. The red plot stands for the trapezoid gradient pulse with ramp time TG=110 μs and the flat top time τ=1200 μs, which is a typical value. The blue plot corresponds to TG=530 μs and τ=250 μs, showing the zeroing out of two clusters (discretized peaks) and one harmonic cluster. A significant reduction of the three acoustic peaks, 1300Hz, 1900Hz and 2600Hz, has been achieved.

What about acoustic noise suppression? Whether we refer to reduction in terms of dB (typically about 30-40dB per peak), or to the verdict of a listener, a marked reduction in sound can be achieved when at least three frequency peaks have been suppressed. (For a finite cycle repeat time TR, each peak is broken up into a cluster with frequency bins of 1/TR.) 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, but at the high cost of 3-4 ms pulse widths (coming from long ramp times). The utilization of multiple pulses for the cancellation of three or more frequencies can lead not only to long-time sequences but also other, new time scales can emerge and enhance other frequencies in the output response spectrum. Nevertheless, a rich variety of possibilities in pulse sequence design, including the TR freedom, may lead to an optimized solution for the significant suppression of MRI acoustic noise within the constraint of imaging sequences.

**References** [1] T. P. Eagan et al., ISMRM 15, 1101, (2007). [2] Y. Wu et al., MRM 44: 532-536 (2000). [3] A. Barnett, MRM 46: 207 (2001). [4] D. Tomasi and T. Ernst, Brazilian J. of Phys, 2006. **36**(1A): 34-39.