Optimized MRI gradient waveforms for Acoustic Noise Reduction

M. Segbers[1], C. V. Rizzo S. [1], H. Duifhuis[1], and H. Hoogduin[1]

[1]University Medical Center Groningen, University of Groningen, Groningen, Netherlands

Introduction

An unwanted side effect of MRI is the production of uncomfortable and sometimes harmful levels of noise. The noise levels can easily reach values above 100 dB sound pressure level (SPL) and are a result of the (fast) switching of the gradient coils. The changing currents in the coil together with the static B-field lead to Lorentz forces which produce vibrations of the gradient coil. Hedeen et al. [1] showed that the relation between the applied pulse sequence and the produced sound can be modelled as a linear time invariant (LTI) model with gradient current as input and produced sound as output. The transfer function (H) relates the gradient input currents to the produced sound and was measured by Hedeen et al. [1] using trapezoids with 1 ms duration and 0.1 ms rise and fall times.

Here we present a similar approach but using a step like change in gradient strength (from 0 to 10 mT/m in 0.1 ms) to determine the acoustic response of a 3T MR-system. In addition, we show how a trapezoidal gradient pulse can be optimized such that a particular resonance frequency of the gradient coil is inherently damped by the gradient waveform itself.

Methods & Results

All measurements were performed on a 3T Philips scanner equipped with a dual Quasar gradient coil. The sound was recorded at the isocenter of the scanner with a Bruel Kjaer condenser microphone (4190), mounted on a non magnetic support, connected to a B&K sound analyzer (2260) through the appropriate preamplifier and a 10 m long extension cable. Acquisition of the scanner gradient current monitor signal and of the microphone signal took place via a 16 bits DAC board (National Instruments 6052E). All analog signals were low-pass filtered before acquisition at a 100 kHz sampling rate.

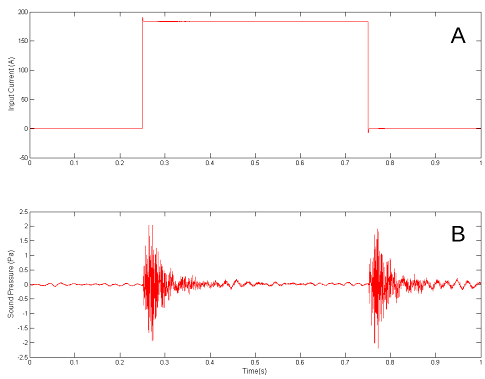

Figure 1: Trapezoidal input waveform (A) and acoustic response (B)

A series of trapezoidal waveforms (0.1 ms rise and fall times with a 500 ms plateau of 10 mT/m) was presented every 0.7 s for 18 seconds (Figure 1*)* to each gradient axis separately. The 24 acoustic responses to the trapezoidal waveform were averaged after applying a high-pass butterworth filter (cutoff frequency 5 Hz). Figure 1 shows that the responses are clearly separated and limited to the blocks rising and falling edges (i.e., in first approximation positive and negative step responses). Figure 2A shows the calculated transfer function for the X-gradient using the Fourier transform (FT) of the derivative of the current as input and the FT of the produced sound as output. The main resonance frequencies are at 617, 1070 and 1281 Hz for the X-gradient, 618 and 968 Hz for the Y-gradient (transfer function not shown) and 1336 and 1576 Hz for the Z-gradient (transfer function not shown).

We noticed (not shown here) that the responses to the rising and falling edges were almost identical apart from having an opposite phase. This observation was exploited to design gradient waveforms that inherently damp certain resonance frequencies of the gradient coil. By appropriately timing the falling edge, a particular resonance frequency can be damped because it is excited out of phase with respect to the rising edge. Or to be more precise: Each trapezoid can be constructed as a convolution of two block pulses. Furthermore, the FT of a block pulse (of width L) is a sinc function with its first zero at $f=1/L$ in the frequency domain. Because a convolution in the time domain translates to a product in the frequency domain under an FT, each trapezoid inherently damps two frequencies. Or the other way around: By appropriately determining the width of two block pulses, a trapezoidal waveform can be constructed that damps two resonances of the gradient coil. This is illustrated in figure 2B where we show the acoustic response of the X-gradient to a trapezoidal gradient waveform that was constructed by the convolution of blocks with width $L1=1/1070=0.93$ ms and $L2=1/617=1.6$ ms. As can be seen in the figure the two main resonances at 617 and 1070 Hz are clearly damped. The third resonance at 1281 Hz is also suppressed because it is close to the first harmonic of the resonance at 617 Hz.

In addition, figure 2C and D show the responses to a trapezoidal and triangular waveform with equal duration and gradient area but having maximum and minimum slew rate, respectively. The measured SPL for the three waveforms was 76.0, 85.5 and 78,9 dB for optimized convolution, trapezoidal and triangular pulse, respectively.

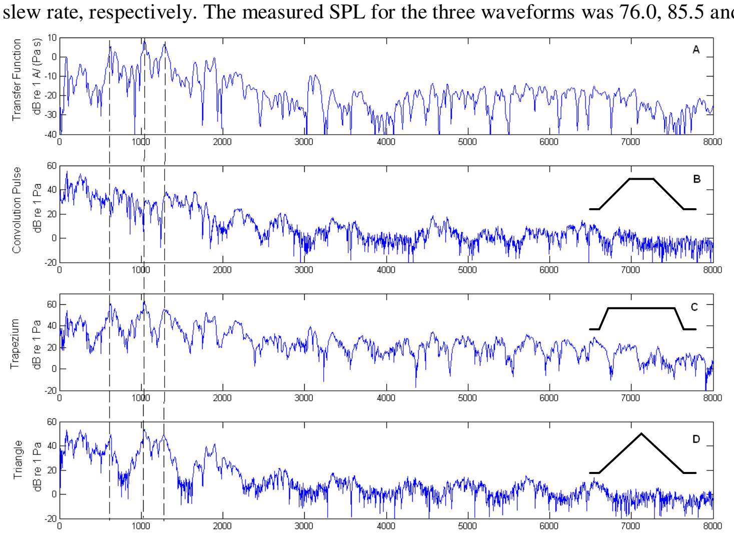

Figure 2: Transfer function for the X-gradient (A) and acoustic responses to the optimized convolution pulse (B) trapezium with maximum slew rate (C) and triangle with minimum slew rate (D). The area under the envelope and the length of the gradient pulses were kept constant.

Discussion

In addition to the existing literature [2], [3] on 'silent' gradient waveforms, we provide a theoretical framework that allows designing gradient pulses that inherently damp certain resonance frequencies. The optimal trapezoidal pulse reduced the SPL by 9 dB compared to a trapezoidal with maximum slew rate, equal area and identical length. A drawback of the proposed convolution pulse is that the timing and length (2.5 ms) are completely fixed by the resonance frequencies of the gradient coil. Ideally, in future coil design the resonance frequencies should be matched to the maximum gradient performance using the proposed method.

Finally, we like to note that in contrast to the work of Hedeen et al. [1] we calculated the transfer function using the derivative of the current as input instead of the current itself. Although mathematically this only leads to an additional 1/f factor in the transfer function it also reflects more clearly the fact that it is the change in current that produces the sound. In addition, it leads to a transfer function that falls off as at least 1/f. The latter is to be expected for a realizable physical system because a flat spectrum corresponds to an unlimited amount of energy in the system.

In the future we hope to extend the work on 'silent' gradient waveforms from single pulses to EPI like readout trains.

References

[1] R. Hedeen and W. Edelstein, "Characterization and prediction of gradient acoustic noise in MR imagers," Magn. Reson. Med., vol. 37, pp. 7-10, 1997.

[2] F. Hennel, F. Girard and T. Loenneker, "'Silent' MRI With Soft Gradient Pulses", Magn. Reson. Med., vol 42, pp 6-10, 1999.

[3] T.P. Eagan, T. N. Baig , J. Derekshan, J. L.Duerk and R.W. Brown, "Acoustic Noise Suppression: Gradient Self-Help?", ISMRM 2007.