Simple Method for MR Gradient System Characterization

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Introduction: One issue with fast MR imaging, particularly with non-Cartesian trajectories, is the deviation of the actual *k*-space trajectories from the ideal trajectories due to system imperfections such as eddy currents, timing errors and amplifier nonlinearities. Without correcting for these effects, artifacts such as ghosting, signal modulation and geometric distortions can occur. One solution to this problem is to measure and use the actual trajectory for image reconstruction. However, to measure every trajectory would be a time consuming process. A more time efficient solution is to characterize the gradient system once, and use the system model to estimate the actual trajectory achieved on the scanner for any trajectory. In this work, we use a single impulse-like gradient waveform to characterize the system. This method is significantly more time efficient than previous work, which required the acquisition of sinusoids of multiple frequencies[3,5].

Theory: The MRI scanner's slew rate limit, prevents generating a perfect impulse waveform on the system to directly measure the impulse response. In general, sinc, Gaussian and triangle functions are used as approximations to an impulse function. We chose a triangle function as the test waveform, because for a given slew rate, it can achieve the largest bandwidth. Gurney[2] has developed a gradient measurement method, based on work by Duyn et al.[1]. By slice selecting and reading out in the same axis, the gradient waveform can be calculated from the acquisition signal phase of two or more slices. To achieve higher SNR, multiple acquisitions are performed at each slice for both positive and negative polarities of the gradient waveform. This allows the signal phase of eddy current effects from B_0 to be separated from the phase from the applied gradient waveform. The gradient is calculated by taking each acquired signal's angular derivative and using a weighted-least-squares estimation. Acquisitions of gradient waveforms for trajectories extending far in *k*-space are likely to have segments of low signal which produces noise in the signal phase. Techniques[3-5] exist to begin acquisition off isocenter to provide reliable signal phase for such trajectories. For a given waveform, modeling the acquisition process as an LTI system, the system response can be calculated as $H_{sys}(f) = F\{G_{measured}(t)\}/F\{G_{theoretical}(t)\}$, where *F{}* is the Fourier transform operator and *G(t)* is the gradient waveform. The nulls in the Fourier Transform of the triangle function lead to very large values in actual implementation of this operation. This can be mitigated with the use of a low pass filter.

Method: Experiments were run on a 1.5T GE Signa Excite Scanner with CRM gradients. (40mT/m, 150 mT/m/ms). A triangle function with a pulse width of 72 μs and max amplitude of 5 mT/m was used to characterize the system. To analyze the effect of triangle function parameters on the system response, triangle functions with pulse widths ranging from 50 to 450 μs, and gradient amplitudes 2.5 to 35 mT/m were used. Aside from bandwidth differences, consistency could be seen over a range of pulse widths and amplitudes for triangle waveforms operating near the max slew rate. To test our method, we compared 3 spiral gradient waveforms estimated by the system response with their corresponding measured and theoretical waveforms. Design parameters for the 3 trajectories respectively were; 8, 16 and 24 interleaves; FOV = 24, 20, 15 cm; max gradient amplitude = 24.5, 29.5, 32.5 mT/m; resolution = 1.5, 1, 1.5 mm. For each spiral sequence a 140 T/m/s max slew rate was used. The different spirals were chosen to observe the ability to estimate for gradient waveforms contains different ranges of frequencies. For the chosen sequences, those ranges were, 500 to 3,800Hz, 340 to 2,600Hz and 800 to 1,800Hz. Gradients were measured by a GRE based sequence, performing slice selection and readout in the same directions. Parameters for the sequence were, TE = 5ms, TR = 200ms, 4 slice locations ±3 and ±1 cm, 32 averages/slice, receiver bandwidth = ±125kHz and scan time = 93 sec. A Hamming windowed low pass filter with a cutoff frequency of 20kHz was used to reduce spikes in the frequency domain resulting from the nulls.

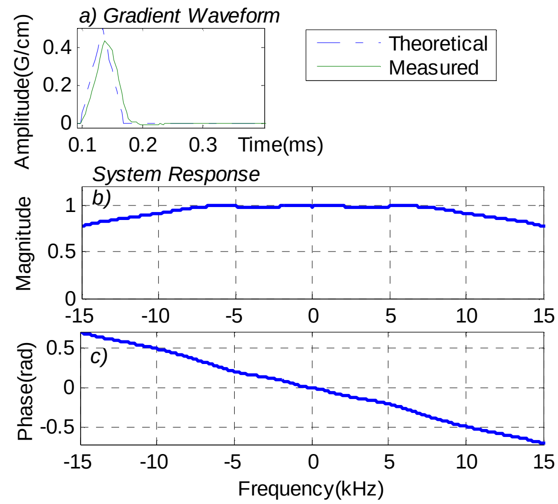
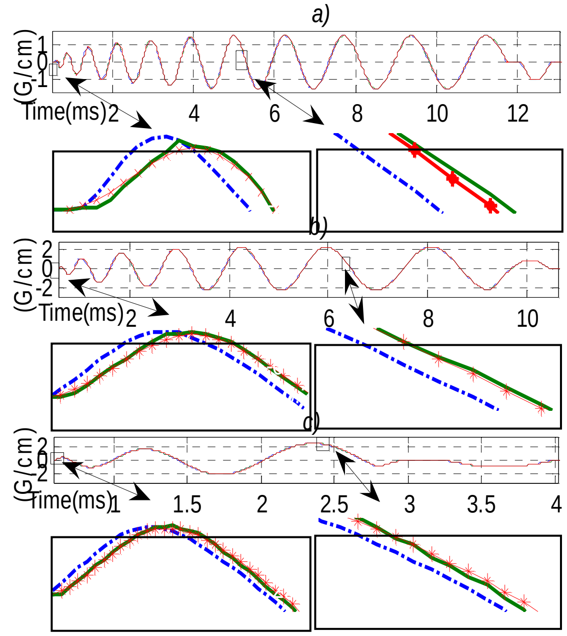


Figure 1: a) Measured and theoretical triangle gradient waveforms. b) Magnitude Response. c) Phase response.



Legend: - - Theoretical – Measured -+- Estimated

Figure 2: a) 8 interleaves, 24cm FOV, 24.5mT/m amplitude, 1.5 mm res b) 16 interleaves, 20 cm FOV, 29.5 mT/m amplitude, 1 mm res. c) 24 interleaves, 15 cm FOV, 32.5 mT/m amplitude, 1.5 mm

Results/Discussion: The first step of our method is measuring a triangle waveform. This is shown in Fig. 1a, where the delay between the theoretical and measured waveform can be seen. Figures 1b and 1c show the system magnitude and phase response based on the triangle waveform. The magnitude response is flat up to about 6kHz, and the phase response is roughly linear. Figure 2 shows the x-axis gradient waveform for each spiral sequence along with zoomed plots at two time locations, showing the theoretical, measured and system model estimated waveforms. The improvement in tracking of the estimated waveform over the theoretical wave form can clearly be seen in the zoomed in plots. The first zoomed in plot is taken at the start of the acquisition and the second partway through the acquisition. Both show the close tracking of the estimated waveform.

References: [1] Duyn et al, JMR, 132:150-153, 1998. [2] Gurney, PhD Thesis, Stanford University, 2007. [3] Kerr, PhD Thesis, Stanford University, 1998 [4] Beaumont et al, MRM 58:200-205, 2007.[5] Cheng et al, ISMRM, 1155, 2008.