Gradient Waveform Pre-Equalization using the Magnetic Field Gradient Waveform Monitor Method

Introduction: The accuracy of applied magnetic field gradients in magnetic resonance imaging directly impacts the corresponding image quality and measurements of molecular motion. Magnetic field gradient distortions result from the generation of eddy currents within the magnet structure and from distortion of the magnetic field gradient coil excitation current due to gradient current amplifier limitations (such bandwidth and stability). The gradient coils provide a reactive load to the gradient current amplifiers which fundamentally limit the minimum excitation current rise and fall times which further distort the applied magnetic field gradient.

Performance improvements through the use of gradient pre-emphasis through fixed time-constant exponential functions being added to the gradient amplifier current excitation waveform have been discussed in [1 - 3] and the methods used to identify the corresponding amplitudes and time-constants tends to be tedious and time-consuming [3] despite common efforts to correct for gradient waveform infidelity through data post processing at the image reconstruction stage. Adjustments to the gradient waveforms as described here are still common for research systems.

A method has been developed that utilizes the magnetic field gradient waveform monitor (MFGM) method [4] to measure the magnetic field gradient waveform and determine a pre-equalized gradient amplifier current excitation waveform such that an optimal approximation of the desired / ideal magnetic field gradient results. Pre-equalization techniques are commonly employed in communications systems for similar reasons. The entire process for a given waveform (for one gradient axis) can be typically completed within tens of minutes. Several iterations may be required such that the pre-equalized gradient amplifier current excitation waveform converges to the optimal waveform.

Methods: The MFGM method is used to measure the magnetic field gradient waveform which corresponds to a defined magnetic field gradient waveform [4] and uses the pulse sequence shown in Fig. 1. The measured gradient waveform is compared to the desired waveform and a pre-equalized waveform that compensates for system distortions is calculated using MATLAB®. The pre-equalized waveform is then used as the gradient current excitation waveform for the following measurement. The MFGM method is used to measure the resulting magnetic field gradient waveform performance. This procedure is repeated until the desired response is observed and/or the fundamental limits of the system have been obtained.

Using MATLAB®, the measured magnetic field gradient waveform is time synchronized to the desired gradient waveform. The difference between the measured and ideal waveforms is then calculated. The pre-equalized waveform is then calculated based on the linear combination of the ideal waveform and half of the difference (between the measured and ideal waveforms). This pre-equalized waveform is then used as the gradient waveform excitation current for the following measurement.

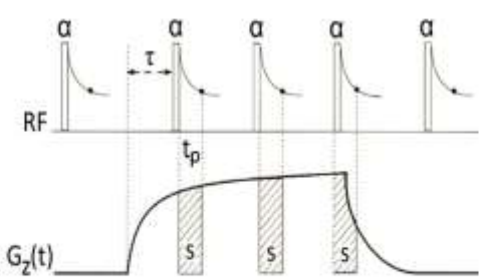

Fig. 1: MFGM pulse sequence.

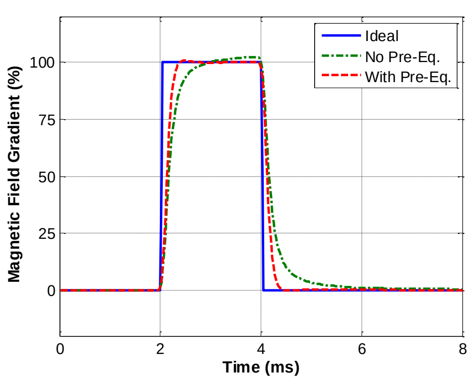

Fig. 2: Ideal and measured magnetic field gradient waveforms before and after excitation current pre-equalization.

Results and Discussion: Experiments conducted on an Oxford Instruments Maran DRX HF 8.5 MHz system have validated the basic concept.. Optimal waveforms for magnetic field gradients applied along both the transverse and longitudinal planes have been determined within 1 and 4 iterations, respectively. The corresponding time frames were approximately 15 minutes for the former and 40 minutes for the latter case. Measured magnetic field gradient waveforms before and after pre-equalization are shown in Fig. 2. The results were obtained after a single iteration and the magnetic field gradient rise time constant was reduced from 170 µs to 70 µs. A custom 14-turn solenoid was used as the magnetic field gradient probe with a 685 mMol $GdCl_3$ sample. The probe and sample were located approximately (1 cm, 1 cm, 1 cm) as referenced in Cartesian coordinates from the gradient isocenter. The OEM solenoidal probe and shield were present during the measurement and the probe's RF shield and magnet pole pieces provided sources of eddy currents that were corrected.

Conclusion: The challenges of low-field permanent magnet systems differ from those encountered in the higher-field systems used in clinical applications. However, the methods used to characterize the distortions of the magnetic field can also be used to correct k-space misregistration due to magnetic field gradient distortions in a post-processing environment. The knowledge of the magnetic field gradient performance can also be used in a guided-pre emphasis setting exercise where the amplitudes and time-constants of the exponential pre-emphasis functions can be determined and set based on the measured magnetic field gradient performance and optimized through the observation of the magnetic field gradient. These methods also lead themselves to more sophisticated techniques in order to determine the strategy used to determine the pre-equalization waveform.

References [1] C.V. Dodd et al. J. Appl. Phys., 39 (6) (1968) 2829-2838. [2] J.J. van Vaals et al. J. Magn. Reson., 90 (1990) 52-70. [3] H.M. Gach et al. Magn. Reson. Med., 40 (1998) 427-431. [4] H. Han et al. J. Magn. Reson., 201, (2009) 212-217.