

Eddy-Current-Compensated RF Pulse Design for Parallel Excitation

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Introduction: High-performance RF coils and shielded Gradient coils [1] for high or ultra high field MRI often require the use of RF shields that are in close proximity to the imaged volume. These shields can sometimes generate Eddy-Currents that are not adequately compensated for using the pre-emphasis algorithm [2] of the scanner. K-space trajectory measurements [3] can be used to compensate for such Eddy-Currents but they require time-consuming calibrations that are not suited for parallel transmit (PTX) RF pulse design. The Eddy-Current distortions induced by the RF coil's shield are heavily dependent on the excitation trajectory and can sometimes severely compromise the practical implementation of highly desirable excitation patterns. In this work, we present a method to produce RF-coil-induced Eddy-current-compensated RF pulse design in PTX. The approach is demonstrated with both simulated and experimental data at 7T.

Methods:

Theory: Various mathematical techniques have been proposed for calculating the characteristic time constants and amplitudes for multi-exponential decay from eddy current field measurements [6-7]. The proposed method relies on such multi-exponential fitting of the eddy current fields in order to produce a model of the expected distortion in the magnetization profile. The mathematical model used for the gradient waveform's distortions due to the eddy currents is as follows,

$$G_{\text{distort}} = -\frac{dG_{\text{ideal}}}{dt} \otimes E(t) \quad (1)$$

$$E(t) = H(t) \sum_n \alpha_n e^{-t/\tau_n} \quad (2)$$

where, H(t) is the unit step function, \otimes denotes the convolution and, to simplify the investigation, we only incorporated first order effects into the model.

Once the model parameters for the eddy currents are known (from experimental measurements), the k-space trajectories can be pre-emphasized and used together with the small tip angle method [5] to generate the required PTX RF pulses. These are solved for using [5]:

$$M_{xy} = i\gamma M_0 \sum_{r=1}^R S_r(x_i) \int_0^T B_{1,r}(t) e^{i2\pi k(t) \cdot x} dt \quad (3)$$

where M_{xy} denotes the transverse magnetization, B_1 is the RF pulses, γ is the gyromagnetic ratio, M_0 is the equilibrium magnetization magnitude, T is the pulse length, $k(t)$ is the time-reversed integration of the gradient waveforms and S_r is the sensitivity map of the coil.

Experiments: All experiments were performed on a 7T Siemens scanner equipped with a PTX extension. A 4-channel Tx/Rx RF coil (Fig. 1) was used to drive independent RF waveforms for each Tx channel. The Eddy current fields for this coil were measured using a small sample and a pulse and collect FID sequence preceded by a short gradient pulse. The B_1 map (128x128 matrix) for each transmit channel was obtained sequentially using a 2D GRE sequence with varying excitation voltage (12.5V to 150V, 12 steps). The RF design was implemented in MATLAB R2009a (Mathworks, Natick, MA, USA). The desired excitation pattern was a smoothed rectangle with a 20cm FOV and 0.3125cm resolution. A spiral trajectory design with maximum gradient amplitude 24mT/m, and slew rate of 120mT/m/s was used. Comparisons of distorted and compensated patterns for both simulations and experiments were examined with regularization parameters (β) of 10 and flip angle of 5° over a range of speedup factors (R).

Results and Discussion: Figure 1 shows the 4-channel Tx/Rx RF coil used for our experiments. Figure 2 shows a comparison of the distorted and compensated gradients. Figure 3 presents the distorted and compensated k-space for the RF design. After compensation, the k-space trajectory is much more symmetrical and passes the k-space center. Figure 4 shows the comparison of distorted and compensated excitation patterns over a range of speedup factors for simulations and experiments, respectively. The excitation patterns are obviously tilted by the eddy current fields and are significantly improved after compensation. As the speedup factor is increased, the distortion increases due to a larger mismatch between the prescribed and actual gradient waveforms. Because we only incorporate the primary eddy current terms, there are still remnant artifacts in both the simulated and experimental results. These could be further reduced if a more complex eddy current model is used.

Conclusion: We have presented an effective method for eddy-current-compensated PTX RF pulse design, and demonstrated its ability to improve excitation accuracy. Our proposed compensation method is simple to implement and effective leads to much improved excitation accuracy.

Reference: [1] P. Mansfield et al., J Phys E19:L129, 1986. [2] R. Wysong, et al., MRM 31:572-575 1994. [3] A. Takahashi et al., MRM 34:446-456, 1995. [4] I. Atkinson et al., MRM 62: 532-537, 2009. [5] W. Grissom et al., MRM 56:620-629.2006. [6] Van Vaals et al, JMR 90:52-70, 1990. [7] P. Jehenson et al, JMR 90: 264-278, 1990.

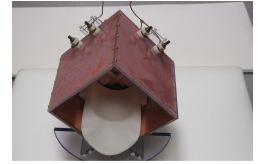


Figure 1: 4-channel Tx/Rx RF coil.

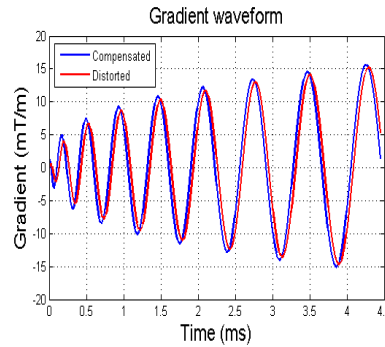


Figure 2: Comparison of distorted and compensated gradient waveforms for R=2 (only real component is shown).

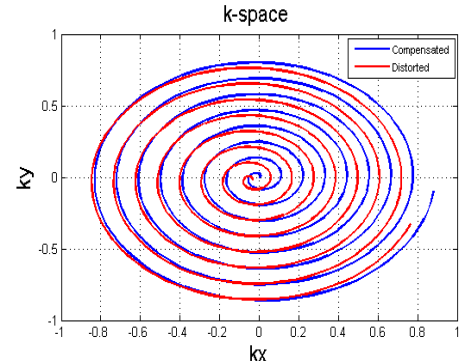


Figure 3: Comparison of distorted and compensated k-space trajectories for R=2.

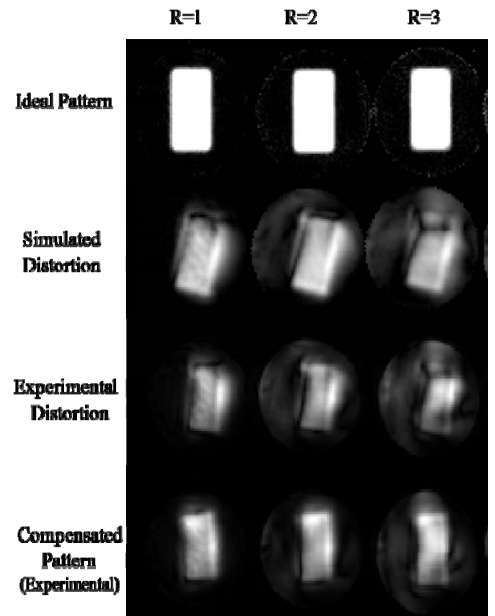


Figure 4: Comparison of distorted and compensated excitation patterns over a range of speedup factors.