A Method to Correct Linear Eddy Currents by K-space Trajectory Estimation

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Introduction: Linear eddy currents distort desired k-space sampling trajectories, and thus cause significant artifacts and distortions in MR images. Duyn has proposed a method to measure actual k-space trajectories of spiral and EPI sequences [1]. However Duyn's method cannot be directly applied with some sequences, such as fast spin-echo (FSE) sequence and SSFP sequence with Cartesian sampling. We present an alternative method to correct linear eddy currents by estimating actual trajectories. Initial experiments with FSE sequence have shown the efficacy of the method.

Materials and Methods: Assume that linear eddy $\bar{g}(t)$ is generated by a linear system with gradient field $\bar{G}(t)$ as the input as $e_g(t)$ as the step response of the system. $e_g(t)$ can be molded by a sum of decaying exponential functions [2]:

$$e_g(t) = \sum_n \alpha_n e^{-t/\tau_n} \quad (1)$$

According the theory of linear system, once given eddy-current parameters: α_n and τ_n, eddy currents produced by arbitrary sequences can be calculated by

$$g(t) = -(dG(t)/dt) \otimes e_g(t) \quad (2)$$

where "$\otimes$" denotes convolution. A simulator is built to calculate linear eddy currents distorted k-space trajectories using the algorithm. To correct linear eddy currents, the gridding method is selected to reconstruct image using computed k-space sampling trajectories.

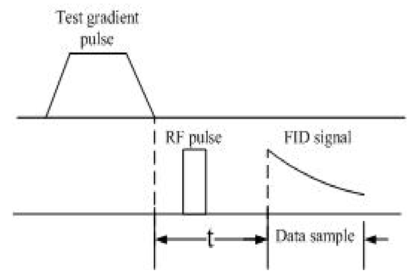

Figure 1 eddy-current measurement sequence

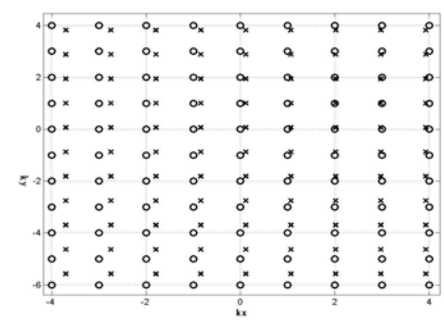

Figure2 ideal (o) vs. estimated (x) k-space sampling

Parameters of eddy currents are very important to accurately estimate actual k-space trajectories. We have developed an image-target optimization process to automatically obtain best eddy currents parameters. An objective function is designed to quantitatively evaluate image qualities. The objective function mainly contains two aspects: 1) distortions are evaluated by measuring the difference between the geometric size of the calibration image and the actual size of the phantom; 2) artifacts are evaluated by detecting and measuring edges of the image. A uniform phantom with given geometric size is first used to obtain a calibration image. Then SQP (Sequential Quadratic Programming) algorithm is selected to obtain optimal parameters to achieve best qualities of the calibration image. Eddy currents parameters are bounded into reasonable range during the optimization. Initial values of eddy currents parameters can be obtained by simple measurement using small phantom placed at two different locations with the sequence shown in Figure 1.

MR experiments were performed on a 0.3T vertical permanent open scanner. The eddy current pre-emphasis device in the gradient amplifier was disabled to produce strong distortions in actual k-space trajectories. Images of a uniform cylinder phantom and a structure phantom are acquired with FSE sequence. Acquisition parameters were: TE=70ms, TR=2500ms, ETL=4, echo center=2, FOV=25cm×50cm, 256×384 matrix size. Images were tailored into 256×256 matrix size for display.

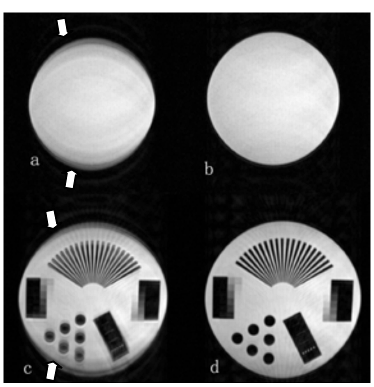

Figure 3. Phantom experiments. (a,c) with no eddy-current correction. (b,d) with eddy-current correction.

Results and discussion: Figure2 shows ideal versus estimated eddy-current distorted sampling points in k-space. Figure 3a is the calibration image without eddy-current correction. The radius of the circle is 84 pixels, while the actual radius is 88 pixels. Figure 3b is the calibration image with correction. The radius is 88 pixels demonstrating the reduction of distortions. Figure 3b also illustrates that artifacts are significantly suppressed after correction. The comparison between the image of a structure phantom without correction (Figure 3c) and that with correction (Figure 3d) further demonstrates the effectiveness of the presented method in reducing eddy-current induced artifacts. It took about one hour to obtain optimal eddy currents parameters using presented optimization process on a PC with 1.6G CPU and 512M memory. Since this optimization need only to be done once, such long computation time is tolerable. The simulator took several seconds to estimate actual k-space trajectory.

Conclusions: A method to correct linear eddy currents by estimating actual k-space sampling trajectories is presented. An optimization process is also presented to determine eddy currents parameters. Initial phantom study has demonstrated the efficacy of the method. Similar method can be applied to estimate B0 eddy currents induced phase error for the correction of B0 eddy currents.

Reference: 1. Duyn et al. JMRI, 132 150(1998). 2. Beinstein et al. "Handbook of MRI pulse sequence", Elsevier, 2004.