Measurement of Cross-Axis Gradient Eddy Currents

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Introduction: Traditionally, it has been assumed that eddy currents produced by switching a given gradient channel manifest themselves as gradient eddy currents on the same axis. However, as gradient slew-rates have increased, cross-axis eddy currents have been observed. Various methods to measure actual k-space trajectories [1,2,3,4] produced by the gradient hardware have been described in the literature. We have taken the self-encoding method, first described by Onodera et al. [1] processed the data using the Fourier transform method described by Alley et al. [4] and expanded the method to quantify the cross-axis gradient contribution.

Methods: Figure 1 depicts all the gradients and RF waveforms used to measure the k-space trajectory. Let us first assume that the Z gradient is used as a test waveform. The pulse sequence begins with a non-selective RF pulse reducing the risk of inducing eddy currents from the slice-select gradient. A self-encoding gradient pulse is then applied on the Z axis. Simultaneously, a cross-encoding gradient is applied on the X or Y-axis. After a short delay (256us) the test gradient is applied on the Z-axis. The self- and cross-encoding gradients are then rephased, the test gradient is rephased and finally, killer gradients are played to dephase the magnetization left in the transverse plane. The sequence then repeats after a prescribed delay time. Data acquisition begins after the self-encoding pulse and ends before the self-encoding rewinder gradient pulses. The self- and cross-encoding gradients are stepped in a 2D fashion resulting in a 3D (kx, kz, time) data set. When this is complete the cross-encoding axis is switched to Y and the sequence is repeated. A 10cm sphere was placed at the isocentre of the magnet and shimmed and used for these experiments.

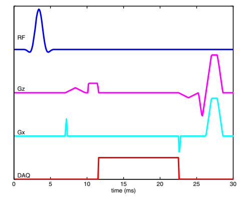

Figure 1. Pulse Sequence used to measure gradient and cross-axis eddy currents

The step size in the self-encoding dimension is set to $\Delta kz=1/(FOV)$ resulting in a phase-encoded image with an FOV slightly larger than the phantom. We chose 15cm. The algorithm to extract the on-axis k-space trajectory is exactly as described by Alley [4] In the cross-encoding dimension, the k-space deviation is expected to be a small fraction (typically less than a percent) of the on-axis dimension. To measure this smaller k-space trajectory, we chose Δkx and Δky to be 1/10 of the on-axis dimension. The number of cross-encoding steps was also reduced to sixteen to make acquisition time reasonable. The small Δkx and reduced number of cross-encodes made it impossible to process the cross-axis data using Alley's technique as the phantom was reduced to a single pixel in x or y. (Pixel size=$FOV*10/N_{self}$=10*15cm/16=9.375cm.) As described by the original self-encoding paper, the k-space trajectory can be found by locating the peak of the signal in the self-encoding dimension. With a well shimmed spherical phantom, the magnitude of the k-space data in the cross-encoding dimension is a Jinc-like function and its central part was fit with a quadratic equation. The peak of the fitted parabola was then used to determine this k-space trajectory.

Results and Discussion: The measured k-space trajectories on the X, Y and Z-axes are plotted in Figure 2. The waveform on the Z axis is the expected trajectory for a trapezoidal test gradient. The last plot on Figure 2 shows the Z-gradient waveform calculated by differentiating the measured Z k-space trajectory. The eddy current is driven by the time derivative of the gradient waveform. For a trapezoid, the driving function is a positive rect function during the up-ramp and a negative rect function during the down-ramp as seen in Figure 3. The actual eddy current is a convolution of this driving function with a small number of single-sided exponential decay terms. To demonstrate this, the cross-axis eddy current compensation was deliberately misset. The measured cross axis trajectories are plotted in Figure 4. The characteristics of the curves change as a function of the exponential term amplitude and time constant.

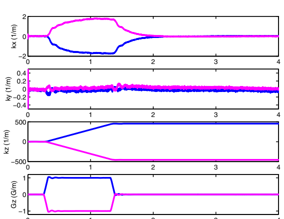

Fig 2. Measured X, Y and Z k-space trajectories. Gradient waveform at bottom is derived from measured kz waveform.

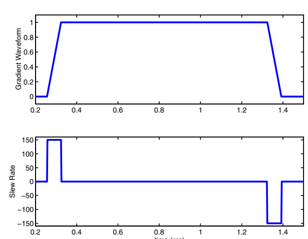

Fig 3. Gradient waveform and Slew-rate waveform. Any induced eddy currents are driven by the dB/dt waveform.

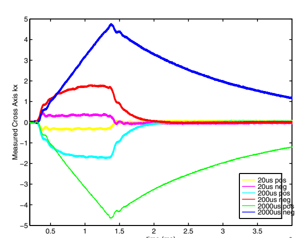

Fig.4. Measured cross-axis eddy current k-space trajectory.

Conclusion: This technique shows promise for calibrating a system to reduce or eliminate cross axis gradient eddy current distortion. However there are some limitations of the measurement technique. Generally, this technique can only be applied on a system that has already been roughly calibrated. Long term eddy currents will bias the results. Only eddy currents shorter than the T2 of the phantom can be measured. Despite these limitations, we are able to characterize the short time constant cross-axis eddy currents.

References:

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