Time Constant Sensitivity of Eddy Current Characterizing Pulse Sequence

D. B. Ennis[1], M. T. Alley[1], B. A. Hargreaves[1], N. J. Pelc[1]
[1]Department of Radiology, Stanford University, Palo Alto, CA, United States

INTRODUCTION: Eddy current compensation is important for a number of applications in magnetic resonance imaging. Eddy current induced fields impart phase on the acquired signal that can distort both magnitude images and phase estimates used to measure tissue velocities, displacements, and temperatures. Eddy current pre-emphasis provides first-order correction, but more sophisticated techniques are needed to account for a broad range of short and long time constants and spatial non-linearities. A previously described pulse sequence was designed to measure the system's eddy current response and use this to correct the eddy current induced artifacts for an arbitrary pulse sequence using an impulse-response formalism [1]. Herein, this pulse sequence was modeled with Bloch and Monte-Carlo simulation to characterize the sensitivity and bandwidth of measured time constants (τ). The ability to model, and thereby compensate for, short τ eddy currents is dependent upon a pulse sequence that can sensitively measure them.

METHODS: *Pulse Sequence*: Fig. 1 diagrams a spin-echo pulse sequence that was modified to support: 1) eddy current inducing test gradients (TG) of amplitude G_{max}, 2) a long τ eddy current nulling gradient (dummy gradient, DG), and 3) 3-D phase encoding. In order to measure phase shifts that arise from short τ eddy currents the pulse sequence was designed to acquire data (DAQ) for 62ms immediately after a large TG. The acquisition parameters were TE/TR=17/100ms, FOV=28cm, 10x10x10 encoding matrix, DAQ BW=±62.5kHz. *Simulation*: Simulated eddy current induced mono-exponential gradients were generated with $0.01\text{ms}<\tau<200\text{ms}$ and peak eddy current gradient strengths of $0.1G_{max}/\tau$ for the sequence shown in Fig. 1. Steady-state gradient fields were defined by simulating cumulative gradient effects for a duration equivalent to 15τ or two TRs, whichever was longer. Bloch simulation was used to simulate the signal response (time step=8μs, T_1=250ms, T_2=25ms) over a broad range of τ. Monte-Carlo simulation was used to demonstrate the sensitivity to quantifying the phase response of each eddy current τ. Random Gaussian noise was added to the I/Q channels based on the experimentally observed SNR which decayed from 465 to 80 during DAQ. Mono-exponential τ were estimated for 100 repeated simulations at each τ using a non-linear least squares algorithm. The time constant error was defined as the standard deviation of estimating the eddy current τ normalized by the τ and the eddy current model ($0.1G_{max}/\tau$).

RESULTS: Fig. 2 shows the phase accrual during DAQ for $10\mu\text{s}<\tau<200\text{ms}$. The pulse sequence with the DGs doesn't stimulate and is therefore insensitive to long τ eddy current effects, but is sensitive (phase accumulation $>\pi$) to $25\mu\text{s}<\tau<25\text{ms}$. The simulation also demonstrates that without the DGs long time constant ($\tau>25\text{ms}$) eddy currents generate measurable phase accumulation during the 100ms TR (data not shown). Fig. 3 demonstrates the time constant error associated with fitting the time constant of a mono-exponential function to the phase response of a gradient induced eddy-current with a single τ. Errors are lowest near τ=5ms indicating maximum sensitivity to estimating time constants of this magnitude. Estimates of the mean τ from the Monte-Carlo simulation deviated from the prescribed τ by 0.06%±0.2%.

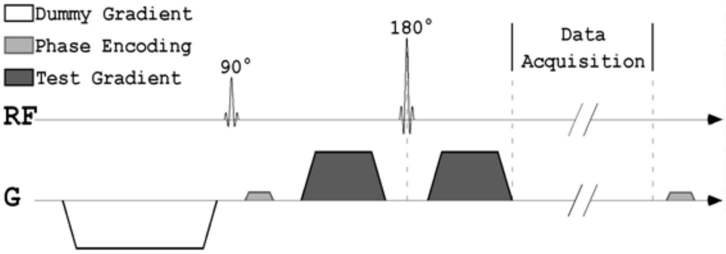

Figure 1

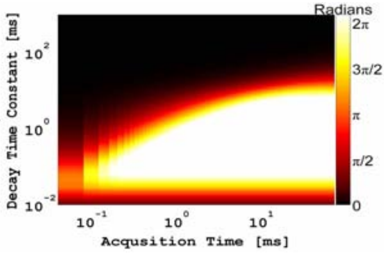

Figure 2

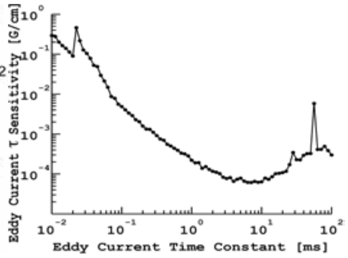

Figure 3

CONCLUSIONS: The Bloch simulation demonstrates that the pulse sequence is maximally sensitive to short τ of ~5ms, but with good sensitivity to $25\mu\text{s}<\tau<25\text{ms}$. The fact that DAQ begins immediately after a gradient slew, combined with the high SNR of the sequence and the fact that short τ effects are not sensitive to T_2 decay combine to make measurement of short τ effects possible. The Bloch and Monte-Carlo simulations show that it is judicious to limit modeling of eddy currents to $25\mu\text{s}<\tau<25\text{ms}$ when using this pulse sequence. The pulse sequence is sensitive to short τ allowing for their accurate measurement and use in eddy current compensation and correction techniques. Furthermore, the DGs impart long τ eddy-current insensitivity. TRs can be much shorter when using the DGs because long τ eddy current induced phase shifts are minimized rather than the alternative of waiting for them to decay.

REFERENCE: [1] Alley MT, *et al*, Proc. Intl. Soc. Mag. Reson. Med., Toronto, Ontario, Canada, 2003

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