Design and Implementation of a Z0 Vibration Compensation Unit

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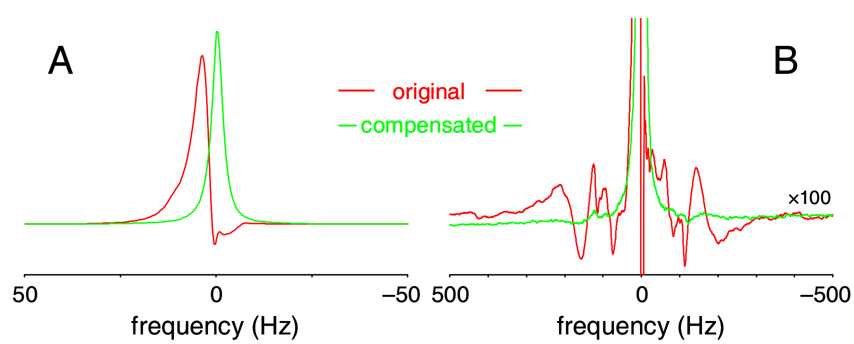
Introduction – It is well known that pulsed gradients induce eddy currents in nearby conducting structures, like the magnet cryostat, which lead to artifacts in MRS and MRI. In addition, the Lorentz forces acting on the gradient coil windings lead to a damped oscillation of the main magnetic field, which ultimately leads to modulation sidebands of large signals, like water [1, 2]. While these sidebands are typically small (< 5%), they form the main obstacle for non-water-suppressed MRS [2]. Here we present the design and implementation of a hardware based Z0 Vibration Compensation Unit (VCU), as a first proof-of-principle step towards the development of a fully digital form of pre-emphasis and Z0 compensation with arbitrary waveforms.

Methods - All experiments were performed on a 4.0 T Magnex magnet (Magnex Scientific Ltd, Oxford, UK) interfaced to a Bruker Avance Spectrometer (Bruker Instruments, Billerica, MA) equipped with Magnex gradients capable of switching 36 mT/m in 2000 us. A LASER sequence (TR/TE = 4000/100 ms) selected a $2 \times 2 \times 2$ cm^3 volume in a 3L spherical phantom containing water. All observed temporal phase modulations were assumed to be independent of spatial position, which is to a first approximation justified because (1) the small volume is selected in the magnet isocenter and (2) residual magnetic field inhomogeneity was negligible (FWHM = 2 Hz). Temporal frequency modulations were calculated in Matlab 7.0 from the FID signal in the time domain and were modeled as the sum of (1) a constant frequency offset, (2) five decaying exponentials for (residual) eddy current induced modulations and (3) up to fifty damped sinusoids for vibration induced modulations. After scaling for the Z0 coil efficiency, the digital waveform was loaded into the microcontroller (Rabbit Semiconductor, Davis CA) of the VCU, which subsequently converted and stored the data in a compatible format in a waveform memory card. The waveform memory card consisted of a memory bank (64 Kb) and a Digital-to-Analog converter (D/A). Following a trigger pulse from the NMR sequence, the Z0 waveform was read out with a 50 us dwell time, converted to an analog signal and summed with the Z0 shim drive.

Results – Fig. 1 shows the principle result of hardware-based Z0 vibration correction. While the effects of eddy current induced frequency variations have been compensated through conventional pre-emphasis/Z0 compensation with the commonly used 3 exponentials per channel, the excellent magnetic field homogeneity allows the detection of residual eddy current effects (Fig. 1A). Furthermore, a multitude of vibration-induced modulation sidebands can be observed with frequencies up to 500 Hz (Fig. 1B). Application of the Z0 vibration compensation as outlined in the Methods section eliminates any residual eddy-current induced distortions, resulting in a near-perfect Lorentzian lineshape (Fig. 1A) and simultaneously removes almost all vibration-induced sidebands (Fig. 1B). Residual sidebands are most likely due to incomplete modeling of the >50 sideband frequencies.

Conclusions – Here the principle of hardware-based compensation of arbitrarily shaped field modulations has been demonstrated. While similar results could have been obtained through post-processing software correction [e.g. 3], the presented method allows extension to subject-independent compensation of any unwanted field, as well as gradient modulations. A more general compensation unit could be designed whereby calculations are performed in real-time using the gradient pulses as input. Alternatively, a less demanding solution would be to extend the present method whereby complete waveforms are calculated for a given pulse sequence and downloaded to memory prior to the experiment. Both solutions could be implemented with variable hardware multipliers to account for temporally-varying phase-encoding gradients. Either approach will require additional studies to establish the sideband frequency, phase and amplitude dependence on gradient length, duration and separation, spatial position, different gradient combinations, patient weight distribution and other complicating factors. However, even with the current, limited implementation the benefits for MRS are clearly apparent, i.e. the removal of residual eddy-current effects leads to more Lorentzian-shaped lines, thereby greatly improving spectral quantification algorithms, like LCmodel. Furthermore, the removal of vibration-induced sidebands opens the way for routine non-water-suppressed MRS, with the convenience of the large water resonance for internal concentration referencing, phasing and frequency correction.



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