

Pre-emphasis Compensation of Oscillatory Phase Offsets in Phase-Contrast Flow Measurements

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Introduction: Despite its value in the research setting, the translation of phase-contrast magnetic resonance imaging (PC-MRI) into the clinical realm is still limited. Background phase offsets have been identified as one of the key issues [1]. While concomitant and non-linear field effects can be well compensated for [2, 3], correction of phase offsets from eddy currents has been more demanding. Using magnetic field monitoring (MFM) [4,5] it has been demonstrated that background phase offsets in PC-MRI exhibit a complex spatiotemporal behavior [6]. Besides temporally smooth 0th and 1st order offsets, phase oscillations were found to cause various degrees of phase offsets depending on the echo time point within the sequence [6]. These oscillations have been associated with mechanical gradient coil vibrations and have led to the conclusion that MFM calibration is required for every PC-MRI protocol. As this calibration step adds to the complexity of the overall scan procedure, a generic system-specific pre-emphasis compensation would be preferred over scan-by-scan MFM calibration in practice. In view of the overall goal, the present work aims at studying the response of oscillatory pre-emphasis calibration based on gradient impulse response functions (GIRF) measured with MFM [7]. Phantom and in-vivo experiments are presented to demonstrate that oscillatory pre-emphasis calibration reduces background phase offsets in PC-MRI well below 1% error of the encoding velocity.

Theory: In PC-MRI velocity is proportional to the phase difference of two encoding segments with different first order gradient moments Δk_v according to:

$$\Delta \varphi_v(r, t) = \Delta k_v(t) v(r, t) + \varphi_e(r, t). \quad (1)$$

The error phase φ_e in the general case includes spatiotemporal terms including gradient field oscillations at characteristic mechanical resonances f_i which can differ depending on the physical gradient axis concerned. Accordingly, the oscillatory gradient component $\delta G_{osc}(t)$ for one physical gradient axis may be modeled as:

$$\delta G_{osc}(t) = \text{Re} \sum_i A_i \exp[j(2\pi f_i + \varphi_i) \pm t / \tau_i], \quad (2)$$

with the initial phase φ_i , amplitude A_i and time constant τ_i .

Method: For magnetic field monitoring a proton-based dynamic field camera consisting of 16 NMR probes distributed on a 20 cm sphere [8] was used in a 3T Achieva system (Philips Healthcare, Best, The Netherlands). Gradient impulse response functions (GIRF) [7] were recorded for each physical gradient axis and phase coefficients up to third spatial order were determined. The GIRFs were approximated by a sum of two Gaussians and a Lorentz function. Using linear regression the phase and frequency of the oscillatory gradient offset were subsequently determined. Upon coarse calibration, oscillatory amplitude and time constant were fitted to the first order phase difference obtained from a separate MFM measurement. Only the z-gradient oscillation was considered in this initial study. Phantom data of a 20 cm diameter oil-filled sphere were acquired using a two-dimensional cine PC-MRI sequence (TE/TR: 3ms/100ms, flip-angle: 10 deg) in sagittal orientation with the read-out and the flow encoded direction aligned with the axis of the z-gradient coil. Data was acquired with a spatial resolution of 1.9 mm in-plane and a slice-thickness of 10 mm. In-vivo data of aortic flow were collected in healthy subjects using the same cardiac triggered PC-MRI protocol. The encoding velocity was set to 150 cm/s in all PC-MRI scans.

Results: Figure 1 shows GIRFs of the z-gradient coil without and with oscillatory pre-emphasis. The Lorentzian peak at 1.3 kHz corresponding to the mechanical resonance of the z-gradient coil was successfully reduced with oscillatory pre-emphasis. Without oscillatory pre-emphasis, the time evolution of the first order phase coefficient in z shows sinusoidal oscillations after application of the bipolar velocity encoding gradient (Fig. 2). With pre-emphasis oscillations were reduced tenfold from 1 to 0.1 radian/sec. In Fig. 3 the linear phase offset induced by gradient oscillation is shown in a static phantom at an echo time of 3 ms. The phase error across the phantom reaches up to 3% of the encoded velocity (venc). Using oscillatory pre-emphasis the phase error was reduced to less than 0.5% of the encoding velocity. In-vivo, spatially linear phase offsets are apparent in background tissue (Fig. 4). Comparison of the phase error without and with pre-emphasis shows a reduction from $\pm 3\%$ to less than 1%.

Discussion: In this work it has been demonstrated that oscillatory terms can be compensated using pre-emphasis adjustment derived from magnetic field monitoring data. Thereby background phase offsets in phase-contrast flow measurement can be reduced to below 1% of the encoding velocity without the need for individual experiment-specific MFM calibration as presented previously. At the current point only oscillations caused by mechanical resonances of the z-gradient were addressed. Future work will investigate a comprehensive pre-emphasis compensation including cross-term oscillations. Overall, the MFM pre-emphasis approach holds considerable promise in providing the accuracy and robustness required for clinical use of PC-MRI.

References: [1] Gatehouse et al., JCMR'10;12:5; [2] Bernstein et al. MRM'98;39:300-308; [3] Markl et al., MRM'03;50:791-801; [4] Barmet et al., MRM'08;60:187-197; [5] Wiesinger et al., ISMRM'08, 392; [6] Giese et al., MRM'11, doi 10.1002/mrm.23111; [7] S.J. Vannesjoe, ISMRM'10, 1536; [8] Barmet et al., ISMRM'09, 780;

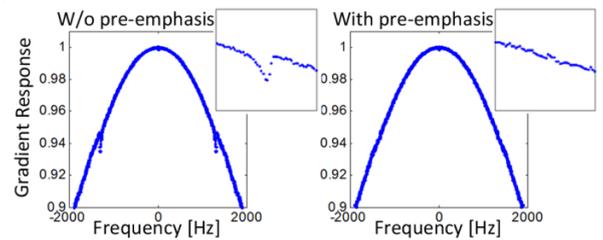


Figure 1: Gradient impulse response functions (GIRF) of the z-gradient with and without pre-emphasis. The insets zoom into 1200 to 1400 Hz.

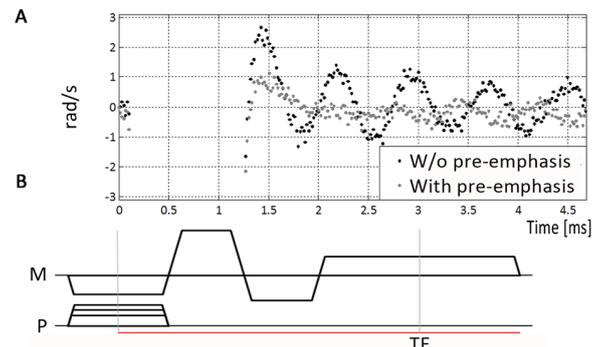


Figure 2: A) Comparison of time evolution of first order phase difference in z without and with oscillatory pre-emphasis of the z-gradient coil, B) Phase-contrast pulse sequence including probe acquisition (red).

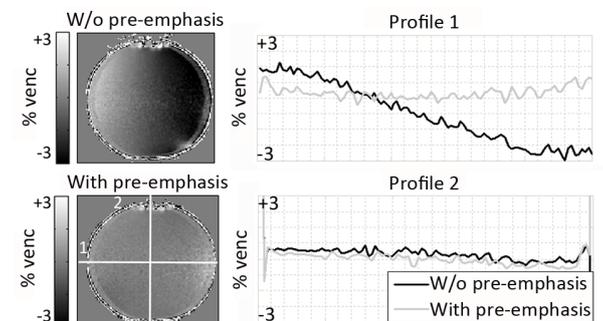


Figure 3: Visualization of first order phase offsets along the read-out direction in a static phantom with and without oscillatory pre-emphasis of the z-gradient coil.

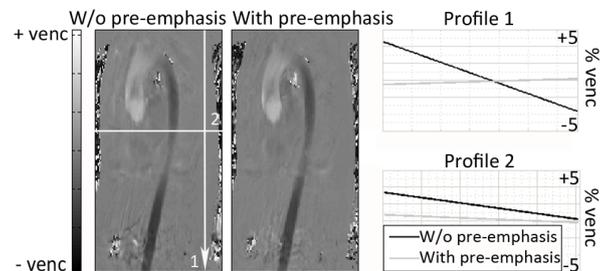


Figure 4: Background phase offsets in the static tissue in-vivo due to field fluctuations in the z-direction, without and with oscillatory pre-emphasis. Profiles correspond to phase fitted to static tissue.