Digital cross-term pre-emphasis for higher-order dynamic shimming

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Introduction: MRI and MRS frequently suffer from B_0 inhomogeneities, and the problem is especially severe for applications with long echo times or readouts, and at high field strengths. Dynamic updating of the shim fields can improve homogeneity by allowing the shims to be optimized for smaller volumes [1-4]. Depending on application however, this may require the shim fields to switch and settle within milliseconds. Eddy currents induced at shim switching limit the dynamic performance of the shims, and can also produce significant cross-term responses. To counteract the eddy current effects, pre-emphasis can be applied to the input waveform and the cross-terms could in principle be compensated for by driving the corresponding shim channels to cancel out the cross-term fields. Cross-term pre-emphasis to selected cross-term responses has been implemented using exponentially decaying analogue circuits [2-4]. A more flexible approach to pre-emphasis, however, is to set a digital filter to the input waveform. This has previously been implemented for the shim self-terms, basing the pre-emphasis calculation on measured shim impulse response functions (SIRFs) [5]. Here, we investigate the feasibility of comprehensive SIRF-based digital shim pre-emphasis including cross-term compensation.

Theory and Methods: The shim system is regarded as a linear time-invariant system, for which the output is a frequency-domain multiplication of the input with the system response. In vector notation: $\bar{O}(\omega) = H(\omega)\bar{I}(\omega)$,

where $\bar{I}(\omega)$ is the vector of inputs to the different shim channels, $H(\omega)$ is the system response matrix with the cross-term responses as the off-diagonal elements, and $\bar{O}(\omega)$ is the output in the different field terms. The task of finding an optimal pre-emphasis thus becomes that of finding a pre-emphasis matrix $P(\omega)$ such that:

$$\bar{O}_t(\omega) = H(\omega)P(\omega)\bar{I}(\omega),$$

where $\bar{O}_t(\omega)$ is the targeted response to a specified input. Ideally, $\bar{O}_t(\omega)$ would equal $\bar{I}(\omega)$, in which case $P(\omega)$ becomes the inverse of $H(\omega)$. This is however not feasible on a physical system, since it would imply infinite bandwidth of the response. Instead, we can set the targeted response as $\bar{I}(\omega)$, attenuated by a chosen low-pass filter $\lambda(\omega)$:

$$\bar{O}_t(\omega) = \lambda(\omega)\bar{I}(\omega).$$

This yields $P(\omega)$ as the inverse of the response matrix, scaled by $\lambda(\omega)$:

$$P(\omega) = \lambda(\omega)H^{-1}(\omega).$$

Effectively, $H^{-1}(\omega)$ removes the cross-term components of $H(\omega)P(\omega)$, while $\lambda(\omega)$ sets the desired shape of the self-term responses and must be chosen such as to not exceed hardware limitations for the resulting effective input:

$$\bar{I}_{eff}(\omega) = \lambda(\omega)H^{-1}(\omega)\bar{I}(\omega).$$

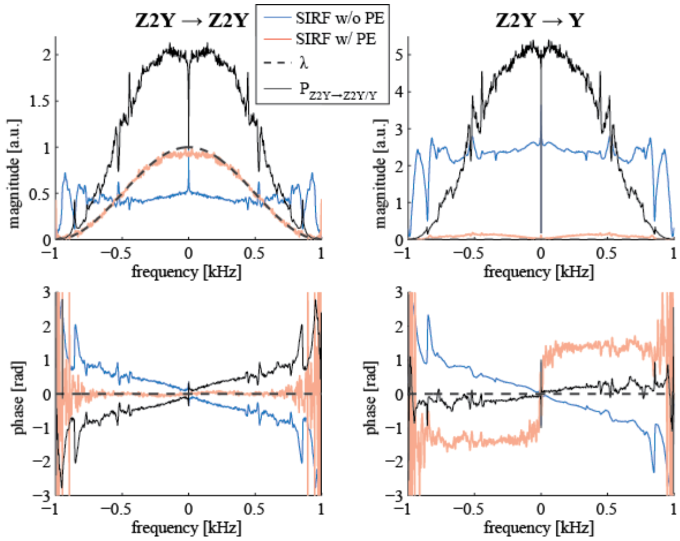

Fig 1: Measured SIRFs with and without pre-emphasis (PE) for the Z2Y self-term (left) and cross-term in Y (right). The chosen λ(ω) is plotted together with the respective coefficients of the calculated pre-emphasis matrix, P. The magnitude plots are scaled to the DC response of the self-term.

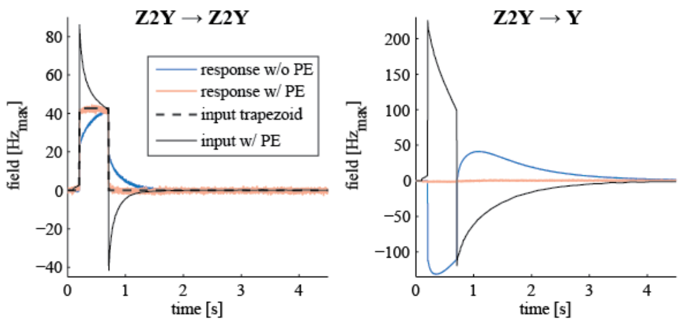

Fig 2: Measured response to a trapezoidal input with and without pre-emphasis (PE) for the Z2Y self-term (left) and cross-term in Y (right). The plots are scaled to maximum field shift induced by the respective field term in a sphere of 20 cm.

Experimental pre-emphasis determination was performed on a whole-body 7T Philips Achieva system, with full 3rd-order spherical harmonic shim coils. The shims were controlled via digital-to-analog converters (16 bit, 25kS/s, National Instruments) connected to the shim amplifiers, and programmed with LabView. The output shim fields were measured with a 3rd-order dynamic field camera [6,7]. Shim system calibration was done by measuring the SIRFs using linear frequency sweeps as inputs [5]. Cross-term pre-emphasis is demonstrated for the example of Z2Y and Y shim channel interactions, since the former has been seen to induce strong eddy currents with a Y field component [4]. The desired self-term response, $\lambda(\omega)$, was chosen to be a raised cosine with FWHM of 1kHz and roll-off factor of 1. With the calculated pre-emphasis applied to the input waveforms, the resulting SIRF for the Z2Y shim channel was determined. The pre-emphasis was then applied to a sample trapezoidal input waveform (5ms slope, 0.5s plateau) and the resulting field response was measured.

Results: The measured SIRF for the Z2Y channel shows strong attenuation of frequencies above ≈1Hz (Fig. 1, top left), due to long-living eddy currents, and several distinct resonances in the response. The cross-term response in Y is maximally around 2.5 times the DC response of Z2Y (Fig. 1, top right), as compared to the maximal field shift in a sphere of 20 cm induced by the respective field term. With pre-emphasis, the measured self-term SIRF for Z2Y lies very close to the targeted shape, except for a slight deviation at low frequencies. Also the phase response is very close to the desired response (Fig. 1, left). The cross-term response was suppressed by pre-emphasis to be maximally about 5% of the original response (Fig. 1, right). The cause of this slight remaining cross-response is not yet understood and is subject of further investigation. For the trapezoidal input, the pre-emphasis effectively counteracted eddy currents in the self-term, and the Y response was very close to zero during and after the pulse (Fig. 2). Thus implemented, cross-term pre-emphasis reduced settling times for stepped shim updates from around a second to the desired order of milliseconds.

Conclusion: SIRF-based digital cross-term pre-emphasis enables full flexibility in shaping the shim field response within the hardware limitations of the shim amplifiers. With digital pre-emphasis it is straight-forward to include all cross-terms in the compensation. Shim settling times could thus be reduced to milliseconds, which is indispensable for fast applications of dynamic shimming. Furthermore, with digital pre-emphasis it will be feasible to adjust the pre-emphasis parameters for each individual input waveform, such as to always make full use of system capabilities.

References: [1] Blamire et al, MRM 1996;36:159-165 [2] de Graaf et al, MRM 2003;49:409-416 [3] Koch et al, JMR 2006;180:286-296 [4] Juchem et al, Conc Magn Res Part B 2011;37B:116-128 [5] Vannesjo et al, Proc. ISMRM 2012;p.142 [6] Barmet et al, Proc. ISMRM 2009;p.781 [7] Wilm et al, MRM 2011;65:1690-1701