Measurement and pre-emphasis of shim responses using frequency sweeps

Signe Johanna Vannesjo[1], Benjamin Dietrich[1], Christoph Barmet[1], Bertram J Wilm[1], David O Brunner[1], and Klaas P Pruessmann[1]
[1] *Institute for Biomedical Engineering, University and ETH Zurich, Zurich, Switzerland*

Introduction. The use of dynamically controlled higher-order magnetic fields is gaining importance in various MR applications, as a means of improving static B_0 [1-2], and for increased degrees of freedom in the signal encoding process [3]. Such applications require precise control and knowledge of the dynamic characteristics of the higher-order magnetic fields, and necessitate an implementation of active pre-emphasis to counteract eddy currents and resonance effects. This system optimization process can be greatly facilitated by knowledge of the shim impulse response function (SIRF) for each shim channel. It has previously been shown that the SIRFs can be measured using a dynamic field camera [4], and a series of rectangular test functions [5]. The rectangular functions however, are inherently of limited sensitivity at high frequencies. Here, frequency-modulated test pulses are implemented for high-sensitivity SIRF measurements over a wide bandwidth. The utility of the resulting SIRFs is demonstrated by full-band digital shim pre-emphasis.

Methods. *SIRF theory:* The SIRF of a system can be calculated through a division in the frequency domain of the measured shim response, $S(\omega)$, by the input function, $I(\omega)$: $SIRF(\omega) = S(\omega)/I(\omega)$. For high sensitivity $I(\omega)$ should be large, and for even spectral sensitivity it should contain even spectral power within the measurement bandwidth. A rectangular function can be designed to cover a wide bandwidth by making it suitably short - the total power however is then reduced, and the sensitivity suffers accordingly. Similar to in RF pulse design [6], this dilemma can be overcome with frequency modulation at constant amplitude (chirp), which permits reconciling arbitrary duration with arbitrary bandwidth (Fig 1). The sensitivity of the measurement then depends on the amplitude and the full bandwidth of the chirp pulse. In order to use thus measured SIRFs for designing a digital system pre-emphasis, $P(\omega)$, the desired system response, $H(\omega)$, is to be multiplied with the inverted SIRF:

$$P(\omega) = H(\omega)/SIRF(\omega), \quad H(\omega) = e(i\omega\tau)\cdot rc(\omega) + SIRF(1 - rc(\omega)).$$

Here $H(\omega)$ was set to achieve unit response with linear phase, τ, within a specified bandwidth, and to leave the response untouched at higher frequencies. A smooth transition between the two regimes was ensured by a raised cosine filter, $rc(\omega)$.

Hardware & acquisition: The shim response measurements were performed on a 7T Philips Achieva system (Cleveland, USA), equipped with full 3rd-order spherical harmonic shim coils and shim amplifiers (Resonance Research Inc, Billerica, USA). The shim amplifier interfaces permit dynamic control of output currents via analog input voltages, which were generated with 16-bit digital-to-analog converters (25 kS/s, +/-10V output range, National Instruments) connected to a PC and programmed with LabView. Shim field responses were monitored using a 16-channel NMR field camera [4], enabling recordings of full 3rd-order field evolutions at high temporal resolution. The length of each coherent acquisition is limited by the signal decay of the field probes, therefore a series of measurements had to be implemented. Here, 10 measurement repetitions were required to obtain the full time-domain response of one chirp pulse. Data from different acquisitions were concatenated and re-sampled on a regular time-grid using linear interpolation. Single-sample peaks occurring at the concatenation frequencies (1/TR, $1/T_{acq}$ and harmonics thereof) were removed.

Results. Measured SIRFs for the X2-Y2 shim channel are shown in Fig 3, revealing a sharp peak at DC due to eddy currents, and a resonance at 1 kHz. These features are consistent with previous SIRF measurements using rectangular inputs, but are here resolved in much more detail (5). The SIRF used to base pre-emphasis on was constructed from two different chirps (20Hz and 2 kHz bandwidth), as particularly high sensitivity was needed to resolve the DC peak accurately. The pre-emphasized system response ($SIRF_P$) had close to a plateau of unit magnitude and nearly linear phase response within the designed bandwidth (1.4 kHz, FWHM). Pre-emphasized rectangular pulses with 1 ms slope showed fast settling, and suppression of the 1 kHz resonance, in measurements (Fig 4, left) and simulations (Fig 4, right). Fig 5 shows one selected cross-term response of the native SIRF.

Conclusion. SIRF measurements based on chirp pulses offer high and even sensitivity over a wide bandwidth and can provide detailed information on the shim field response. It has here been demonstrated that digital pre-emphasis based on the SIRFs could enable a flat frequency response, within system capabilities, and shim settling on the order of 1 ms. The SIRF measurements are fast, and inherently contain also cross-term responses, which could in a further step form the basis for digital cross-term preemphasis. With self- and cross-term pre-emphasis implemented on all channels, the shim system would be ready for per-TR shimming in common imaging and spectroscopy sequences.

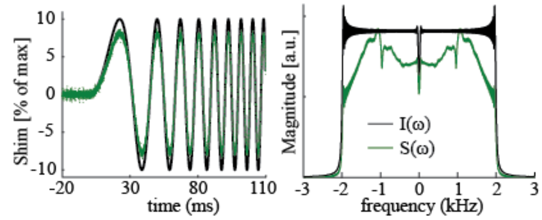

Fig 1: Chirp pulse (short segment shown) and measured shim response in the time and frequency domain.

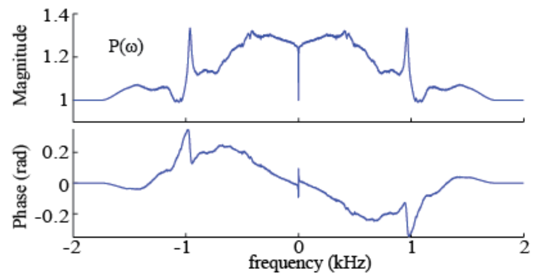

Fig 2: SIRF-based digital preemphasis, P(ω)

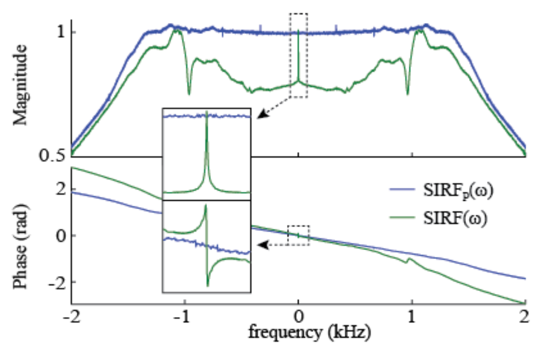

Fig 3: SIRFs measured with ($SIRF_P$) and without (SIRF) preemphasis

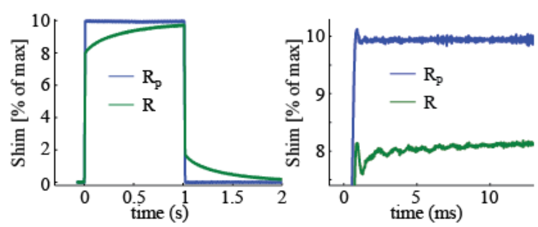

Fig 4: Rectangular pulses with (R_p) and without (R) preemphasis

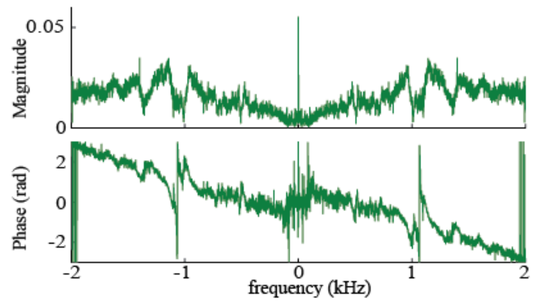

Fig 5: SIRF cross-term (X2-Y2 to Y)

References. [1] Blamire et al., MRM 1996; 36:159-165 [2] Juchem et al., Concept Magnetic Res Part B 2011; 37B:116-128 [3] Hennig et al., MAGMA 2008; 21:5-14 [4] Barmet et al., MRM 2008 ; 60 :187-197 [5] Vannesjo et al., Proc. ISMRM 2011; p.719 [6] Schulte et al., JMR 2003; 166:111-122