**Faster Feedback Field Control using Shim Pre-Emphasis**

Yolanda Duerst1, Bertram J Wilms1, Signe J Vannesjo1, Benjamin E Dietrich2, Simon Gross3, David O Brunner4, Thomas Schmidt5, and Klaas P Puenßmann1

1ETH Zurich, Zurich, ZH, Switzerland

**INTRODUCTION**

Real-time feedback field control has recently been shown to improve MR imaging [1] and spectroscopy [2] at high field strength. The field control system enables real-time adjustment of gradient and shim terms to correct for field changes due to, e.g. temperature drifts and physiological motion. If not corrected for, these field deviations cause inconsistencies in spatial encoding but also increased T₂* decay and off-resonant application of RF pulses which cannot be corrected retrospectively. So far the implementation of the system [1] relied on the simplified assumption that the shims react instantaneously to inputs and that coupling between the different shim channels can be neglected. Both assumptions are generally violated to a certain degree – primarily in higher-order shim channels [3] – which can derogate the performance of multivariable feedback loops [4]. To enable faster and more robust field control we present the incorporation of gradient and shim pre-emphasis including cross-terms in a real-time field feedback system.

**METHODS**

Real-time shim feedback control (Fig. 1) was implemented on a Philips 7T Achieva scanner (Philips Healthcare, Cleveland, USA). Field sensing was performed using 16 fluorine NMR field probes [5] and a separate spectrometer [6]. In each feedback cycle the measured field values were transformed to shim amplitudes by multiplication with the inverse of the steady state shim response (C) [1]. Subsequently the deviation between target and measured shim amplitude were calculated for each shim channel and fed to the controller. As detailed below, the Controller calculates the required correction voltages. Pre-emphasis is applied to the resulting shim demand before being sent to the input of a full 3rd-order spherical harmonic shim system (Resonance Research Inc., Billerica, USA) and to the gradients as first order shims, hence controlling 16 harmonic terms.

**Controller** – Feedback control was implemented by 16 independent control loops (Fig. 1). A proportional-integral (PI) controller was used to determine the correction voltage for each shim channel at time $t_k$: $u_{cor}(t_k) = K_p (e(t_k) + 1/T_e \cdot \Delta u_{mea}(t_k/e(t_k)))$ to minimize the error, $e(t_k) = u_{mea}(t_k) - u_{target}(t_k)$, of the measured to the targeted shim amplitude. The proportional constant $K_p$ and the integral time $T_e$ were used to tune the controller and the control loop ran at a rate of 10 Hz.

**Pre-emphasis** – The shim impulse response function (SIRF, Fig. 2) relates an input at the $i$th shim amplifier to the response measured in the $j$th shim channel: $O_j(i) = SIRF_{ij}(i) \cdot 1$. The individual SIRFs together make up a matrix with the cross-terms as the off-diagonal elements: $O_{ij} = SIRF_{ij} \cdot 1$. The measurement of the SIRF matrix is shown in reference 3. A digital pre-emphasis was obtained by multiplying the inverse of the SIRF matrix with the desired system terms: $H = \frac{1}{O_r}$. All self-terms and the dominating cross-terms ($Z \rightarrow Z$, $Z \rightarrow X$, and $Z \rightarrow Y$) were taken into account in the pre-emphasis calculation.

**Experiments** – To compare field feedback with and without pre-emphasis, closed loop responses to a step change of a target field configuration was observed for both implementations. Two target shims were tested: One 2nd-order (ZX) and one 3rd-order (ZXX) shim term to also assess cross-term effects. The feedback rate was 10 Hz; 5 field measurements were interleaved with the feedback to allow for observation of the field evolution between shim updates.

**RESULTS**

The feedback response to a step change without pre-emphasis shows a slow initial rise due to eddy currents which misleads the feedback to overshoot (Fig. 3a). For shim channels with strong cross-terms (e.g. ZXX→X, Fig. 3b) field control without pre-emphasis results in strong oscillatory disturbances. With pre-emphasis, eddy current effects including cross-term responses are compensated, which results in an accelerated response to changes in the target field (Fig. 3c & d). The measured fields reached and stayed within 5% of the target after 0.1 s (for ZX) and 0.3 s (ZXX) as compared to 0.5 s and 1.4 s, respectively in the non-pre-emphasis case. This is also reflected in the root-mean-squared errors over all probes (Fig. 3e & f). In vivo experiments show considerably increased image quality in T₂*-weighted sequences (Fig. 4) when applying field control. Ghosting and signal dropout artifacts due to deep breathing of the subject were reduced.

**CONCLUSION**

We presented enhanced field feedback control by incorporating gradient and shim pre-emphasis. The approach also included cross-term pre-emphasis, thereby the individual shim channel responses are decoupled which justifies the use of parallel feedback loops. Further increase in the feedback bandwidth will be useful, e.g., to correct for rapid limb motion. By decreasing the latency of the control loop, hence increasing the feedback rate, the setup may enable faster and more robust field control at high field strength. The field control system enables real-time adjustment of gradient and shim terms to correct for field changes due to, e.g. temperature drifts and physiological motion. If not corrected for, these field deviations cause inconsistencies in spatial encoding but also increased T₂* decay and off-resonant application of RF pulses which cannot be corrected retrospectively.