An Autonomous System for Continuous Field Monitoring with Interleaved Probe Sets

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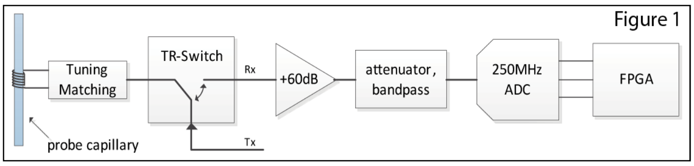
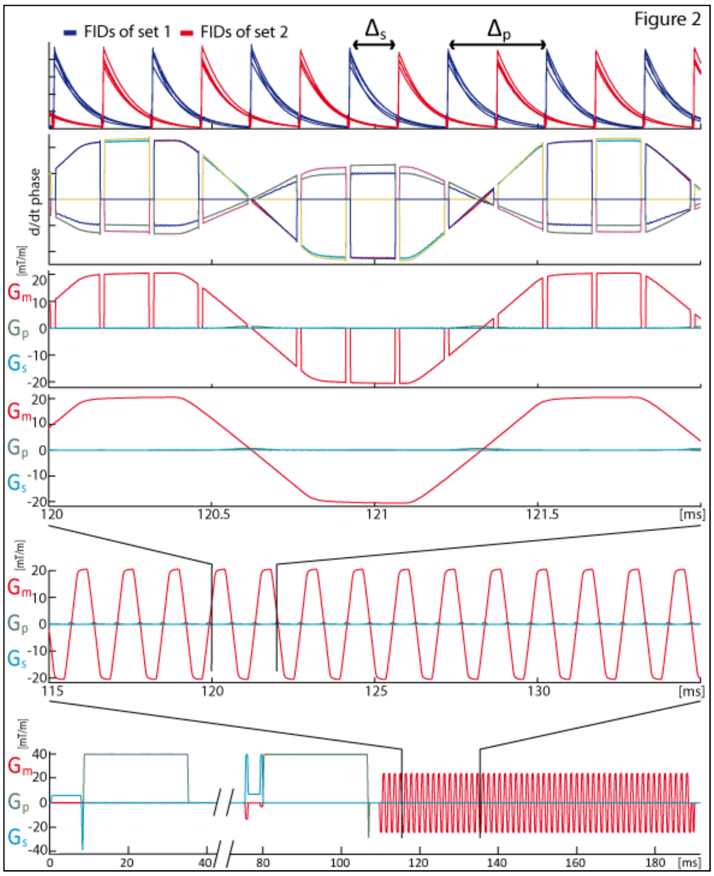
Introduction: By means of magnetic field monitoring [1,2] with NMR probes, the spatio-temporal field evolution during MR experiments can be observed. In current monitoring systems, the acquisition duration is limited by decay of the probe signals due to T_2 relaxation and/or dephasing caused by internal field variation or externally induced fields. Therefore, the continuous monitoring of scans with strong dephasing gradients (such as in diffusion MRI) or long coherence trains (such as in balanced SSFP) has not been possible so far. Fast re-excitation of such probes causes confounding superpositions of coherences of different history. To address these issues, very short relaxation times T1,T2 can be chosen [3], which however still leaves a certain dead time of each probe once its signal has dropped below useful levels. To address these issues, in this work it is proposed to work with two equivalent sets of short-lived transmit/receive probes and alternating excitation and acquisition between them. In this fashion, continuous, real-time field monitoring of very high sensitivity is achieved. This approach poses high demands on the speed, sensitivity, and flexibility of the spectrometer hardware used. Therefore it was implemented in an autonomous system that is entirely independent of the MR scanner to be monitored.



Method: Interleaving the excitation and acquisition of field monitoring data among subsets of probes allows balancing between the needed temporal coverage of the measurement and sufficient relaxation of the probes, preventing echo formation by subsequent RF pulses. Due to remnant coupling, probe signals are unusable during high power excitation. However, provided sufficiently fast switching, the missing gap can be interpolated based on the band limitation of the magnetic field evolutions that occur in MR systems. Hence pulse duration, transient times of the T/R switches and filter group delay gain crucial importance. For this reason a dedicated system was designed comprising high-speed solid-state switches, block pulse generation (5W, 3us) for excitation, high speed digitization (14Bit, 250MHz analogue to digital converter, NI5761, National Instruments, Austin, USA), and real-time demodulation and filtering to 1 MHz bandwidth with field-programmable gate arrays (NI FlexRIO 7954R). A schematic of the receive system for one channel is shown in Fig. 1. The field camera head consists of eight proton NMR probes arranged in two nested tetrahedral sets. The probes were built from a (2.2mm inner diameter, 3cm length) glass capillary filled with H_2O and doped with $GdCl_3.6H_2O$ such that T2 ≈ T2* ≈ T1 ≈ 110µs. Six-turn solenoids (250 µm PTFE-coated silver wire) around the capillary served as receive and transmit coils. Care was taken to avoid any materials containing protons in the entire field camera head to avoid parasitic NMR signals. For each interleave, the phase evolution of the high SNR set is extracted, the corresponding gradient waveform calculated and concatenated. The excitation gaps were interpolated based on the assumption that the field evolution is limited to a bandwidth of 60 kHz.

Results and Discussion: Figure 2 shows the continuously measured gradient waveform of a diffusion-weighted spin-echo EPI sequence (G_{max} = 40mT/m, b=5000s/mm^2) and Fig. 3 shows the field evolution during a balanced SSFP sequence monitored with a per probe re-excitation period of 300µs (Δ_s), interleave time of 150µs (Δ_p) and 3µs block excitation pulses. This leads to a total dead interval of 13µs and hence a gradient monitoring resolution of 1/13µs = 76 kHz. The zoomed part of Fig. 2 shows some of the involved processing steps (top-down: magnitude of the FIDs, probes' field evolutions, the gradients within each time frame and the interpolated result). The measured probe SNR is in the range of 1200 at an acquisition bandwidth of 1 MHz, yielding a field resolution of 12 nT according to Ref. [1].



Conclusion: Fast interleaved re-excitation of short living probes enables monitoring of the evolution of magnetic fields over arbitrary durations independent of the internal or externally induced dephasing of the field probes. As a main advantage over conventional field probes, the maximum measureable gradient moment is not primarily determined by the probe size which otherwise limits the achievable resolution in imaging experiments. The presented hardware implementation allowed very high acquisition duty cycles with high bandwidth, T/R switching rates that are to our knowledge unachieved by PIN diodes (below 1µs) and robust splicing of the individual acquisition time intervals. Further reductions of the excitation gaps through the use of even shorter excitation pulses might increase the unambiguously measurable bandwidth of the field evolution to the order of 100 kHz.

[1] DeZanche et al. MRM 60:176–186 (2008) [2] Sipilä et al. ISMRM 2010 p.781 [3] Han et al. JMR 201: 212–217 (2009)