Time-interleaved radiation damping feedback for increased steady-state signal response

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INTRODUCTION

Radiation damping (RD) describes a second-order effect where the signal-induced current in the receiver coil acts back onto the primary spin system [1]. According to Lenz's law, the RD field acts in a way to oppose its original cause. In that sense RD can be understood as a 1) self-generating and 2) self-regulating flip-back pulse, which causes the transverse magnetization to return to equilibrium more rapidly than it otherwise would [2,3].

The natural RD effect is characterized by the RD damping time constant according to $\tau_{RD} = 2 / (\gamma\ \mu\ M_t\ \eta\ Q)$, with γ the gyromagnetic ratio, μ the magnetic susceptibility, M_t the transverse magnetization, η the coil filling factor and Q the quality factor. Accordingly, natural radiation damping can only be observed with very high Q and/or high filling factor arrangements, but typically not under normal MRI conditions.

Recently, RD feedback loops have been introduced into the transmit-receive (Tx/Rx) RF signal path to artificially boost the natural RD effect. Using such feedback circuits, it was demonstrated that the natural RD could be amplified in a way to become effective as a signal recovering mechanism [2,3]. While previous RD circuits were limited in terms of RD feedback gain, here we present a new feedback circuit, which principally circumvents this problem via time separation of RD receive and transmit.

MATERIALS and METHODS

The left side of Fig. 1 shows the basic setup for a direct RD feedback loop using two separate coils for transmit and receive. The receive signal (s_{Rx}) gets phased and amplified, characterized by the complex feedback gain g, to form the transmit input for the RD feedback (s_{Tx}). Mathematically, this results into following recursive equation:

$$s_{Tx}= g(s_{Rx}+cs_{Tx}) = g(s_{Rx}+cg(s_{Rx}+cs_{Tx})) = g(s_{Rx}+cg(s_{Rx}+cg(s_{Rx}+cs_{Tx}))) = gs_{Rx}(1+cg+(cg)^2+(cg)^3 +\ldots) = (c^*g<1) = s_{Rx}^*g/(1-c^*g) \qquad [1]$$

with c denoting the inductive transmit-receive coupling. The geometric sum converges only for $c^*g \leq 1$, which effectively confines the feedback gain to values smaller than the inverse transmit-receive coupling. Experimentally, this limits the RD feedback signal recovery effect to setups with high Q and/or high filling factors.

Here, we present a novel RD feedback circuit, which circumvents this limitation via time separation of RD transmit and receive (cf. right part of Fig. 1). The time-separation happens via a sample and hold (S/H) device in combination with a fast transmit-receive (T/R) switch. In order to achieve RD transmit-receive switching in the Δf ~ kHz range, quadrature de- and remodulation is required, which is indicated by the two mixing stages (X).

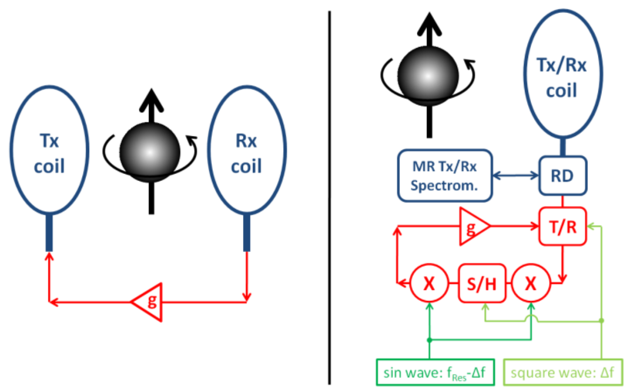

Fig.1: Left: Illustration of basic feedback loop, with g denoting the complex feedback gain. Right: Time-interleaved, Tx/Rx RD feedback using sample and hold (S/H) in combination with quadrature de- and remodulation (X) and a fast Tx/Rx switching (T/R). RD denotes a switch for changing between normal Tx/Rx operation and RD feedback.

Experiments were performed on a 1.5T GE HDx system (GE Healthcare, Milwaukee, WI). The time-interleaved RD feedback circuit was used in combination with a standard quadrature transmit-receive birdcage head-coil (diameter=12cm, length=30cm). The sample and hold switching was adjusted to Δf=50kHz. Via an additional T/R switch (RD) it can be selectively activated under pulse sequence control.

RD signal recovery was demonstrated for 3D, short-TR, short-TE gradient echo imaging (TR=50ms, TE=2.5ms, BW=125kHz). The RD feedback was directly applied after image data acquisition for a duration of 4ms. Balanced imaging gradients were used in order to maximize the receive signal, which provides the input for the RD feedback.

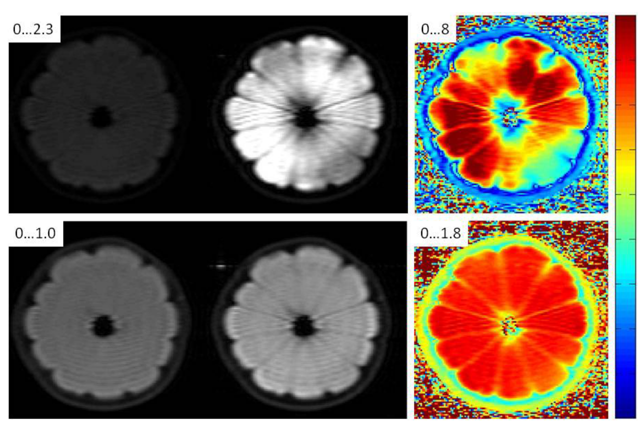

Fig 2: Grapefruit imaging examples with 90° (top row) and Ernst angle (33°) excitation (bottom row). Left without, middle with RD feedback and right corresponding signal enhancement factors. Color scales are annotated in the upper left corner.

RESULTS and DISCUSSION

RD experiments were successfully performed for several different phantoms including tap water (long T1), $CuSO_4$ doped water (short T1~200ms) and several fruits. Figure 2 shows results obtained from a grapefruit, which is known to have relatively short T1 values, for 90° (top row) and Ernst angle (33°) excitation (bottom row). The columns contain images obtained without (left) and with (middle) RD feedback. Signal enhancement factors (right column) of up to 8 and 1.8 were found for 90° and Ernst angle excitation respectively. Besides boosting the steady-state signal response, the RD feedback also enhances T2* and off-resonance contrast. In particular, it enhances the skin structures within the fruit. This is also consistent with literature, where RD feedback was applied as a contrast enhancement mechanism in between RF excitation and image data acquisition [4].

In order to maximize the NMR signal that drives the RD feedback, the spins have been rephased following the image encoding using balanced gradient waveforms. By nature the RD effect is not volume selective; i.e. it acts on all spins within the sensitive region of the RF coil. For slice selective imaging, the RD effect needs to become volume selective, which might be possible by applying a slice selection gradient simultaneous to the RD feedback, similar to what is done for slice selective excitation.

In comparison to previous RD feedback implementations the presented implementation allows significantly higher RD feedback gain values. This will enable RD feedback induced signal recovery to be applied also for in-vivo applications, with intrinsically low filling factor and/or low quality factor (i.e. low natural radiation damping effect).

REFERENCES

[1] N Bloembergen et al, Physical Review 95: 8-12 (1954). [2] SY Huang et al, MRM 60: 1112-1121 (2008). [3] F Wiesinger et al, ISMRM Honolulu: p.2655. [4] SY Huang et al, Concepts MR: 30A: 378-393 (2007).