Robust Parallel Excitation Pulse Design

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Introduction Parallel excitation employs multiple transmit channels and coils, each driven by independent waveforms, to afford the pulse designer an additional spatial encoding mechanism, i.e., transmit sensitivity encoding, that complements gradient encoding. However, in contrast to parallel reception, parallel excitation requires individual high-power amplifiers for each transmit channel, which can be cost-prohibitive. Several groups have explored the use of low-cost transmit amplifiers for parallel excitation, e.g. [1-3], however, such amplifiers commonly exhibit temporal non-idealities that distort the RF waveform. To overcome this problem, we introduce a novel regularization technique for parallel excitation pulse design that yields pulses with smoother magnitude envelopes. We demonstrate experimentally that pulses designed with the new technique suffer less amplifier distortion than unregularized pulses.

Theory Roughness penalties have been explored in MR image reconstruction [4], where they can improve problem conditioning by balancing data consistency with image smoothness. In parallel excitation, we can use roughness penalties to balance excitation error with RF magnitude envelope smoothness, reflecting our knowledge that the RF amplifiers exhibit sluggish tracking of rapid changes in the envelope, i.e., steep AM modulations. We hypothesize that in our parallel transmit system this non-ideality arises from amplifier bias distortion and DC power supply drop-outs [5]. We enforce RF envelope smoothness by designing pulses to minimize the function [6]:

$$\Psi\left(\boldsymbol{b}_1, \ldots, \boldsymbol{b}_{N_c}\right) = \|\boldsymbol{d} - \sum_{c=1}^{N_c} \boldsymbol{S}_c \boldsymbol{A} \boldsymbol{b}_c\|_{\boldsymbol{W}}^2 + \beta \sum_{c=1}^{N_c} \|\boldsymbol{R}|\boldsymbol{b}_c|\|^2,$$

where $\boldsymbol{b}_c$ is coil c's pulse, N_c is the number of coils, $\boldsymbol{d}$ is the desired excitation pattern, $\boldsymbol{S}_c$ is a diagonal matrix containing coil c's transmit sensitivity, $\boldsymbol{A}$ is an NUFFT matrix [7], $\boldsymbol{W}$ is a diagonal error weighting matrix, β is a regularization parameter that is used to balance roughness and excitation error, and $\boldsymbol{R}$ is a finite-differencing matrix that yields the first or second-order differences of the pulse envelope $|\boldsymbol{b}_c|$. Note that $\boldsymbol{R}$ could contain the impulse response of any high-pass filter derived from knowledge of the amplifier's frequency response; we choose first-order differences here as an initial demonstration. We solve this optimization problem by alternating conjugate gradient iterations with roughness penalty updates in which we incorporate the current pulses' conjugated phase into $\boldsymbol{R}$.

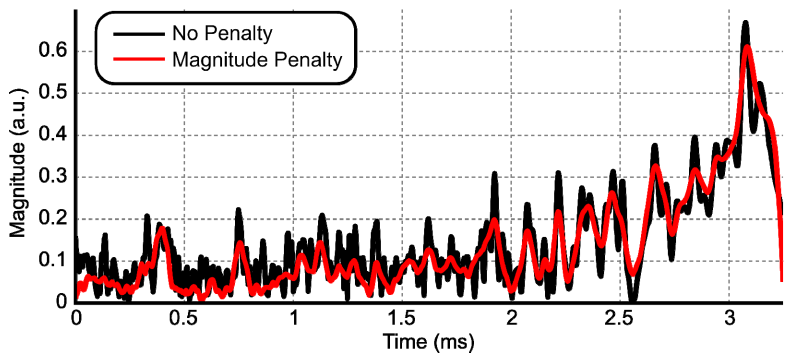

Fig. 1. Parallel excitation pulses (one coil of four shown) designed using no roughness penalty and the proposed magnitude roughness penalty. The unregularized pulse contains many narrow peaks that are difficult for the amplifier to track. The magnitude roughness penalty produced a significantly smoother magnitude envelope.

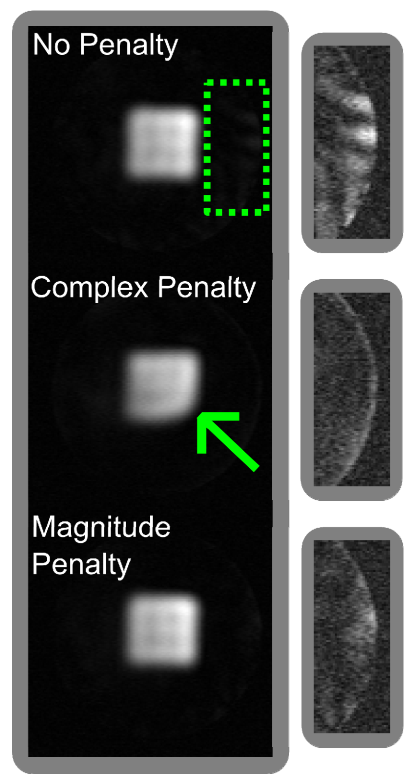

Fig. 2. Experimental results. Images in the left column show the full excitation patterns. The right column magnifies the region indicated by the dashed rectangle for each case. The amplifier had difficulty tracking narrow peaks in the unregularized pulse's magnitude envelope, resulting in ringing-like artefacts (right column, top). The complex roughness penalty reduced these artefacts significantly, but at the cost of increased excitation error, evidenced by the rounded lower right corner of the square (arrow). In comparison, the magnitude roughness penalty reduces artefacts and maintains excitation accuracy.

Methods Imaging was performed on a GE 1.5T Signa Excite scanner (GE Healthcare, Waukesha, WI). The parallel excitation system was comprised of 4 surface coils driven by 300W in-house built power amplifiers that were in turn fed vector-modulated RF signals [1]. B1+ maps were measured in a 12cm disk phantom [8]. Pulses were then designed using the method in [6] along a 3.2ms spiral-in trajectory, with FOV 6 cm (2x acceleration) and resolution 0.5 cm. The target excitation pattern was a 3.4 cm square with flip angle 20° and with error weighting in the stop band set to minimize nominal stop band ripple and aid in our comparisons. Three pulse sets were designed: in the first, no roughness penalty was used, the second used a complex roughness penalty (same cost function as above but with $|\boldsymbol{b}_c| \rightarrow \boldsymbol{b}_c$ in the regularization term) with $\beta = 0.1$, and the third used the new magnitude roughness penalty, also with $\beta = 0.1$.

Results and Conclusions Figure 1 plots unregularized and magnitude roughness regularized pulses for coil 1. The unregularized pulses had a norm-squared magnitude roughness of 2.97, while the complex and magnitude-regularized pulses had similar magnitude roughnesses of 0.4 and 0.3, respectively. Figure 2 shows that the magnitude penalty pulses significantly reduced erroneous excitation outside the square, while maintaining the shape of the square. These results demonstrate that magnitude roughness penalties can be used to effectively address RF magnitude envelope distortions caused by amplifier non-idealities.

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