Phase Constraint Relaxation in Parallel Excitation Pulse Design

A. B. Kerr[1], Y. Zhu[2], and J. M. Pauly[1]

[1]Electrical Engineering, Stanford University, Stanford, CA, United States, [2]GE Global Research Center, Niskayuna, NY, United States

Introduction: Parallel excitation is a promising technology that offers new flexibility in the design of selective excitation pulses. This flexibility can be utilized to accelerate multidimensional selective excitation and reduce SAR [1-5]. Parallel excitation design to date, however, has not exploited the advantages of relaxing a uniform phase constraint on the target excitation profiles to improve performance. This is an important factor as a parallel transmit array, unlike a birdcage resonator, does not generally have an eigenmode [6] with both a flat magnitude and phase profile. An iterative approach to pulse design is presented here that adapts the phase of the excitation profile during the design process and achieves significantly improved performance.

Methods: A spatial-domain approach for parallel excitation design [3] is used as the basis for our method. In this approach, pulse design can be formulated in the small-tip regime as a linear system of equations:

$$\mathbf{m} = \mathbf{E}\,\mathbf{b} \tag{1}$$

where **m** is a vector representing the desired complex magnetization within the region of interest, **b** is a vector representing the concatenated RF waveforms from each coil, and **E** is a matrix including the effects of coil sensitivity, excitation gradient trajectory, and DFT coefficients. Equation 1 is solved using a least-squares iterative conjugate gradient approach (Matlab, The Mathworks, Inc.).

To date, parallel excitation designs have prescribed target magnetization profiles that include a desired magnitude profile and a flat phase profile. This is unreasonably restrictive when designing an RF pulse for homogeneous slice selection or ROI selection where the phase profile is not required to be flat. This phase constraint is relaxed in our design approach in two ways. First, we perform an eigenmode decomposition analysis of the RF array and choose the eigenmode with minimum magnitude deviation over the target excitation region. The phase profile of this eigenmode is used for the phase profile of the target magnetization profile **m**. Second, we update the phase profile of **m** to equal that produced by the parallel RF excitation as determined by the product **E b** following each conjugate gradient iteration.

Results: The frequency and phase-locked multi-transmit platform [7] based on an integrated set of four GE Excite II system electronics was used for our experiments. An 8-coil transmit-and-receive array (Fig. 1) was used to image a thin-slice phantom oriented in the axial plane. The transmit coil sensitivity profiles were measured using a multi-angle B_1 mapping technique [8]. The 1st and 4th eigenmode decompositions of the array sensitivity profiles are shown in Fig. 2. Note the 1st eigenmode has nominally flat phase but a null in the center of the magnitude profile, while the 4th eigenmode has nominally flat magnitude but a significant phase ramp.

Figure 3 demonstrates the simulated RF profiles obtained from the design of a cylindrical ROI excitation that includes the entire phantom. The excitation gradient is a 2x accelerated 1.9-ms duration spiral. The flat phase constraint design results in Fig. 3 a-c show that while a flat phase profile is nominally achieved, there is a significant dropout in the magnitude profile. In contrast, the relaxed phase constraint design using the phase of the 4th eigenmode as a starting point achieves a flat magnitude profile. The RF waveforms for the relaxed phase constraint pulse have 20% larger peak amplitude but less high-frequency components compared to the flat-phase constraint pulse design. Figure 4 shows the tip-angle maps calculated from a double-angle application of the relaxed phase constraint ROI excitation pulse. The excitation angles were nominally 50° and 100° with the variation in tip-angle being less than 10%.

Conclusions: Several important applications of parallel excitation, including ROI and homogeneous slice excitation do not require a flat phase profile. A method for relaxing the phase constraint of parallel excitation pulse design is presented here that significantly improves the design of an ROI excitation. The pulse is validated in phantom images with an 8-coil transmit-and-receive array.

References: [1] Zhu, Mag. Res. Med., 51:775-84, 2004. [2] Katscher, Mag. Res. Med., 49:144-50, 2003. [3] Grissom, Mag. Res. Med., 56:620-9, 2006. [4] Ullmann, Mag. Res. Med., 54:994-01, 2005. [5] Setsompop, Mag. Res. Med., 56:1163-71. [6] King, Con. Mag. Res. B, 29B:42-49, 2006. [7] Zhu, P. ISMRM, p. 14, 2005 [8] Kerr, P. ISMRM, p. 2561, 2006.

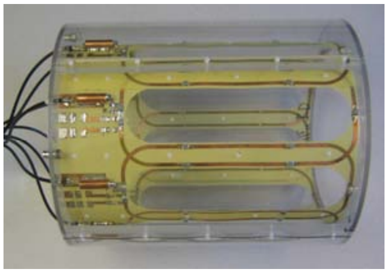

Figure 1: A Tx/Rx head-sized array of 8 13.4x31.0-cm loop coils azimuthally distributed on a 28-cm dia. cylinder.

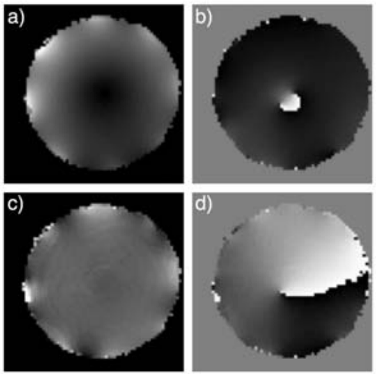

Figure 2: Normalized magnitude and phase of the 1st (a,b) and 4th (c,d) eigenmodes of the transmit sensitivity profiles. Note the central null in the magnitude of the 1st eigenmode.

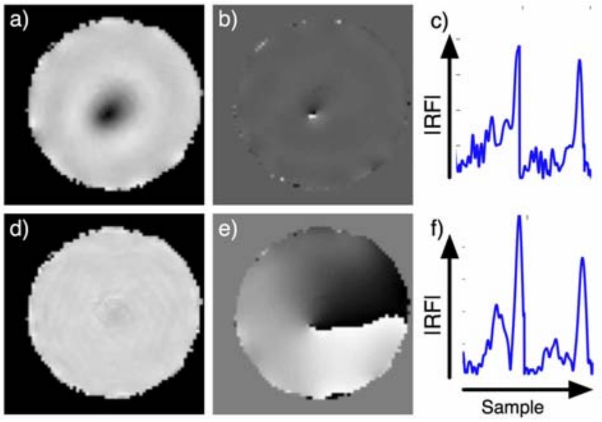

Figure 3: Simulated magnitude and phase of ROI excitation, and concatenated coil 1 & 2 RF waveforms for designs with: a-c) flat phase constraint, d-f) relaxed phase constraint.

Figure 4: Calculated tip-angle from phantom images acquired with the relaxed phase constraint pulse on the 8-coil transmit-and-receive array. Double-angle images were acquired at nominally 50° and 100°. Tip-angle variation is less than 10%.