SLR Design of Broad Bandwidth RF Pulses using Higher Order Phase Functions

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Introduction

Radio-frequency (RF) pulses with high bandwidth are often required in MRI/MRS applications. However, the achieved bandwidth is limited by the B_{1max} of the system. For reducing the B_{1max} requirements of high bandwidth pulses, quadratic (i.e. 2nd order) phase envelopes can be argued to be near-optimal [1]. In this work we show that further reduction of B_{1max} and hence increased bandwidth is still possible by combining second- with higher even-order phase functions.

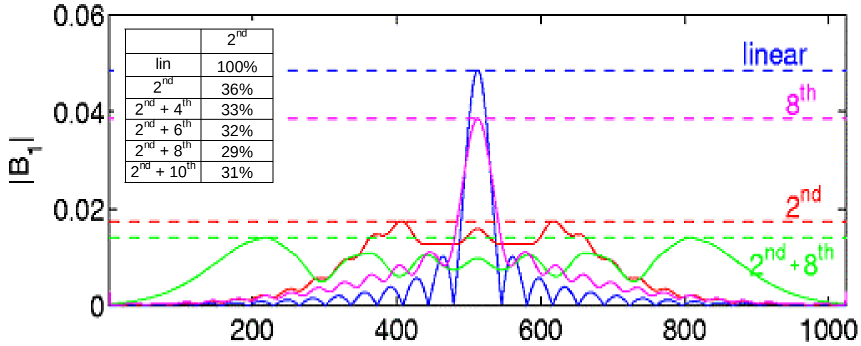

Fig. 1: Amplitude modulation of pulses with different phase functions. The table in the inset lists the reductions of B_{1max} relative to linear-phase design.

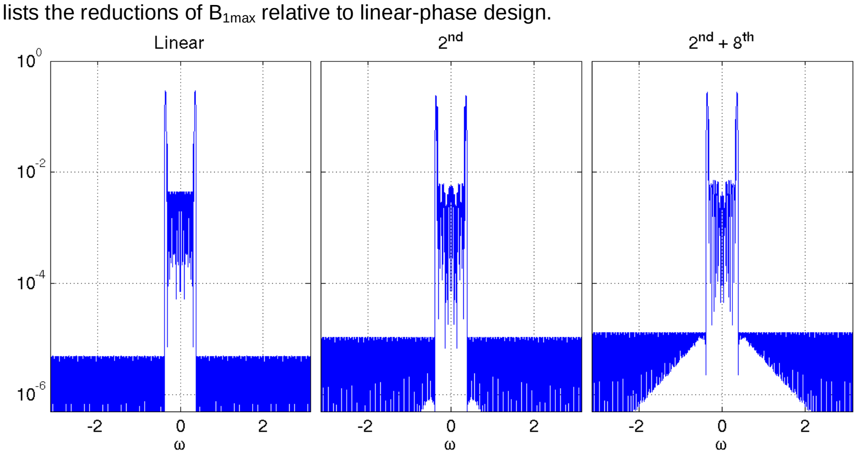

Fig. 2: Error in the longitudinal magnetisation plotted on logarithmic scale for linear (left), 2nd order (middle) and the optimal combination of 2nd and 8th order phase functions.

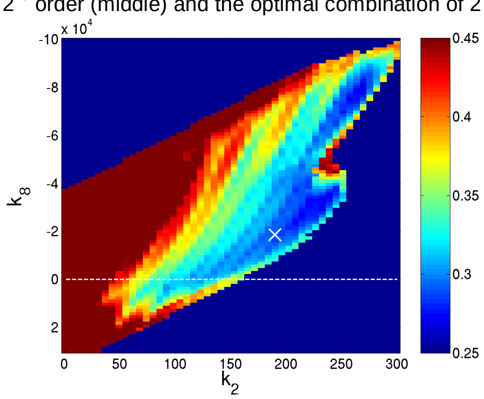

Fig. 3: Map of B_{1max} (colour axis) for different amount of 2nd (k_2; x-axis) and 8th (k_8; y-axis) order phases. Due to symmetry, only positive k_2 are shown. The blue outer region is excluded because of excessive fitting errors (>0.5). The minimal B_{1max} with acceptable error (0.0025) is marked with a cross and was selected.

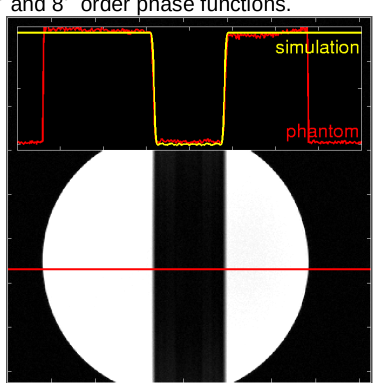

Fig. 4: Profile of exemplary 2nd + 8th order phase pulse used for suppression. The yellow line shows a numerical integration of the Bloch equation, whereas the red line and the image depict the measurement of a phantom on a Philips Intera 1.5T using a spin echo sequence.

Methods

RF pulses are obtained from finite impulse response (FIR) filters through the Shinnar-Le Roux transformation [2]. FIR filters that minimise the Chebyshev (i.e. maximum) error norm are generated with the complex Remez exchange algorithm [1,3]. The fitting target for these FIR filters is specified by

$$D(\omega) = R(\omega)e^{i\varphi(\omega)}$$

$$R(\omega) = \begin{cases} 0 & for\ \omega \ge \omega_s \\ \sin\frac{\theta}{2} & for\ \omega \le \omega_p \end{cases}$$

$$\varphi(\omega) = \sum_{\alpha} k_\alpha \omega^\alpha ,$$

where $-\pi \le \omega \le \pi$ is the normalised frequency, ω_s and ω_p are the stop and pass band frequencies, k_α a scaling constant and α the order of the phase function. All pulses shown here have a time-bandwidth product of 180 (in radians), a fractional transition width of 0.1 and a flip angle of 90°. For 256 samples, this translates into $\omega_s = 0.315$ and $\omega_p = 0.385$. In this work, integer-valued orders of up to ten were investigated. For finding the minimal B_{1max}, quadratic-phase functions were systematically combined with higher orders. As shown in Fig. 3, the optimal k_α was determined by iterating through different phase functions. The selection criterion for the optimal pulses was a minimal B_{1max} with a fitting error below 0.0025 (instead of 0.0015 for the linear phase pulse).

Results

Different order phases can be combined to further reduce B_{1max} beyond the reduction achieved with a pure quadratic phase. As in the case for quadratic phase [1], the design parameters for these higher-order phase pulses are subject to certain restrictions, so not all parameter specifications result in acceptable pulses with a lower fitting error. The best combination was found to be 2nd and 8th order phases (k_2 = 189.8, k_8 = -18586). Odd-order phase functions are generally not capable of reducing B_{1max} significantly, since they are purely amplitude modulated with asymmetric pulse shapes. Various pulses are shown in Fig. 1. For a pulse duration of 5 ms, B_{1max} was reduced by 71% from 37.3 μT (linear phase) to 10.8 μT (2nd + 8th order phase). The error in M_z did not increase significantly, as depicted in Fig. 2. Figure 4 shows the experimental verification of the pulse.

Discussion and Conclusion

The 2nd order phase is near optimal if the desired selection profile is smooth with a sufficient amount of quadratic phase. In practice, both conditions are somewhat violated. As a result, B_{1max} can be further reduced by combining the 2nd order phase with higher even-order phase functions. The optimal choices for k_α could be found more efficiently by non-linear optimization instead of an exhaustive search, since the parameter landscape (Fig. 3) is relatively smooth.

References

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[2] J. Pauly, et al., IEEE T Med Imaging 1989;10:53.
[3] L. Karam, et al., IEEE T Circuits-II 1995;3:207.