Broadband RF Pulses with Polynomial-Phase Response

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Introduction

Broad-bandwidth radio-frequency (RF) pulses are important for various kinds of MR experiments. The achievable RF field strength B_1 of the transmitting system is limited on whole-body scanners, leading to small bandwidths of regular amplitude-modulated RF pulses. In order to increase the bandwidth, pulses with inherently reduced maximum B_1 amplitude (B_{1max}) are necessary. Overlaying a quadratic phase in the frequency domain leads to frequency-modulated pulses, which are near optimal in terms of minimising B_{1max} [1]. Some further reduction of B_{1max} has been achieved by complementing a quadratic phase with a single higher-order phase term [2]. In this work, we generalise this concept towards combining multiple higher-order terms with a direct search algorithm, hence providing considerably improved bandwidth and selectivity.

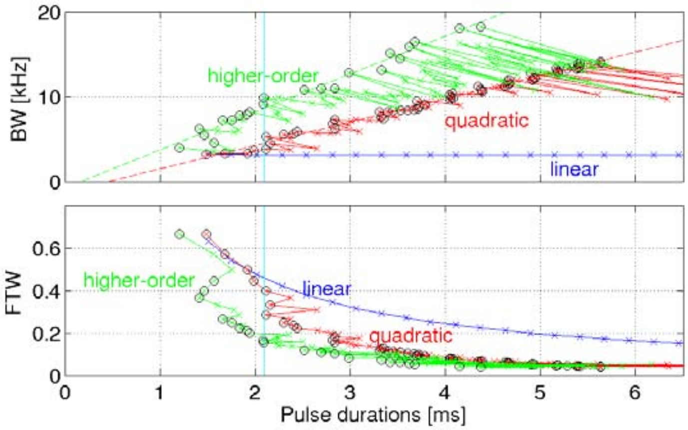

Figure 1: Bandwidth (BW) and fractional-transition width (FTW) as functions of the pulse durations for linear, quadratic and higher-order-phase pulses. All pulses are designed with approximately the same error of 0.00125 and scaled to a B_{1max} = 20 μT. The proposed optimisation does not always converge; hence only favourable pulses are circled and fitted by linear regression.

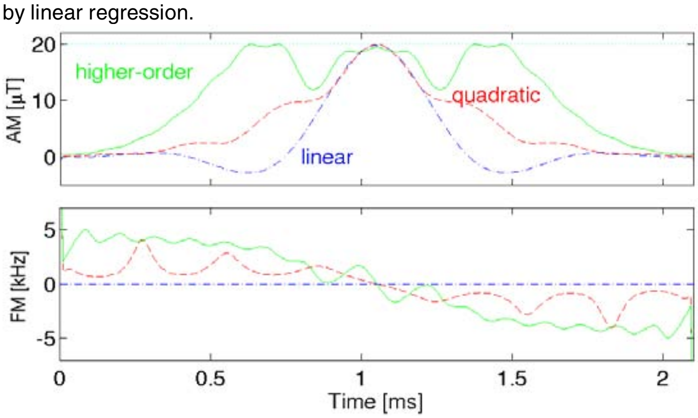

Figure 2: Selected RF pulses with the same B_{1max} (20 μT) and duration (2.1 ms; as indicated in Fig. 1), but various phase functions. The BW is increased from 3.1 kHz for a linear and 3.8 kHz for a quadratic phase to 9.9 kHz for a higher-order phase pulse.

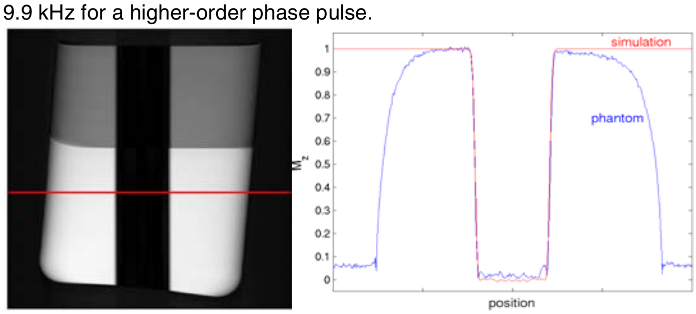

Figure 3: Suppression profile of higher-order-phase pulse (B_{1max} = 20 μT, duration = 2.1 ms) demonstrated on a water-fat phantom.

Methods

RF pulses are obtained from Finite Impulse Response (FIR) filters with the Shinnar-Le Roux (SLR) transformation [3]. Equi-ripple FIR filters that minimise the maximum-error norm are designed with the Complex-Remez-exchange algorithm [4] by directly specifying its complex frequency response [1,2]. The polynomial phase is given by

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

where α counts the polynomial terms and k_α denotes their coefficients. All even-order phases from second up to tenth order were optimised simultaneously.

The problem is to find the optimal phase polynomial to minimise the B_1 amplitude for a given profile, specified by the bandwidth (BW), fractional transition width (FTW) and flip angle. The maximum tolerable error of the response function was the same for all designed pulses. These requirements amount to a non-linear optimisation. The cost value to minimise is $(B_{1max})^2$ plus a squared penalty term, which penalises the deviation of the designed pulse beyond the maximum tolerable error. A direct search strategy was chosen, because no analytical gradients for the cost function can be provided and the parameter landscape is not sufficiently smooth.

All functions were implemented in MATLAB V7.0 SP2 (R14) [5]. The non-linear optimisation was performed in three stages. A pattern search algorithm (MATLAB function "patternsearch"; [5] and references therein) was used for the first two stages, while the last stage applied a Nelder-Mead Simplex method ("fminsearch"; [5]). The added penalty term was gradually increased during the three stages.

Results and Discussion

The gain in bandwidth (BW) achievable with higher-order phase can be considerable (Figs. 1 and 2) and depends on the parameter selection. For linear-phase pulses, the BW is independent of the pulse duration, while the selectivity increases. With both quadratic and higher-order phase, the achievable BW grows approximately linear with the pulse duration along with further enhanced selectivity (Fig. 1). Higher-order-phase pulses have two advantages over quadratic ones: the gain in BW starts at shorter pulse durations and is steeper throughout. An example for the application as outer-volume suppression pulse is shown in a water-fat phantom (Fig. 3) on a Philips Intera 1.5T scanner.

Conclusions and Outlook

The bandwidth and selectivity of RF pulses can be considerably increased by combining multiple higher-order-phase terms as compared to both linear and quadratic phases. An ideal application for non-linear phase pulses is the saturation of magnetisation. Outer-volume suppression is generally most effective when the time between it and the acquisition is short. This places tight constraints on RF pulse durations. Higher-order-phase pulses are particularly beneficial for short RF pulses and hence it considerably enhances outer-volume suppression.

References

[1] RF Schulte, et al., J Magn Reson 2004;166:111.
[2] RF Schulte, et al. ISMRM 2004: 189.
[3] J Pauly, et al., IEEE T Med Imaging 1989;10:53.
[4] L Karam, et al., IEEE T Circuits-II 1995;3:207.
[5] http://www.mathworks.com