Refine Phase Modulation Function Sampling Step Size in Off-Center Variable-Rate Selective Excitation with Rf Pulse Magnitude Replication

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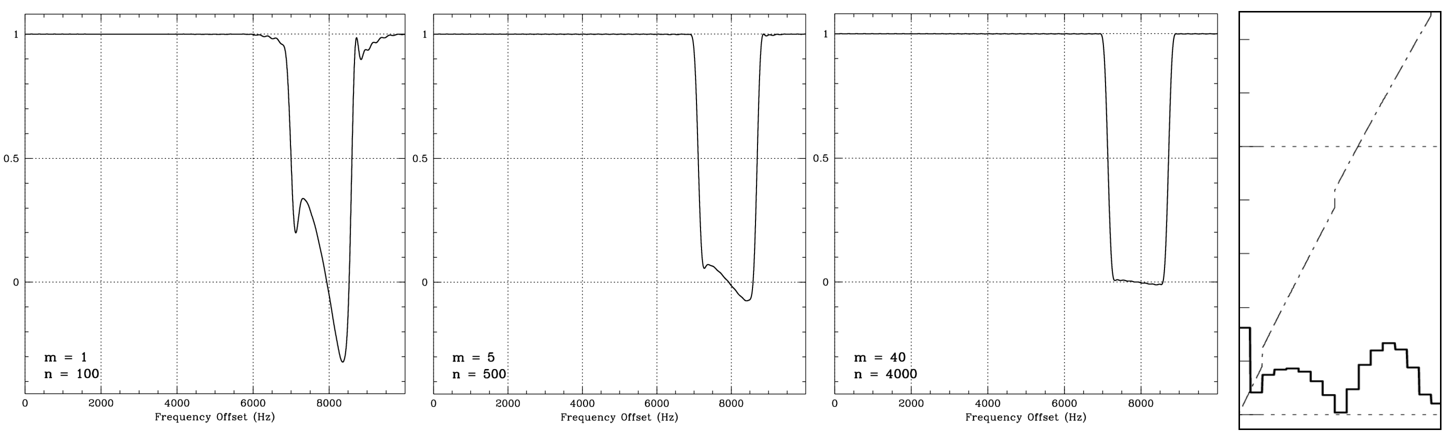
Introduction: Variable-rate selective excitation has been proposed to reduce rf power deposition [1]. The use of a time-varying gradient $G(t)$ to accelerate and decelerate the excitation *k*-space traversal rate makes it often necessary to implement a time-varying phase modulation function $\phi(t)$ in place of the frequency shift $\Delta\omega$ for fixed-rate, in order to obtain a spatial offset Δx of the excitation location, since it is often impossible to directly realize a time-varying frequency function $\Delta\omega(t)$ on many commercial scanners.

Although it is theoretically simple that $\phi(t)=\int_0^t \Delta\omega(t')dt' = 2\pi\gamma\Delta x\int_0^t G(t')dt'$, in the real world a continuous $\phi(t)$ can be only mimicked by a piece-wise constant phase step function. This discrepancy often leads to the degeneration of excitation profile quality in spatially offset slices. The variable-rate scheme actually makes the situation worse, since the $\phi(t)$ changes quickly in the fastest traverse regions that are compressed in time. A sampling rate which is originally adequate for magnitude function may soon becomes inadequate for the phase function (or the I and Q waveforms), resulting in severe phase aliasing for relatively large Δx values.

Variable-rate rf and gradient waveforms can be interpolated in various ways to contain a greater number of points, thereby reducing the sampling step size to better mimic the continuous $\phi(t)$. However, many optimized waveform designs, such as the Shinnar-La Roux (SLR) pulses [2], are commonly derived with a small number of points *n*, and under the "hard pulse approximation". They are designed as stepped functions and not ready for further envelope interpolations in nature, especially with the presence of the so-called "Conolly wings", the singular points often at the ends of the SLR waveforms. The common interpolation schemes tend to cut the area under the singular point at the beginning by half, and boost the area under the ending point, resulting in excitation profile distortions.

Method: We propose the use of an easy oversampling method in place of more elaborate interpolation schemes. Each of the "source" pulse point amplitudes is simply repeated *m* times in order to multiply the number of support points by *m*. This fits naturally the piece-wise-constant nature of modern rf excitation and the "hard pulse" assumption, but it allows for much finer phase modulation step sizes without changing the characteristics of the original pulse design. In this approach, the phase continuously evolves over the period in which the rf magnitude simply repeats. The areas under the "Conolly wings" are well preserved; under-sampling induced phase aliasing is easily avoided, and the errors from mimicking the continuous $\phi(t)$ with a stepped phase waveform are minimized.

Example: The saturation profile of a 5*ms* long variable-rate converted minimum-phase SLR pulse (SAR reduction factor 40%, 100 points, time-bandwidth product=8) directly shifted to an offset Δx=5×(FWHM selection width) is severely degraded (left). Applying a multiplication factor of 5 before the conversion, the 500 point pulse produces a much better profile at the same Δx (center). Oversampling the conversion result to 4,000 points further minimizes the errors (right, front portion waveform in box, solid =magnitude and dashed=phase). The offset-thickness ratio is adequate for common 3D applications that often present SAR problems.



Discussions: There are intrinsic limitations in mimicking a continuous rf frequency function with a phase function, and mimicking the continuous phase function with a stepped phase waveform. For variable-rate pulses, it is practically true that the more points possible, the better the results. The simple pulse magnitude multiplication method helps to preserve the selection quality of the original fixed-rate pulse designs that invert the Bloch equations using the "hard pulse approximation" without introducing additional interpolation errors. The basic principle of minimizing phase function sampling errors with a refined step size is relevant to all the practical offset selection cases, such as multiple-band excitation pulses using *Cos*(*t*) modulations, and SLR pulses employing multiple-band finite impulse response (FIR) filters designs, where pushing for higher order (>100) often creates numerical instabilities.

References: 1. Conolly SM, *et al*., JMR 78(3): 440-458, 1988. 2. Pauly JM, *et al*. IEEE TMI 10(1): 53-65, 1991