RF Amplifier Nonlinearity Correction for Multiband RF Pulses

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Purpose: Multiband RF pulses are more likely to incur RF system nonlinearities than standard RF pulses because they typically push B1 to RF amplifier limit and their envelope requires rapid RF supply current changes. Nonlinear distortion on a multiband RF pulse results in undesired higher harmonics being excited in the frequency domain. In this work, an RF pre-distortion approach [1,2], which compensates for the error between desired and measured RF waveforms, is adapted to mitigate the nonlinear distortion on multiband RF pulses.

Methods: Figure 1 shows a detailed schematic plot of the RF pre-distortion process.

Transmit RF Field Measurement: Transmit RF field is measured on a 3T Discovery MR750 scanner (GE Healthcare, Milwaukee, WI). A desired multiband pulse, denoted as $RF_{desired}(t)=\Sigma_z RF_{single}(t)exp(i2\pi f(z)t)$, is played out on the scanner with all gradients turned off. $RF_{single}(t)$ is a single-band pulse and $f(z)$ is the center frequency of the z-th slice. Before the sequence is played, a phantom is loaded into the scanner, along with a signal pickup loop. A coaxial cable connects the pickup loop to an oscilloscope (Agilent Technologies, Santa Clara, CA) through a common mode choke and an analogue band-pass filter. A trigger pulse and a 10 MHz reference signal from the scanner are connected to the oscilloscope to synchronize the measurement and the RF transmission.

RF Waveform Processing: The measured transmit RF waveform is loaded into Matlab (The MathWorks, Natick, MA) and demodulated by a coarse estimation of the center frequency for water resonance. A Hamming window with a width of 500kHz is then applied in the frequency domain to low-pass filter the measured waveform. Next, the waveform is demodulated by a fine estimation of the center frequency, which is found on an interpolated frequency profile with 0.1 Hz resolution. Last, the time delay between the measured and desired waveforms is adjusted.

RF Waveform Predistortion: The pre-distorted RF waveform is calculated as $RF_{predistort} = RF_{desired} + RF_{error}$, where the waveform error is $RF_{error} = RF_{desired} - RF_{measured}$. After being down-sampled to the 0.5 MHz sampling rate for the RF amplifier, the pre-distorted RF waveform can be applied to all subsequent acquisitions that use the same RF parameters.

Exemplary Three-Band Pulse: Using a Hanning windowed sinc with time-bandwidth product of 4 as the single-band pulse, an exemplary three-band pulse of 3.2ms is calculated. The ratio of the slice thickness to the slice separation is 1:11.5. The peak RF amplitude is 0.1861G for the desired RF and 0.1895G for the pre-distorted RF.

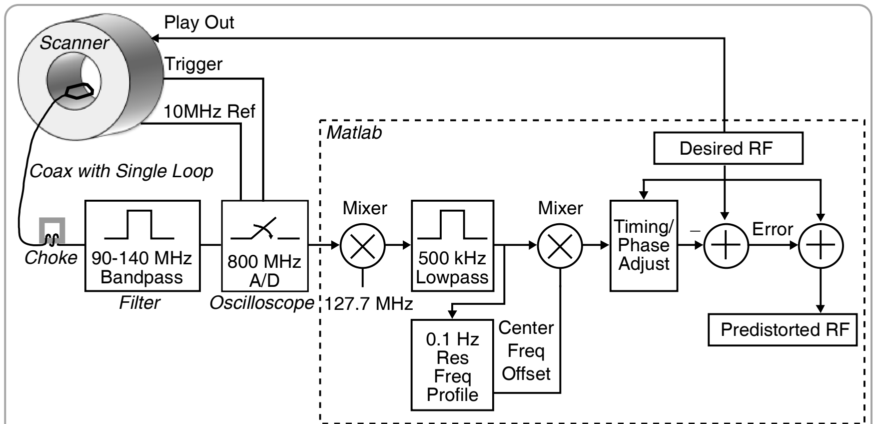

Fig. 1. *Schematic plot of the proposed RF pre-distortion approach.*

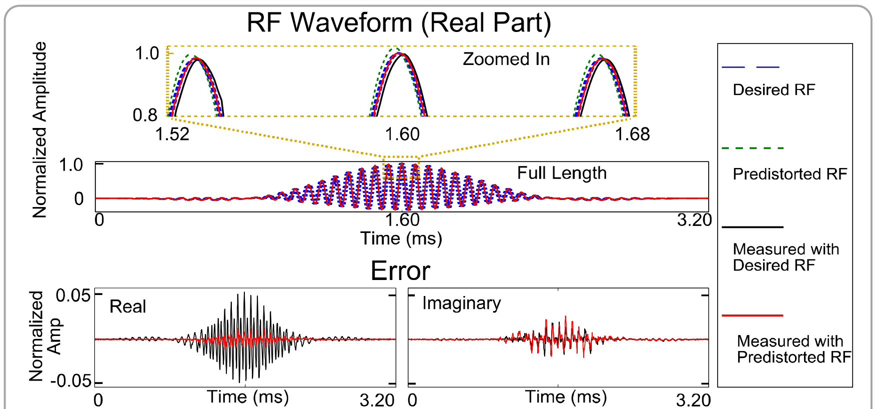

Fig. 2. *Comparison of the desired and pre-distorted RF waveforms. Dashed lines are waveforms that were fed to the scanner. Solid lines are from oscilloscope measurements. Errors are between oscilloscope measurements and the desired RF waveform.*

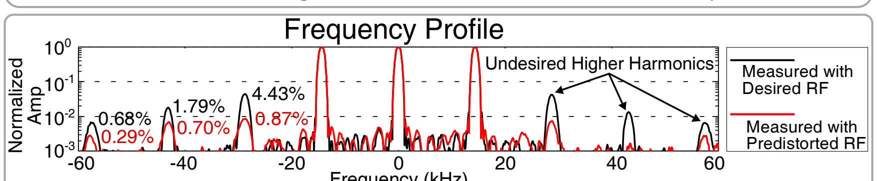

Fig. 3. *Measured frequency profiles of the desired and pre-distorted 3-band RF waveforms. The three desired bands are excited at 0kHz and ±14.375kHz. All other side-lobes are undesired higher harmonics introduced by the nonlinear behavior of the RF amplifier.*

Results: Figure 2 displays the multiband RF waveforms. When the initial desired RF (blue dashed line) is played out on the scanner, the measured waveform (black solid line) does not track the rapid change of the desired RF, especially near the peak. While the pre-distorted RF (green dashed line) is being applied, the measured waveform (red solid line) overlaps with the desired waveform with little error. Due to the fact that our current implementation of the multiband sequence utilizes a real RF waveform, only the real part of the pre-distorted RF waveform is fed back to the scanner, thus the error is substantially reduced in the real part with minimal change to the imaginary part. Nonetheless, the error is relatively small in the imaginary part, and reducing the error in the real part alone helps to suppress the largest amplitude of the undesired higher harmonics from 4.43% to 0.87% (a 5-fold reduction) of the main-lobe signal level (shown in Fig. 3).

Discussion: In multiband imaging, signal from undesired higher harmonics contribute to the measured signal and will alias with signal from the desired bands. Although the undesired band signal may be hard to notice in the reconstructed images due to its small signal amplitude, its existence may confound further analysis of the multiband images. The proposed pre-distortion approach successfully suppresses the undesired higher harmonics of a multiband RF pulse. In future work, applying a complex pre-distorted RF instead of a real-valued one may further improve its performance.

References: 1. Stang PP, et al, ISMRM 2009. p. 396. 2. Zanchi MG, et al, IEEE Trans. Med. Imag 2011;30:512-522.