

Phase Coherent Multi-Channel Synthesizer of Transmit Pulses at Larmor Frequencies up to 512 MHz

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Target audience: The method applies to creation of high quality RF pulses for MRI scanners up to 12 Tesla that incorporate multi-channel transmit coils fed by a set of independent synthesizers to produce phase-coherent images, even when frequencies in each channel and/or slice differ.

Introduction: In a previous abstract (1) we described a single channel waveform generator based on a Pentek (Upper Saddle River, NJ) PCI card model 78621. It was used to create multi-band pulses at the Larmor frequency with a modulating waveform at 2 ns update rate. This rate limited the output frequency to a maximum value of 200 MHz. In anticipation of arrival of a 7T whole body MRI scanner, we purchased another set of Pentek cards, model 78671. Each card has four output channels fed by a pair of Texas Instrument DAC3484 chips. At maximum DAC clock and up-sampled modulating waveform, smooth stair-step less pulses can be created at sampling rate as low as 0.8 ns.

These cards are intended for radar beam manipulation and require an additional, stand alone, model 7192 card for synchronizing up to four units. We found that this card is not suitable for MRI. It has inputs for a reference clock and a trigger, as does the older 78621 card, but also has an additional external SYNC input that is intended to synchronize clocks of all 78671 cards. However, during device driver development on a Linux system, it was found that the SYNC pulse must be applied at some point during the process of clock synchronization. For this reason it cannot be created by an MRI sequence or even applied manually. At our request Pentek made changes to this card to make it MRI compatible. The ability to create an internal SYNC pulse was added. This pulse could be initiated by a device driver via a special communication line used for standard programming of the 7192 card. A further modification required incorporation of an additional D flip flop, with clock fed from the external reference input to achieve synchronized switching, ON and OFF, of the multiplexer, which is the part of the 7192 card that delivers high frequency clocks to all 78671 cards.

After this modification full synchronization was achieved in the following way. First, the internal clock of the 7192 card was programmed to deliver a frequency of 1280 MHz. After that, the synchronization process looped until this clock was synchronized with an external 20 MHz reference clock supplied by the MRI scanner. This 20 MHz clock is used by the scanner to create all pulses and it warranties that pulse edges are in sync with edges of this clock. After the initial synchronization, the multiplexer on the 7192 card is switched OFF and all 78671 cards stop running. Then an internally created SYNC pulse is delivered to the 78671 cards to reset all clock dividers to levels that remain until the multiplexer is switched ON again. Switching occurs on the edge of 20 MHz clock thanks to the use of the D flip flop. From this moment on, all clocks of the wave-form generators were in absolute sync with the scanner master clock as required. Additional pulse programming created pulse shaped modulating envelopes in I and Q forms and stored them in the 78671 cards memories. The Larmor frequency was set in DAC3484 chips in NCO registers. At a total 128 times up-sampling, the modulating waveforms could be programmed within a range of 10 MHz, allowing the creation of required frequency offsets for different slice selections. When the scanner delivers a trigger at the edge of a transmitter unblanking pulse, the I and Q envelops are called from the memories and at the same time the accumulators of the NCO oscillators are reset to zero. In this way, phases of all pulses are in sync, not only among themselves but also with the scanner sequence. For this reason, no reference waveforms were required for MRI signal detection, unlike the method used on all commercial scanners.

Methods: Synchronism of 8 channels obtained by two 78671 cards was tested using an Agilent Technologies DSO6104A oscilloscope at maximum resolution of 500 ps/cm. This test preceded MRI experiments because only one transmit channel was available on a Bruker 9.4T (400.3 MHz) animal scanner. Additional channels were monitored on the oscilloscope for intrinsic coherency. For absolute phase behavior, a gradient EPI sequence of our own design (2) was used. Acquisition parameters were: TR=1 sec, BW=400 kHz, FOV=5 cm, slice 1 mm, 1 NEX, 64×64 resolution and TE=14.4 ms.

Results: Testing of RF pulse phase conservation was made by time-course series of EPI images using software designed for fMRI applications. Acquisition was performed with the time course of image phase shown in the form of a graph that was updated in real time. After about 10 acquisitions the scanner was stopped and restarted later. In the mean time, the RF pulse program was restarted with all procedures of clock resynchronization. This process was repeated, and in each case the graph continued at the same level. If there was only a single missing period of the 1280 MHz clock, it would show as a phase jump by about 112 degrees, a well visible step. No such event was seen. To force such a variation, the 10 MHz reference clock of the scanner was used instead of 20 MHz. In a simple test with the oscilloscope only, trigger pulses were occasionally close to the positive or negative part of the sinusoid. Because no other positions were shown, the MRI sequence master clock was indeed running at 20 MHz. In a subsequent experiment, the RF pulse program was initiated only once for 1000 subsequent excitations of the same slice, and as expected, the phase graph changed values occasionally with each scan restart but only two distinct levels were displayed.

Discussion: The 78671 card can be used at higher magnetic fields than the older 78621 card, up to 12 Tesla (512 MHz). Pulses created can be manipulated to achieve phase-coherent slices as described in (3) and without use of any reference signal. The excitation of multiple transmit channels can also be carried out coherently. At a current 0.8 ns sampling rate, RF pulses surpass in quality any other pulses created on commercial scanners that run modulation in the stair-step fashion in the range of sampling rates from 50 to 2000 nanoseconds.

Conclusion: The tests showed that multiple Pentek 78671 cards can be used to excite up to 16 different transmit channels. The required phase shifts and amplitudes of different channels can be manipulated by the I and Q values of modulating envelopes. In addition a frequency offset can be added independently when needed. The latter is not possible with hardware that uses a sinc pulse for input and output waveforms with amplitude and phase modification only.

References:

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