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A Programmable FPGA-based 8-Channel Arbitrary Waveform Generator for Medical Ultrasound Research Activities

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Abstract—**In modern ultrasound imaging systems, digital transmit beamformer module typically generates accurate control of the amplitude of individual elements in a multielement array probe, as well as of the time delays and phase between them, to enable the acoustic beam to be focused and/or steered electronically. However, these systems do not provide the ultrasound researchers access to transmit front-end module. This paper presents the development of a digital transmit beamformer system for generating simultaneous arbitrary waveforms, specifically designed for research purposes. The proposed architecture has 8 independent excitation channels and uses an FPGA (Field Programmable Gated Array) device for electronic steering and focusing of ultrasound beam. The system allows operation in pulse-echo mode, with pulse repetition rate of excitation from 62.5 Hz to 8 kHz, center frequency from 500 kHz to 20 MHz, excitation voltage over 100 Vpp, and individual control of amplitude apodization, phase angle and time delay trigger. Experimental results show that this technique is suitable for generating the excitation waveforms needed for medical ultrasound imaging researches.**

I. Introduction

In modern pulse-echo ultrasonic imaging systems the segment that typically generates the necessary digital transmit signals with the proper timing, amplitude and phase information to produce a focused and/or steered transmit signal is called transmit beamformer [1]. The sophisticated transmission technique employs arbitrary waveform generator (AWG), traditionally controlled by application-specific integrated circuits (ASICs) [2], for generating the independent excitation of each piezoelectric element to produce complex transmit waveforms with low second order harmonic distortions and bandwidth up to some MHz, depending on the application [3]. However, this transmit technique requires additional expensive electronics, e.g., digital-to-analog converters (DACs) and linear high-voltage amplifiers to translate the digital waveform to an amplified analog signal to drive the transducer elements, and thus, generally reserved for more expensive and less portable high performance ultrasound (US) systems. Despite the recent advances in electronic technology, most of these systems are not suitable for the development and test of new transmit investigation methods, that typically requires the possibility of transmit particular excitation signals or sequences to optimize image quality. Their typical often “closed” architecture does not provide the ultrasound researchers to have access to the transmit beamformer [4]. In this paper we present the design of a fully programmable FPGA-based 8-channel AWG, specifically designed for US research purposes, to fit the requirements of flexibility and programmability, which are necessary for the implementation of original transmission strategies.

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II. Digital Transmit Beamformer Basics

Fig. 1 illustrates the principle of ultrasound (US) transmit beamforming with the geometry that is usually used to determine the channel and depth-dependent delay of a focused transducer array. During transmit operations, the transducer elements are excited at different times depending on the location of a focal point and the element's position on the transducer [1]. Appropriate time delay τ_{di} for a specific element i (i = 1, 2, 3, …, N) is supplied to accomplish the focusing and steering needed. A delay resolution, as fine as possible, is desired in order to obtain a well-focused beam [5]. The functions of a transmit beamformer also include high driving voltage and apodization weight w_i for each

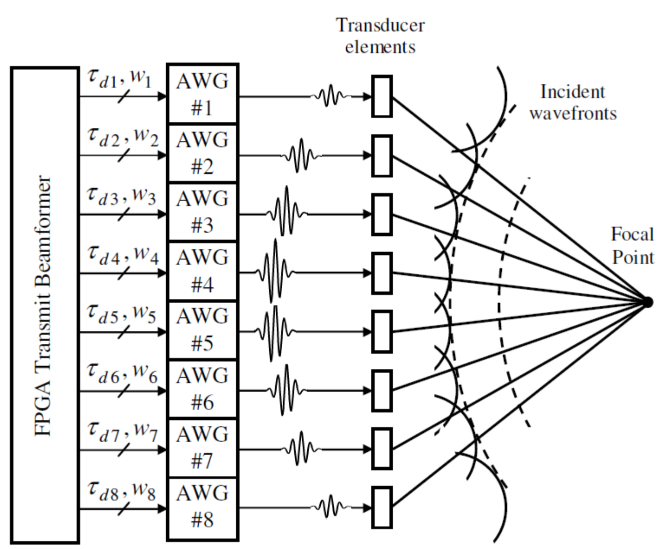

Figure 1. Basic focusing type beamformation with symmetrical delays about phase center.

element i during transmit to reach a satisfactory signal-to-noise ratio (SNR), as well as a good penetration depth [6].

III. SYSTEM DESCRIPTION

As shown in the block diagram in Fig. 2, the proposed research transmit platform consists of a computer that serves as the user interface, an eight-channel transmitter, a FPGA-based transmit beamformer, and an eight-channel transceiver (T/R switches). The overall hardware consists of 2 PCB boards: a digital FPGA-based transmit and control board, and an AWG and analog transceiver board.

The typical needs of US transmit research have been taken into account in the system concept (see Table I) to introduce the possibility of providing extensive user control of transmission parameters during pulse-echo experiments. Individual excitation, including amplitude, phase and time delay, can be transmitted to each transducer element and arbitrarily changed between consecutive pulses at a frequency called the pulse repetition frequency (PRF) [2] that can range from 62.5 to 8 kHz depending on the desired depth of interrogation. For example, it would be possible to develop coded excitation to improve sensitivity without resolution tradeoff [7] or special waveforms capable of compensating each transducer response [8].

The transmit beamformer architecture was implemented using a commercial FPGA test board, which communicates with the AWG board, through a 172-pin High-Speed Mezzanine Card (HSMC) interface.

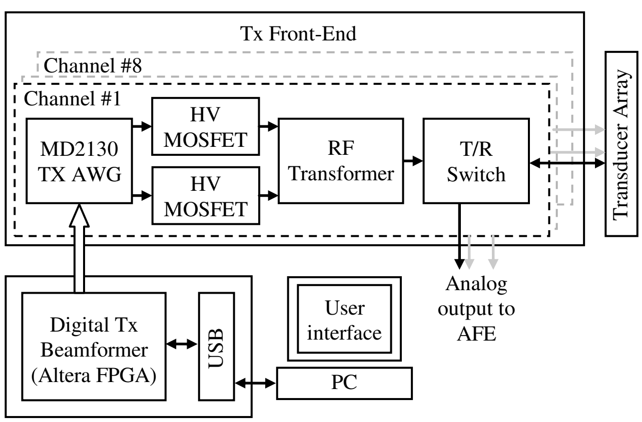

Figure 2. Block diagram of the digital transmit beamformer.

TABLE I. MAIN FEATURES OF THE SYSTEM

System specification	
General features	FPGA-based open architecture 8 independent AWG Tx channels 8 T/R switches 8 SMA connectors for AFE evaluation boards USB interface Compact size: 330 mm x 160 mm
Transmitter	Possibility to independently drive 8 transducer elements High-speed SPI – 20 MHz Amplitude adjustment – 8 bit DAC AWG Phase adjustment: 0° – 360° (multiples of 7,5° step) PRF from 62.5 Hz to 8 kHz Output bandwidth: 500 kHz – 20 MHz Output power: up to 100 Vpp

A. *FPGA Board*

The FPGA board (Cyclone III FPGA Development Board, Altera, San Jose, CA) uses an Altera EP3C120 FPGA and allows communication through an USB interface to a personal computer (PC) in which a specific Graphic User Interface (GUI) is developed for control and configuration. The communication between the FPGA and the AWGs is performed by eight high-speed SPI (Serial Peripheral Interface) to achieve fast updating per-scan-line for changing the beamforming phase angles and apodization amplitudes. Concatenated chain of look-up tables (LUTs) housed in the FPGA memory are utilized to store the excitation arbitrary waveforms to reduce the computational burden. Then, by chaining the tables, the desired reproduction excitation sequence, with a specific burst and adjustable frequency, amplitude and phase angle, can be applied to the transducer.

B. *AWG Board*

The two layers AWG board consists of eight high-speed arbitrary waveform push-pull source driver MD2130 (Supertex Inc., Sunnyvale, CA), a high voltage (HV) N-type MOSFET pair DN2625 (Supertex Inc., Sunnyvale, CA) for each IC AWG, that operates as a high-speed inverting push-pull switch, eight RF transformers ADT1-6T (Mini Circuits, Brooklyn, NY) for impedance matching and isolation, and eight SMA 50 Ω jacks (Samtec Inc., New Albany, IN) to connect the transducer elements. Following the transformers, eight T/R switches were used to prevent overload of the receive analog front-end, since eight output SMA 50 Ω jacks allow connection with analog-front end (AFE) evaluation boards such as the AFE5805EVM (Texas Instruments Inc., Dallas, TX) and HSC-ADC-EVALC (Analog Devices, 2007). Pairs of 0.1 µF and 1 nF low impedance bypass capacitors, and chokes are used for decoupling at each important power pin. The 3 A peak output current ensures the pulser's driving capability to transducer piezoelectric materials and connection cables.

The MD2130 circuit consists of the 3,3 V CMOS digital logic input, 8-bit current DAC for the waveform amplitude control and four PWM (Pulse Width Modulation) current-sources, individually controlled by the FPGA. These current sources are constructed with the high-speed in-phase and quadrature current-switch matrix and the built-in sine and cosine angle-to-vector LUT. The angular resolution of the vector table is 7.5° per step with total range of 48 steps. Additional information about the MD2130 IC can be found in [9].

C. *Computer Software*

The computer programming graphical user interface (GUI) has been developed with Matlab R2010a (The MathWorks, Inc.) in the Windows (Microsoft Corp., Redmond, WA) platform. This software can be easily updated and presents a user friendly interface to facilitate the interaction with the 8-channel hardware through the USB 2.0

channel. Multiple transmission parameters can be selected and enabled individually, including amplitude (8-bit DAC), phase angle (0° to 360° with the increment of 7.5°) and a minimum time delay of 3.125 ns between pulsers, based on the research requirement. Others settings, such as, excitation waveform, the PRF, and center frequency are selected for all channels, and could be determined by the requirements of either B-mode imaging or other imaging research. All these settings, used during US researches, can be saved and loaded at any time, as shown in Fig. 3.

IV. Experimental Results

The complete hardware architecture is shown in Fig. 4. The performance of the AWG was evaluated using a RC load (1 kΩ and 220 pF) and the system was set to an excitation waveform with the Gaussian profile centered at 20 MHz, with a -6 dB relative bandwidth (BW_{rel} = 50 %). The power supply was set to +70 V for high-voltage pulse generation. The waveforms shown in this paper were recorded by a digital oscilloscope DSO6034A (Agilent Technologies, Santa Clara, CA).

Fig. 5(a) shows the experimental 20 MHz transmit beamforming waveform generated with amplitude of approximately 100 Vpp, and Fig. 5(b) its spectrum. The second harmonic of the produced pulses were less than −40 dB and no additional active damping circuit was necessary.

By controlling the excitation time, the resulting acoustic beam can be electronically steered onto different lines [2]. In order to give a quantitative evaluation of the AWG timing, eight waveforms were generated with the same amplitude and phase angle control, and time delay with increment of 12.5 ns (Fig. 6).

To verify the produced waveforms with different phase angles and apodization amplitudes, Fig. 7 and 8, display respectively, the output waveforms with 8-bit DAC range value from 15 to 255 with the increment of 15 steps, and the output waveforms of phase angle from 0° to 90° with increment of 7.5°.

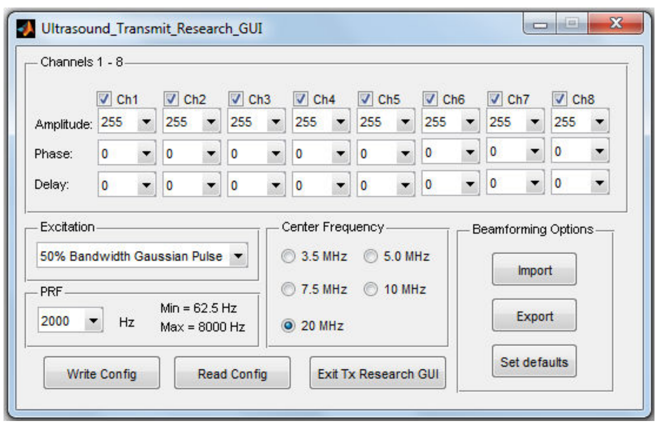

Figure 3. Graphical user interface designed to control the transmission parameters.

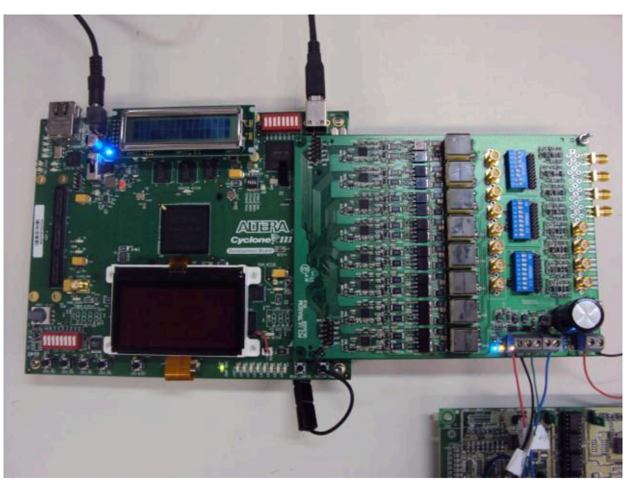

Figure 4. FPGA-based transmit beamformer architecture.

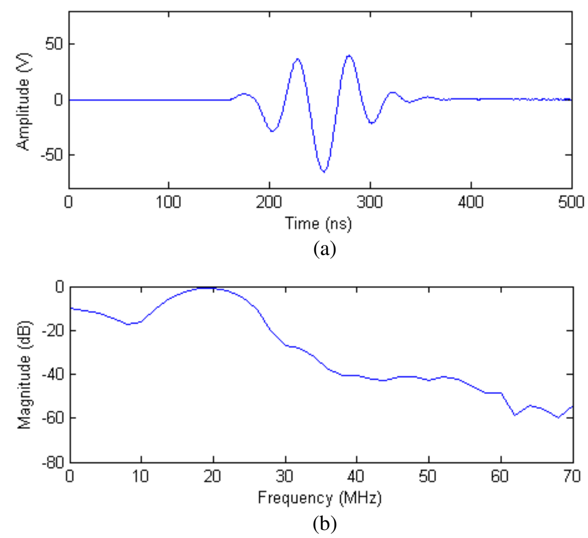

Figure 5. The output waveform measured on a RC load. (a) A 20 MHz (BW_{rel} = 50 %) transmit beamforming waveform with the Gaussian profile and amplitude over 100 V. (b) Pulse frequency spectrum.

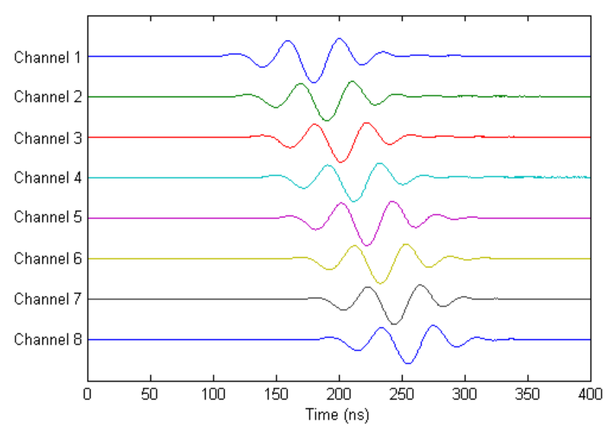

Figure 6. Experimental ultrasonic pulses emitted by the eight channels with same amplitude and phase angle control, and time delay with increment of 12.5 ns.

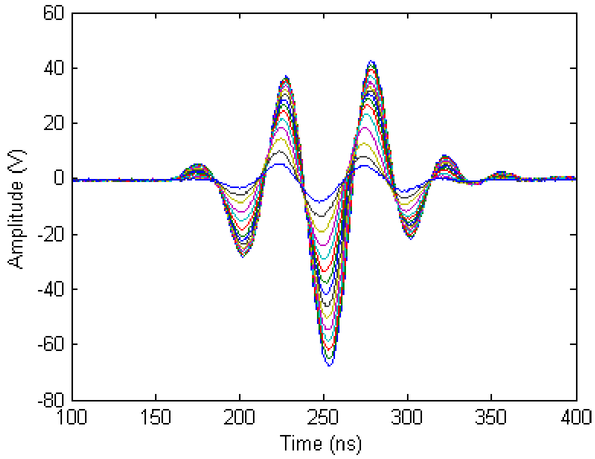

Figure 7. The output waveforms with 8-bit DAC range value from 15 to 255 with the increment of 15 steps.

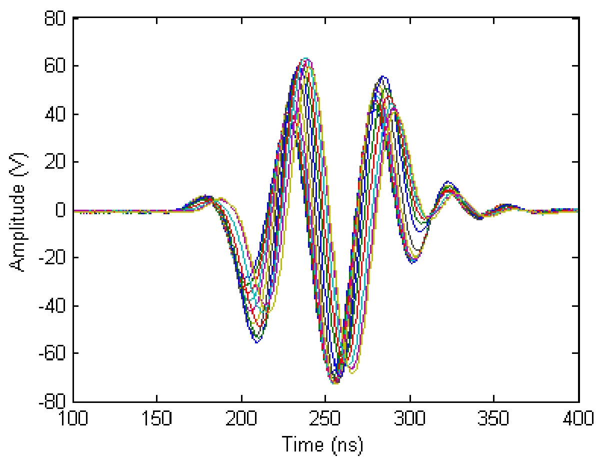

Figure 8. The output waveforms of phase angle from 0° to 90° with increment of 7.5°.

V. CONCLUSIONS

In this paper we describe the design and performance of a programmable 8-channel AWG for the development of new US investigation methods. The flexible transmission FPGA-based platform was implemented using a reasonably inexpensive (~$1000.00) FPGA test board and a house-made dedicated AWG board, which can be connected to any commercial PC through USB 2.0. A GUI software was designed for enabling and selecting the output waveform frequency, phase angle, amplitude, PRF, time delay and programmed excitation waveform. The proposed architecture was tested across onboard equivalent loads and performed exactly as expected, featuring low second order harmonic distortions (< -40 dB) and demonstrating its feasibility. The further optimization of transmit beamforming implementation on the open platform is necessary to facilitate the use on the development and test of new transmission investigation methods.

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