PC-BASED HIGH FREQUENCY IMAGING SYSTEM WITH CODED EXCITATION

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Coded transmission is a technique that gives significant improvement in SNR and enables higher contrast imaging without sacrificing the resolution. A novel HF (20-35 MHz) ultrasound real-time imaging system for research and evaluation of the coded transmission was developed. The digital programmable coder-digitizer module based on the field programmable gate array (FPGA) chip supports arbitrary waveform coded transmission and RF echoes sampling up to 200 MSPS. A novel balanced software architecture supports real-time RF processing and display at rates up to 30 frames/sec. The system was used to gather data for sine burst and 16-bit Golay code excitation using a single element scanning head with thick film focused spherical transducer 25 MHz center frequency and 56% system bandwidth. SNR gain for the Golay codes (referenced to single burst) of 15 dB for 20 MHz and 16 dB for 35 MHz were obtained. In water the axial resolution for both single burst and the Golay codes was the same FWMH=20 ns at 20 MHz and FWMH=15 ns at 35 MHz. The presented system is a practical and low cost implementation of coded excitation technique in HF ultrasound imaging.

INTRODUCTION

Coded excitation is now a widely acknowledged technique for major improvement in SNR and penetration depth in ultrasonic imaging without increasing the peak pressure level [1]. There are many papers devoted to the application of this technique to low frequency ultrasound [3,4]. However, there has been a gap in research that targets high frequency (HF) applications so far. Current HF ultrasound applications encompassing dermatology and ophthalmology are faced with limited penetration depth at frequencies of 20-35 MHz. The visualization depth is limited to 5-7 mm due to rather high attenuation (>18 dB/cm at 25 MHz).

Current applications of ultrasound in dermatology include assessment of tissue edema and wound healing as well as imaging of skin thickness to evaluate diseases such as psoriasis, morphea, scleroderma, and panniculitis. Another important application of ultrasound is the measurement of tumor thickness and volume in skin cancers such as melanoma, basal cell carcinoma and squamous cell carcinoma [2].

Our previous experimental results have shown a great potential of coded excitation in increasing contrast and penetration depth in skin imaging [6,10]. Unfortunately laboratory setup with off-line code compression processing obstructs the real-time evaluation. Thus, we decided to develop a novel real-time signal acquisition and processing system targeted for HF coded ultrasound imaging.

The general idea behind coded transmission is to increase emitted acoustic energy without increasing the peak pressure level by elongating the transmitted waveform. Time compression processing on the receiving side enables to regain resolution. Special waveform modulation types e.g. linear frequency modulation (chirp) and phase modulated binary codes (e.g. Barker, Golay) are characterized by a narrow peak of their autocorrelation function. Time compression is performed on the received RF echoes by means of matched filtering (ie. cross-correlation with the transmitted waveform).

An in-depth overview of the coded excitation technique in medical ultrasound imaging was presented by Misaridis et al. [3]. Pedersen et al. [4] reported a clinical evaluation of the chirp modulation and showed an increase in penetration depth of up to 2 cm for 4 MHz mechanical transducer.

Results for HF coded ultrasound using 16-bit Golay complementary sequences (CGS) were reported by Nowicki et al. [10]. SNR gain close to 14 dB was obtained for 25 MHz $LiNbO_3$ transducer.

Coded transmission requires major modifications in the ultrasound devices (eg. linear analog signal conditioning, high dynamic range RF signal digitization, computationally intensive code compression algorithm) that might be responsible for the few implementations of this technique in commercial equipment [7,11].

1. CODER-DIGITIZER MODULE

The coder-digitizer module is designed as a PC peripheral built on a small printed circuit board (9 x 9 cm) using low-cost and low-power electronic components. The module functionality is controlled by the FPGA and can be easily reprogrammed from the PC at any time. Both the control and data between the PC and the module are passed via a high-speed USB 2.0 interface. Analog input/output amplifiers and power supply are realized as separate modules for greater modularity and noise immunity. Current FPGA design performs the following functions:

- transmission - generation of the arbitrary coded waveforms programmed from the PC,
- acquisition - digitization of the received and amplified ultrasonic RF echoes,
- transfer - streaming of the digitized RF samples from internal buffers to the PC,
- timing - synchronization of the transmission, acquisition and transfer.

Block diagram (Fig. 1) of the module reveals its internal architecture; each part of the design is described below.

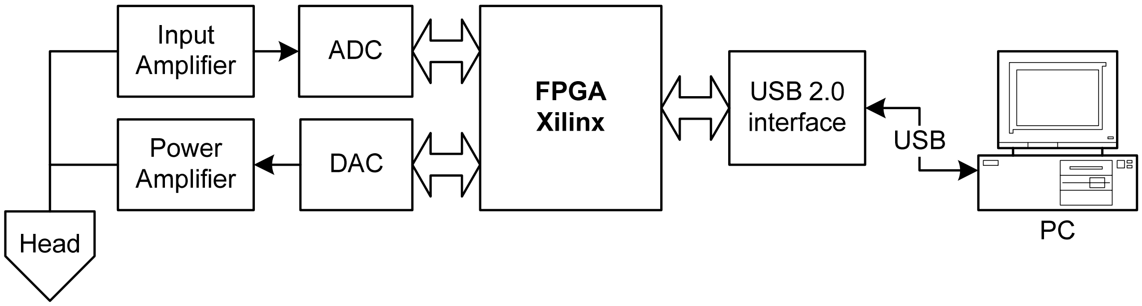

Fig.1 Block diagram of the coder-digitizer module

FPGA

FPGA is the heart of the module that connects and controls all its parts. The low-cost Xilinx® Spartan-3 XC3S400 device provides sufficient speed for 200 MHz operation and resources for internal buffers. Buffers consist of dual TX lines (1024 samples each) - for arbitrary coded waveforms and dual RX (4096 samples each) - for received echoes. Because of the streaming signal processing architecture there is no need for buffering beyond a single (or dual for Golay complementary codes) ultrasonic RF line. Digitized samples are transferred to PC via USB between consecutive line firings. Both the FPGA configuration and transmission/acquisition parameters (buffers depths, acquisition delay, transmission waveforms, etc.) are programmed on-the-fly by the host PC.

ADC, DACs and analog section

A high speed 210 MSPS, 12-bit resolution MAX1214 (Maxim, USA) analog to digital converter digitizes ultrasonic RF echoes preconditioned in the analog section. Two digital to analog converters AD9744 (Analog Devices, USA) with 12-bit resolution and update rate up to 210 MSPS generate arbitrary waveforms stored in the FPGA. The first arbitrary generator is used for the transmitted coded waveforms, the second one is used for programmable time gain compensation. Analog section consists of input low noise amplifier, variable gain amplifier and output linear power amplifier. Linearity of the analog chain is a crucial requirement for the coded transmission system.

USB

USB interface is based on CY68013A (Cypress, USA) chip. For real-time imaging at a reasonable speed (5-10 B-mode frames/second) continuous streaming and processing of the RF samples at 20-30MB/s rate is required. In our system with mechanical sector probe 200 RF lines are acquired per image, each line has 1024-4096 samples depending on the settings.

Transducer

Mechanical sector scan probe consists of 27 MHz center frequency focused spherical transducer (4 mm diameter). The overall bandwidth of the system (transmitter, transducer, receiver) was 56%. The relatively wide bandwidth is achieved using a new thick film PZ-37 transducer (Ferroperm, Kvistgaard, Denmark).

2. DIGITAL RF SIGNAL PROCESSING

Digital signal processing in our system includes 1D RF signal and 2D image processing. To balance the workload and use available resources the processing was split between the main processor (CPU - Central Processing Unit) and the graphics card (GPU - Graphics Processing Unit). This kind of balanced architecture allows us to provide software only processing from the raw digitized RF signal to the B-scan image without any special hardware solutions.

Modern GPU provides enormous processing power and memory bandwidth required for high quality 3D processing. This technology can be used not only for 3D graphics, but also as general processing platform, thanks to the programmable vertex and pixel shader units [8,9].

One dimensional RF signal processing - i.e. pulse compression and envelope detection was implemented on the CPU using optimized Intel® IPP (Integrated Performance Primitives) libraries. Code compression algorithm was implemented in the frequency domain - i.e. correlation of the echo signal and the transmitted replica by FFT spectra multiplication of both signals. This approach is considerably faster than the classical correlation (time domain) for codes lengths exceeding 50 samples. Envelope detection and low-pass filter realization in the frequency domain is also beneficial, because of lower computational cost. To avoid signal distortions caused by the circular nature of the convolution, FFT processing was performed on double length vectors padded with zeros (e.g. 4096 samples RF line was processed using 8192 samples length FFT).

The system works with a single transducer mechanical sector head. To display the scanned sector with correct geometry on the screen, a scan converter is necessary. Two dimensional signal processing, including scan converter and optional 2D image filters, was implemented on the GPU using Microsoft® DirectX library. The sector scan converter was realized using a standard 3D graphics primitive called texture mapping. Texture mapping is a method of laying out rectangular bitmap image onto arbitrary 3D object. In our case the slices of the acquired rectangular B-mode image were mapped onto the generated planar sector shape (similar to the method described by Nikolov et al. [5]). The shape of the sector is automatically recalculated for the current settings (e.g. acquisition depth). Graphics hardware supports automatic texture bilinear filtering which gives good quality results. Implemented GPU software framework supports 2D image filters and color palette mapping. These functions use programmable pixel shaders to perform arithmetic operations on the target image pixels. More advanced image processing e.g.: contrast enhancement, temporal compounding, etc. might be implemented on the GPU in the future. The achieved software processing and display performance on a Pentium 4 PC with NVIDIA® GeForce 7600 graphics card is up to 30 frames/sec. Currently our system works with a frame rate not exceeding 10 frames/sec due to the limited USB bandwidth, which is still reasonably fast for targeted application.

3. RESULTS

At first, the coder-digitizer module was tested in a loop back mode - TX output connected directly to RX input, to verify the signal processing algorithm.

Figure 2 shows the results obtained for the 16-bit complementary Golay sequences. The Golay codes use a pair of firings (Fig. 2a, 2d). The compressed waveforms from two codes (Fig. 2b, 2e) are added together, the sidelobes are completely canceled in the ideal case (Fig. 2c) and the magnitude of the main lobe is doubled. The last step in RF line processing is an envelope detector (Fig. 2f). In this setup perfect Golay codes sidelobes cancellation is obtained.

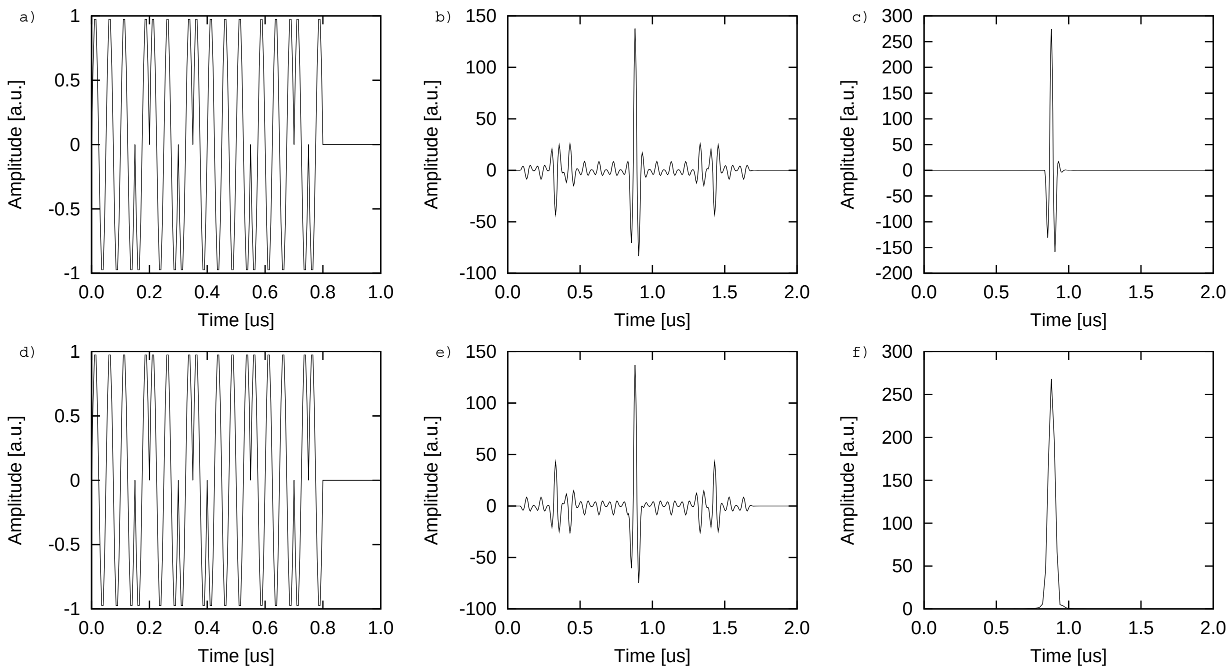

Fig.2 System verification in a loop back mode using 16-bit Golay codes at 20 MHz: a) Golay code A, b) time compressed code A, c) sum of time compressed code A and B, d) Golay code B, e) time compressed code B, f) envelope of the time compressed Golay codes

Next, the system (the module with analog amplifiers) was connected to the scanning head with stopped motor (for m-mode acquisition). Figure 3 shows the echo from a brass reflector located at the focal depth immersed in water with 1 cm of tissue mimicking material when the transducer was excited with a single burst (1 period of 20 MHz sine). The reflected echo envelop (Fig. 3b) had FWHM=30 ns (Full Width at Half Maximum) and SNR=36 dB. Figure 4 shows the echoes from the reflector for transmission of 16-bit Golay code at 20 MHz center frequency. It is clearly visible that the wide band power spectrum of the transmitted Golay code is highly filtered by the transducer and medium (Fig. 4e), but still time compression can restore the axial resolution (Fig. 4f) FWHM=30 ns, the same as for 1-period sine excitation. On the other hand the quality of time compression is influenced by attenuation and sidelobe cancellation is not fully achieved. The real advantage of the Golay excitation is the SNR gain +14 dB (Golay SNR=50 dB versus 36 dB for the sine burst). Code compression gain is proportional to the time-bandwidth product.

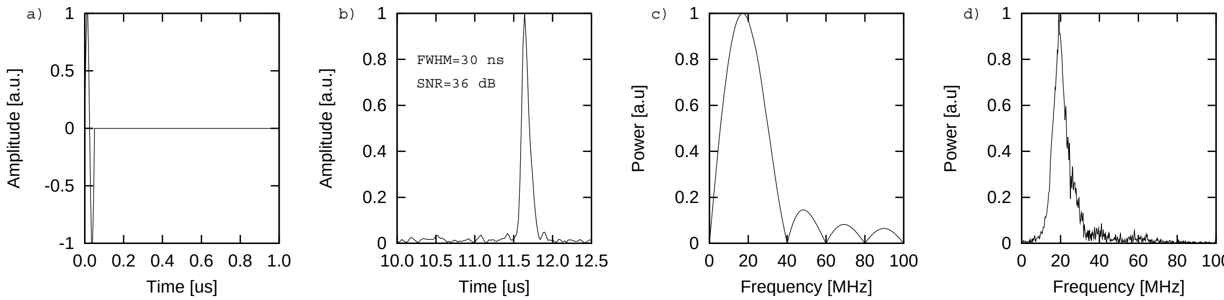

Fig.3 Experimental echoes from the reflector: a) transmitted 1 period sine at 20 MHz, b) envelope of the echo signal, c) power spectrum of transmitted signal, d) power spectrum of received echo

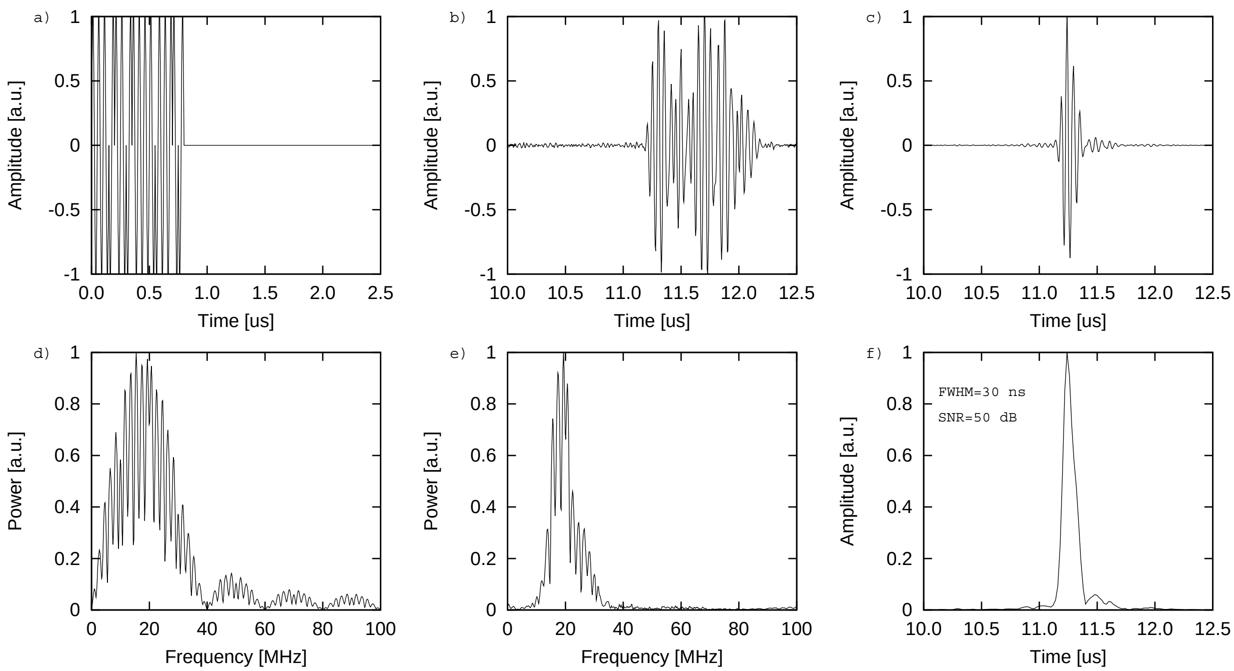

Fig.4 Experimental signals from the reflector: a) transmitted 16-bit Golay code – for brevity one of the pair, b) received code echo from the reflector, c) time compressed echo signal, d) power spectrum of transmitted code, e) power spectrum of received code echo, f) envelope of the compressed echo signal

The in vivo experimental data collected by scanning different skin sites clearly proved increased penetration and SNR comparing to the standard short pulse transmission. To show the possibilities of the Golay codes we present qualitative results obtained for 20 MHz burst and 16-bit Golay excitation for 35 MHz carrier frequency (Fig. 5).

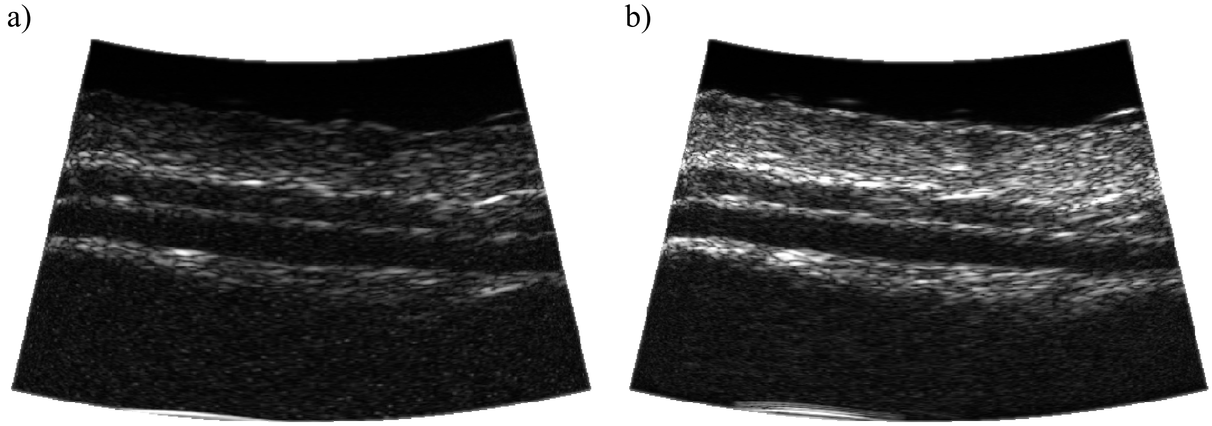

Fig.5 B-mode skin image for: a) 2-period sine excitation at 20 MHz,
b) transmitted 16-bits complementary Golay codes at 35 MHz.
The images show the longitudinal scans of the vein in the palm of the hand

The improved contrast and penetration of the CGS image is clearly visible. Good penetration depth and significantly improved image resolution for 35 MHz Golay excitation is especially interesting. At this frequency single burst excitation imaging was of the very poor quality (not shown). As it was discussed previously, this image exhibits the SNR gain close to 14 dB in comparison to that produced by the sine burst transmission. The noise present in the sine burst image is clearly suppressed in the CGS one, indicating considerable improvement in contrast dynamics.

2. CONCLUSIONS

A novel versatile real-time ultrasonic coded imaging system was developed. The system enables the evaluation and optimization of the coded excitation technique both in a laboratory and clinical environment. High level of system integration and programmability was achieved by the application of programmable hardware (FPGA) and the full software RF processing. The unique feature of the presented system is the real-time coded imaging with the possibility of switching between different excitation schemes during the experiment/examination. Preliminary results confirm the SNR improvement for coded transmission (+14 dB for 16-bit Golay codes at 20 MHz) while preserving axial resolution. The experimental skin images showed visible improvement in contrast and resolution even for the shallow structures, thanks to the higher frequency enabled by the CGS SNR gain. This shows two possible application schemes for the coded transmission. The first is extending the penetration depth, but this is limited by the out of focus resolution for single element transducers. The second is preserving the penetration depth with increased carrier frequency (i.e. increased resolution). The high level of system programmability enables implementation of more advanced processing algorithm. Further research will be aimed at investigating the adaptive mismatched filtering to reduce the range sidelobes caused by the tissue attenuation.

Fig.6 The complete system view

ACKNOWLEDGMENT

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