ARCHIVES OF ACOUSTICS
32, 4 (Supplement), 81–86 (2007)

UNIVERSAL CODED ULTRASOUND IMAGING SYSTEM WITH SOFTWARE PROCESSING

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(*received July 15, 2007; accepted October 2, 2007*)

Coded transmission is a technique to solve the inherent compromise between penetration and resolution required in ultrasound imaging. Our aim was to examine the performance of the coded excitation in HF (20–35 MHz) ultrasound imaging. For this purpose a novel real-time imaging system has been developed. The digital programmable coder-digitizer module supports arbitrary coded waveform generation and RF echoes sampling up to 200 MSPS. All digital RF and image processing was implemented in software. The system performance was evaluated with a single thick-film transducer (focused 25 MHz, 75% bandwidth) scanning head. The RF echoes were acquired from a perfect reflector located with 1 cm of tissue mimicking material. Single sinus burst and 16-bits Golay codes excitations were evaluated. SNR gain for the Golay codes (referenced to single burst) of 15 dB for 20 MHz and 16 dB for 35 MHz were obtained. The axial resolution measured at half maximum was 35 ns for 20 MHz and 25 ns for 35 MHz for both single burst and the Golay codes. It clearly shows that the Golay codes can perfectly restore the resolution while giving respectable SNR gain.

Keywords: medical imaging, coded excitation, high frequency ultrasound, digital signal processing.

1. Introduction

Coded excitation is a technique for major improvement in SNR and penetration depth in ultrasonic imaging without increasing peak pressure levels [1]. There are numerous papers devoted to the application of this technique to low frequency ultrasound. 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 penetration depth shortage at frequencies 20–35 MHz where the visualization depth is limited to 5–7 mm due to rather high attenuation (> 18 dB/cm at 25 MHz).

Our previous experimental results have shown a great potential of coded excitation in increasing contrast and penetration depth in skin imaging [3, 4]. However laboratory setup with off-line processing obstructs the real-time evaluation. Thus, a novel real-time signal acquisition and processing system targeted for HF coded ultrasound imaging was proposed.

2. Coded transmission

The fundamental idea behind coded transmission is to increase the emitted energy without increasing the peak pressure level by elongating the transmitted waveform while still preserving resolution using the time compression processing. Special waveform modulation methods e.g. frequency modulation (chirp), binary codes (Barker) and binary complementary Golay sequences (CGS) codes are characterized by a time localized narrow peak of their autocorrelation function. Time compression is performed on the received RF echoes by means of matched filtration – i.e. cross-correlation with the transmitted waveform. Clinical evaluation of the chirp modulation by PEDERSEN *et al*. [2] showed an increase in penetration depth by around 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*. [4]. SNR gain close to 14 dB was obtained for 25 MHz $LiNbO_3$ transducer. Practical application of coded signals faces some technical challenges: linear signal conditioning in analog input chain, linear power amplification in analog output stage, high dynamic range RF signal digitization and computational intensive code compression algorithm on digitized RF data. These major changes required in ultrasound devices might be responsible for not so numerous implementation of the coded transmission in commercial equipment.

3. Coder-digitizer module

The coder-digitizer module was realized as a PC peripheral. The device functionality is embedded in the FPGA (Field Programmable Gate Array) 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. Currently implemented FPGA design realizes the following functionality:

- generation of the arbitrary coded waveforms for transmission (with support for dual transmission for the Golay codes),
- digitization of the received ultrasonic RF echoes,
- timing and synchronization of the transmission and reception process,
- streaming of the digitized RF samples to the PC.

Block diagram (Fig. 1) of the module shows its internal architecture.

- *FPGA* – a low-cost Xilinx® Spartan-3 device provides sufficient speed for 200 MHz operation and resources for internal buffers. Digitized samples are transferred to PC via USB between consecutive line firings. Both the FPGA configuration and transmission/acquisition parameters are programmed on-the-fly by the host PC.
- *ADC* – a high speed 200 MSPS, 12-bit resolution ADC (Analog to Digital Converter) digitizes ultrasonic RF echoes preconditioned in the analog section.

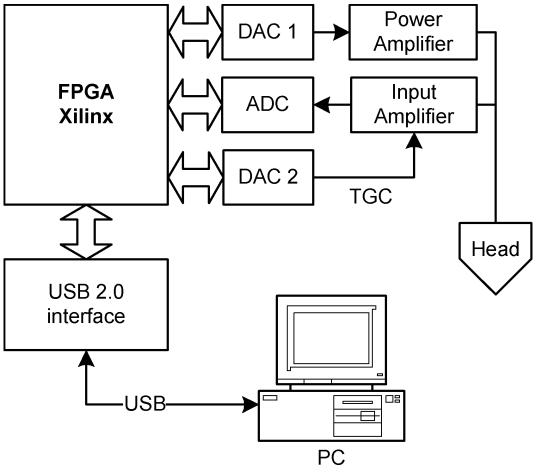

Fig. 1. Block diagram of the coder-digitizer module.

- *DACs* – (Digital to Analog Converter) 12-bit resolution, 200 MSPS generates arbitrary coded waveforms used for transmission. The second DAC is used for programmable TGC (Time Gain Compensation).
- *Analog input/output* – section consists of input low noise amplifier and output linear power amplifier. Linearity of the analog chain is a crucial condition for the coded transmission system.
- *USB* – interface supports real-time streaming of RF samples at a speed of 5–10 B-mode frames/second.
- *Head* – mechanical sector probe consisted of 25 MHz center frequency focused spherical transducer (4 mm diameter). The overall bandwidth of the transducer was 75%. The relatively large bandwidth was achieved using a new thick film PZ-37 transducer (Ferroperm, Kvistgaard, Denmark).

4. 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. The 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 realized in the frequency domain – i.e. correlation of the echo signal and the transmitted replica by spectra (FFT) multiplication of both signals. This approach is considerably faster than the classical correlation (time domain) for codes lengths of 50 samples and more. The system works with a single transducer mechanical sector head. To display the scanned sector with correct geometry, a scan converter is necessary. We decided to implement the scan converter on a GPU using Microsoft® DirectX library. Rectangular to sector scan conversion was realized by a standard 3D graphics primitive – texture mapping. Texture mapping is a method of laying out rectangular bitmap image onto arbitrary 3D object. Graphics hardware supports automatic texture bilinear filtering which gives good quality results. 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.

5. Results

At the beginning the coder-digitizer module was tested in a electrical loop back mode (TX output connected to RX input) in order to verify the signal processing algorithm. Next, the whole system (including analog section) was connected to a wobbler head. Figure 2 shows the echo (single m-mode line) from the reflector immersed in water when the transducer was excited with a single burst (1 period of 20 MHz sinus). The reflected echo envelop (Fig. 2b) has $\mathrm{FWHM} = 30$ ns (Full Width at Half Maximum) and $\mathrm{SNR} = 36$ dB.

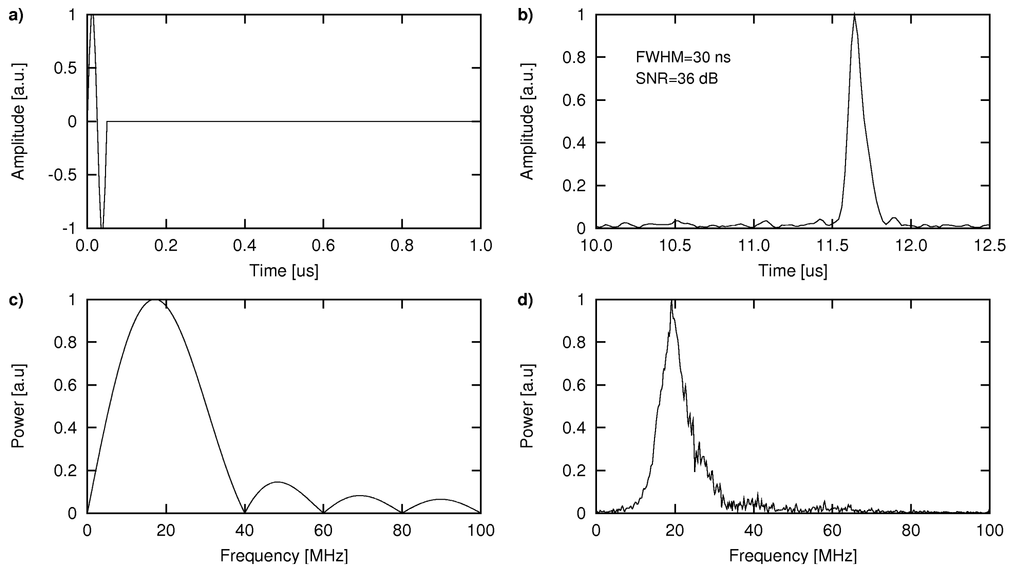

Fig. 2. Experimental echoes from the reflector: a) transmitted 1 period sinus at 20 MHz, b) envelope of the echo signal, c) power spectrum of transmitted signal, d) power spectrum of received echo.

Figure 3 shows the echoes from the reflector in water 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 (Fig. 3d), but still time compression can restore the axial resolution (Fig. 3f) $\mathrm{FWHM} = 30$ ns, as for 1-period sinus excitation. The real advantage of the Golay excitation is the SNR gain $+14$ dB (Golay $\mathrm{SNR} = 50$ dB versus 36 dB for sinus). Code compression gain is proportional to the time-bandwidth product. The presented Golay codes have 20 MHz bandwidth, while the available system fractional bandwidth is 50% (10 MHz).

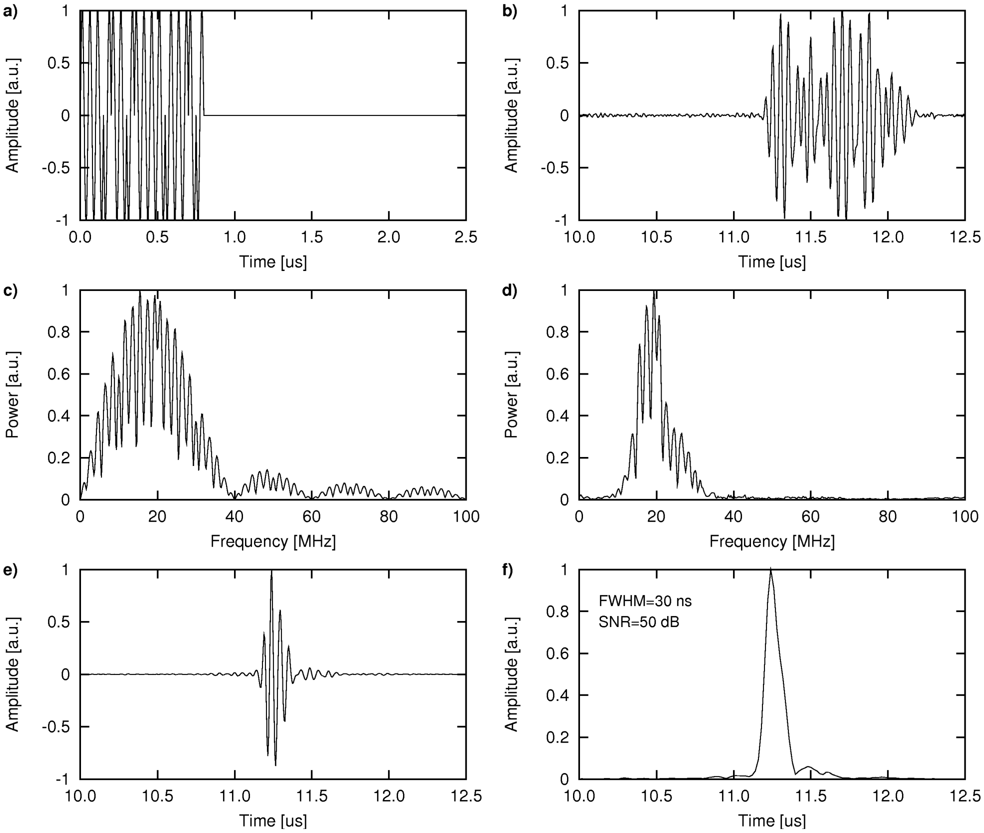

Fig. 3. Experimental signals from the reflector: a) transmitted 16-bit Golay code – for brevity one of the pair, b) received code echo from the reflector, c) power spectrum of transmitted code, d) power spectrum of received code echo, e) time compressed echo signal, f) envelope of the compressed echo 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. The improved contrast and penetration of the CGS image is noticeable (Fig. 4) even when using much higher frequency for the Golay codes (35 MHz versus 20 MHz for sinus). As 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.

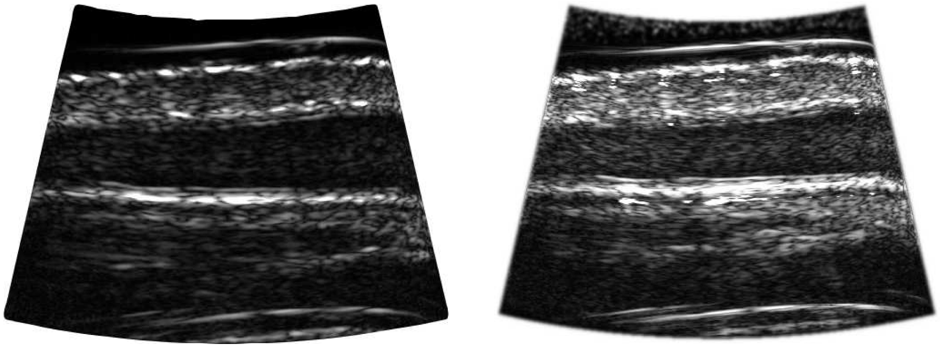

Fig. 4. B-mode skin image for: 2-period sinus excitation at 20 MHz (left), transmitted 16-bits complementary Golay codes at 35 MHz (right). The images show the longitudinal scans of the vein in the palm of the hand. The last one clearly exhibits the improved axial resolution and sensitivity; the backscattered echoes from red cells are visible as well as intima-media thickness.

6. Conclusions

A novel universal 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. 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. High speed coder-digitizer module enables a wide range of ultrasonic application including standard and high frequency imaging.

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 great improvement in contrast and resolution even for the shallow structures, thanks to the higher frequency enabled by the CGS SNR gain. When using 16-bit CGS it was possible to almost double fundamental frequency, thus obtaining better image resolution and at the same time much better contrast at deeper depths in comparison to the single burst excitation.

Acnowledgment

This work was supported by the Polish Ministry of Science and Higher Education as a research project.

References

[1] HAIDER B., LEWIN P. A., THOMENIUS K. E., *Pulse elongation and deconvolution filtering for medical ultrasonic imaging*, IEEE Trans. Ultrason. Ferroelectr. Freq., **45**, 98–113 (1998).

[2] PEDERSEN M. H., MISARIDIS T. X., JENSEN J. A., *Clinical evaluation of chirpcoded excitation in medical ultrasound*, Ultrasound Med. Biol., **29** (2003).

[3] NOWICKI A., LITNIEWSKI J., SECOMSKI W., TROTS I., *On the application of signal compression using Golay's codes sequences in ultrasound diagnostic*, Archives of Acoustics, **28**, 4, 313–324 (2003).

[4] NOWICKI A., LEWANDOWSKI M., SECOMSKI W., LITNIEWSKI J., *High frequency imaging using coded Golay transmission*, IEEE Intern. Ultrasonics Symposium, Rotterdam, The Netherlands 2005.