Ultrasonics 60 (2015) 65–75

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

A real-time chirp-coded imaging system with tissue attenuation compensation

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ARTICLE INFO

Article history:
Received 16 June 2014
Received in revised form 30 December 2014
Accepted 16 February 2015
Available online 23 February 2015

Keywords:
Ultrasound imaging
Ultrasound tissue attenuation real-time coded imaging
Real-time pulse compression
Chirp signal

ABSTRACT

In ultrasound imaging, pulse compression methods based on the transmission (TX) of long coded pulses and matched receive filtering can be used to improve the penetration depth while preserving the axial resolution (coded-imaging). The performance of most of these methods is affected by the frequency dependent attenuation of tissue, which causes mismatch of the receiver filter. This, together with the involved additional computational load, has probably so far limited the implementation of pulse compression methods in real-time imaging systems.

In this paper, a real-time low-computational-cost coded-imaging system operating on the beamformed and demodulated data received by a linear array probe is presented. The system has been implemented by extending the firmware and the software of the ULA-OP research platform. In particular, pulse compression is performed by exploiting the computational resources of a single digital signal processor. Each image line is produced in less than 20 µs, so that, e.g., 192-line frames can be generated at up to 200 fps.

Although the system may work with a large class of codes, this paper has been focused on the test of linear frequency modulated chirps. The new system has been used to experimentally investigate the effects of tissue attenuation so that the design of the receive compression filter can be accordingly guided. Tests made with different chirp signals confirm that, although the attainable compression gain in attenuating media is lower than the theoretical value expected for a given TX Time-Bandwidth product (BT), good SNR gains can be obtained. For example, by using a chirp signal having BT = 19, a 13 dB compression gain has been measured. By adapting the frequency band of the receiver to the band of the received echo, the signal-to-noise ratio and the penetration depth have been further increased, as shown by real-time tests conducted on phantoms and in vivo. In particular, a 2.7 dB SNR increase has been measured through a novel attenuation compensation scheme, which only requires to shift the demodulation frequency by 1 MHz. The proposed method characterizes for its simplicity and easy implementation.

1. Introduction

Pulse compression methods employ the transmission (TX) of coded waveforms and a matched filter in receive (RX). The application to ultrasound (US) imaging addressed to increase the penetration depth in difficult subjects is still challenging because of practical concurrent factors. Differently from radar, specific problems arise from the non-isolated target detection and the usable time-bandwidth product. The latter is restricted by the limited piezoelectric transducer bandwidth, by the need of dynamic focusing the received echoes, and by the frequency-dependent attenuation of human tissues [1,2]. These problems have been considered in several studies that include simulations as well as experimental works. For example, simulations that evaluate the performance of different coded excitation and the effects of tissue attenuation are presented in [3,4] and [5], respectively. More recently, the possible advantages of processing the echo data after coherent demodulation have been evaluated in real-time in [6] and by post-processing simulated and phantom data in [7].

Often, pulse-compression experimental works have been presented only for single element probes. For example, the bandwidth and resolution enhancement obtainable by means of pulse compression have been investigated in [8] through a single-element transducer with a 2.25 MHz center frequency. The University of Leicester has thoroughly tested the possible application of pulse compression in transcranial Doppler investigations based on a 2 MHz probe [9], while some papers have used single-element probes to explore the potential transmission of coded waveforms for contrast imaging purposes (see, e.g., [10]). Single element probes, although mechanically rotated or translated, have also

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http://dx.doi.org/10.1016/j.ultras.2015.02.013
0041-624X/

been used for off-line imaging in [1,11,12], and, by transmitting Golay codes, to produce 10 frames/s in real-time [13]. The use of multi-element array probes obviously increases the technical challenges associated with the physical generation of ultrasound signals with variable amplitude and phase. Off-line images obtained through coded excitation of linear or curved array probes have been shown in [14–16], while in [17] the results obtained with an annular array have been presented. In [18], Barker codes are transmitted through a linear array and the echoes are independently filtered in the RX channels of the powerful RASMUS platform for vector velocity imaging purposes.

Some commercial systems, e.g., ACUSON Sequoia 512 by Siemens Healthcare (Erlangen, Germany), iU22 by Philips Healthcare (Amsterdam, The Netherlands) and modified versions of Logiq 9 scanner by GE Healthcare (Waukesha, WI), actually employ different types of coded transmission. However, not much literature has been made available on the completion of pulse compression methods in real-time imaging systems using array probes. This paper shows that real-time coded imaging can be obtained by properly processing beamformed, demodulated and down-sampled echo-data. For this purpose, the firmware and the software of the ULtrasound Advanced Open Platform (ULA-OP) [19] were suitably extended. By using its multiple Field Programmable Gate Arrays (FPGAs), it is possible to generate arbitrary coded waveforms that will be transmitted from 64-elements of a linear array probe. The RX data will be beamformed, demodulated and down-sampled before being compressed in real-time (less than 20 µs delay) by a mismatched filter.

The system's ease of reprogrammability has been exploited to thoroughly investigate the effects of frequency dependent tissue attenuation. Phantom experiments show that these effects mainly consist in asymmetrically narrowing the received spectra, with consequences in terms of resolution and effective compression gain. By adapting the frequency band of the receiver to the band of the received echo the signal-to-noise ratio and the penetration depth can be increased, as shown by real-time tests both on-phantom and in vivo.

2. Methods

2.1. Pulse compression

In the following, it will be made reference to the signals and the related spectra shown in Fig. 1. Here, $s_{TX}(t)$ represents the chirp signal to be delivered, with appropriate delay, to each active transducer element. It is defined as follows:

$$s_{TX}(t) = a(t) \cdot \sin\left(2\pi f_0 t + \pi \frac{B}{T} t^2\right) \tag{1}$$

where t is time, $a(t)$ is the tapering window, f_0 is the chirp central frequency, B is the spanned band and T is the chirp length. In the receiver,

$$h(t) = w(t) \cdot s_{TX}(-t) \tag{2}$$

is the finite impulse response of the mismatched filter, i.e., a filter matched to $s_{TX}(t)$ and amplitude modulated by a suitable weighting window, $w(t)$. The latter may be chosen in a large class of available windows, each offering advantages and drawbacks in terms of achievable range sidelobe level and resolution in the compressed pulse $c(t)$, which is obtained by convolving the received echo-signal with $h(t)$. Note that the compressed signal $c(t)$, and its spectrum $C(f)$, shown in Fig. 1 are ideal, i.e., they have been obtained by assuming that the backscattered echoes are exact replicas of the transmitted pulse.

2.2. ULA-OP implementation

The experimental work has been based on the ULA-OP open system, which can control up to 64 transmit-receive channels connected to 192-element linear or convex array probes [20]. In this application, the LA533 linear-array (Esaote SpA, Florence, Italy) has been employed. It consists of 192 transducers having 245 µm pitch and performing −6 dB bandwidth between 3.5 MHz and 13 MHz. The active aperture in transmission consisted of 32 elements which were weighted by a Hanning-window apodization,

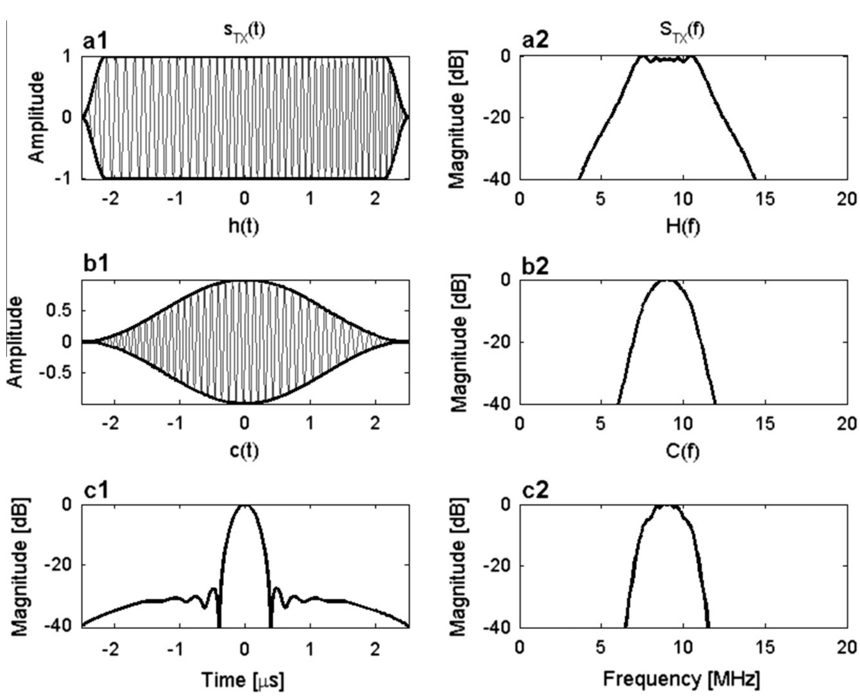

Fig. 1. Main waveforms and spectra involved in a pulse compression system. (a1) signal to be transmitted by each active transducer element; (b1) mismatched filter impulse response; (c1) compressed pulse. (a2), (b2) and (c2) report the spectra corresponding to (a1), (b1) and (c1), respectively.