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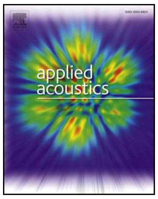

Nonlinear frequency modulated excitation signal and modified compressing filter for improved range resolution and side lobe level of ultrasound echoes

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ABSTRACT

Purpose: A Compensated Frequency Modulated (CFM) code is proposed as an excitation signal of an ultrasound pulse-echo system. It has a flat envelope and a non-uniform spectral energy density distributed throughout the time span and is tuned to equalize the frequency losses imposed by the system, including the transmitting/receiving electronic instrumentation, the transducer and the propagation medium. The CFM synthesis and the compression filter rely on arbitrary variables, one in determining the CFM spectrum magnitude and the other in determining the spectral magnitude of the compression filter that optimizes the side lobe level and duration (range resolution) of the compressed echo pulse.

Methods: The first step is to determine the system transfer function. It is derived from the Fourier transform of an echo signal from a flat reflector, with the transmit/receiving transducer excited by a linear frequency modulated (LFM) signal swept in a frequency range four times the transducer bandwidth, spread symmetrically about the nominal center frequency of the transducer employed in the present work. Experiments were conducted based on a transducer with a half power frequency bandwidth corresponding to 45% of its central frequency and a sweep signal with a time span of 20 μs. Computational simulation was also implemented to determine the effects on the range resolution due to the noise level over the echo signals.

Results: The most relevant results in this research are the range resolution as low as 0.23 mm and the maximum temporal lobes below −36 dB. The range resolution obtained with LFM excitation based on the same ultrasonic system setup was on the order of 1.0 mm.

Conclusions: The novelty of this approach resides in the pseudo-inversion of the system transfer function magnitude. The combined techniques of CFM pre-filtering and pulse compression mode yielded improved performance in relation to the echo signal duration and temporal side lobes; in addition, a gain of 12 dB over the received echo signal was achieved when using an LFM type excitation signal.

1. Introduction

Modulated or coded excitation signals have found a wide range of medical ultrasound applications because of the increased penetration depth. Unlike conventional systems, the −6 dB bandwidth (B) of modulated excitation signals is set independently of the pulse duration (T_p), which can be defined as the interval between start and stop sweep times corresponding to first and last crossings of the modulated excitation signal envelope to the −6 dB level. The independence between B and T_p is very important because the theoretical gain in the signal-to-noise ratio (SNR) by the modulated signals is equal to the time-bandwidth product (BT_p). An additional advantage of using the modulated signals is an increase in the transmitted pulse bandwidth, which can be wider than that of the transducer frequency response [1]. Since the range resolution is inversely proportional to the received echo bandwidth [2], the increase of echo bandwidth improves the range resolution [3–5]. Because of the long duration of the modulated signals, it is necessary to recover the range resolution by a demodulation step, which can be performed through a compression filter applied to the echo signal at the cost of splitting part of the signal energy into undesired temporal sidelobes, which will limit the contrast level applied to the images formed from the compressed echo signal. In addition, temporal sidelobes compromise target detection because of unclear or ambiguous resolution. Considering medical ultrasound, the literature

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recommends the temporal sidelobe maximum level of -45 dB [6].

Modulated echo signals have been compressed by means of a matched or autocorrelation filter, an inverse filter, the cross-correlation between the transducer excitation and echo signals and a Wiener filter [7,8]. Typically, the definition for the efficiency of compression methods resides in the product of the bandwidth and the duration of the compressed echo, with one as the lower limit for this product. Therefore, the closer to one the product is, the more efficient the method becomes.

When the propagation medium is biological tissue, the use of an appropriate synthesis of coded signal becomes more difficult because of the following characteristics of the medium [9]: (1) inhomogeneous wave phase velocity, (2) frequency dependent attenuation, and (3) nonlinear effects on wave propagation. The losses imposed by this medium have a more significant influence if the ultrasound system operates with a wide frequency bandwidth ($> 40\%$), with the losses narrowing the signal bandwidth and displacing the corresponding spectra to lower frequencies. In this case, when employing the simplest scheme of a modulated excitation signal, i.e., the Linear Frequency Modulation (LFM) sweep, no compensation exists for the narrowing bandwidth of the compressed pulse. Even so, the use of LFM sweeps is considered optimum when biological tissues are the propagation media because LFM signals have low sensitivity to the frequency deviations [7,8].

Oelze [9] and Raman [10] presented a different approach to increase the output signal bandwidth of an ultrasound system to beyond that provided with an LFM excitation signal. Instead of compensating the system frequency response by modulating the input energy as a function of time, they tuned the input energy by modulating the amplitude of an LFM excitation signal using an amplitude boost function, that is, the inverse of the system frequency response, precluding the constraint of a constant envelope. The excitation pulse thus formed has relatively higher amplitude values at the beginning and end of its time duration. Moreover, Oelze [9] proposed a resolution enhancement compression (REC) technique that doubled the -3 dB bandwidth of the pulse-echo system output compared to conventional ones. This technique was combined with the pre-enhanced amplitude modulated chirp.

More recently, Fu et al. [11] applied a 13-bit Barker code in a carrier LFM, instead of a sinusoid carrier, to obtain a relative improvement in the range resolution. This encoding resulted in a new excitation signal with reduced dependence on the frequency variations caused by the propagation medium. The phase-coded waveforms, or, more specifically, the binary phase codes, are signals belonging to the B1 subclass of the ambiguity function [12]. They are sensitive to mismatches in frequency in the echo signal caused by the biological tissue and present a relatively high level (> -23 dB) of the temporal sidelobes in the compressed signal, with the maximum sidelobe level calculated as $-20\log(N)$, where N is the length of the Barker code [13]. The robustness of the code proposed by Fu et al. [11] is assigned to the LFM carrier, of the subclass B2 of the ambiguity function, which is insensitive to frequency variations.

The CFM code proposed in this paper has a flat envelope and non-uniform time-spaced amounts of spectral energy density throughout its time span. This approach compensates the spectrum losses from the system, including the transmitting/receiving electronic instrumentation, the transducer and the propagation medium. The CFM synthesis is based on the proposition of a free variable that optimizes the sidelobe level of the compressed pulse and the range resolution.

2. Theoretical basis

The echoes received by ultrasound systems based on transmitted modulated pulses must be demodulated, or compressed, to recover the range resolution provided by the transmitted pulses. As a drawback, temporal sidelobes appear in the compressed signal and compromise the target detection and the contrast capability of the ultrasound system. Pulse compression based on matched filters and applied to the echoes generated by LFM transmitted pulses produces near range sidelobes with unacceptable peaks (-13 dB) compared to the main lobe peak. On the one hand, the near range sidelobes, because of the rectangular shape of the pulse spectrum amplitude, are minimized using mismatched filters, at the expense of range resolution deterioration. On the other hand, the long range sidelobes, because of Fresnel ripples on the pulse spectrum amplitude, are minimized by pre-filtering the transmitted pulse by an envelope-modulated signal [14]. Typically, the near range sidelobes are spaced by the inverse of the pulse frequency bandwidth, whereas the long range sidelobes occur on both sides of the main lobe, and each one is spaced by approximately half of the pulse duration from the center of the compressed pulse. In addition to envelope modulation, pre-filtering of the transmitted pulse can also be performed by pre-distorting the quadratic phase modulation function of the transmitted LFM sweeps. This is equivalent to pre-distortion of the LFM sweep spectrum with a weighting function for the spectral amplitude. In this case, the frequency modulation of the transmitted pulse becomes nonlinear. According to Kowatsch [15], if the pulse has $BT_p < 30$, then cubic phase pre-distortion of the LFM sweep yields better peak reduction for near and long range sidelobes compared to pre-filtering the transmitted pulse using envelope modulation. The time-bandwidth product (BT_p), also known as the compression ratio, defines the relationship between the pulse duration before and after the compression [7]. An illustration on how different phase modulated functions impact on the characteristics of the sidelobes on the compressed pulse is depicted in Fig. 1. A pulse with quadratic phase modulation function (LFM sweep) has compressed pulse near range temporal sidelobe peaks starting at -13 dB from the main lobe peak. However, for a pulse with non-quadratic phase modulation function the corresponding compressed pulse has near range temporal sidelobe peaks starting at -16.3 dB from the main lobe peak. Therefore, the change from quadratic to non-quadratic phase modulation function introduces a reduction of 3.3 dB on the near range temporal sidelobe peak. This effect is at the expense of increasing the main lobe width.

2.1. Phase modulated pulses

Phase modulated pulses are generally expressed as:

$$s_c(t) = \psi_s(t)\exp(j2\pi f_0 t), 0 \leqslant t \leqslant T_P, \tag{1}$$

in which f_0 is the center frequency, t is the time and ψ_s is the complex envelope of the signal, given as $\psi_s(t) = a(t)\exp\{j\varphi_s(t)\}$, with a and φ_s as the amplitude and the phase of ψ_s, respectively. If φ_s is a non-linear function of time, then $BT_p > 1$ [12]. Otherwise, $BT_p = 1$.

By definition, the instantaneous frequency, f_i, and the frequency sweeping rate, γ, are obtained by:

$$f_i(t) = f_0 + \frac{1}{2\pi}\frac{d\varphi_s(t)}{dt}, \tag{2}$$

$$\gamma = \frac{df_i(t)}{dt}. \tag{3}$$

The LFM and time-asymmetric non-linear frequency modulated (NLFM) pulses are advantageous when the propagation medium, such as biological tissue, imposes a spectral displacement to lower frequencies, caused by the frequency dependent attenuation. In such cases, the compression of the LFM and the time-asymmetric NLFM sweeps result in a signal less sensitive to the spectral deviation [13]. Both the amplitude and frequency sweeping rates of the LFM sweeps are constant and have a rectangular spectrum with Fresnel ripples because of the finite pulse width. These intrinsic properties of LFM sweeps inhibit any optimization procedure to minimize near and long range sidelobes. According to Levanon [13], the sidelobes can be minimized by shaping the pulse power spectrum density via a modulation, either