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● *Original Contribution*

INVESTIGATION OF NON-LINEAR CHIRP CODING FOR IMPROVED SECOND HARMONIC PULSE COMPRESSION

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Abstract—Non-linear frequency-modulated (NLFM) chirp coding was investigated to improve the pulse compression of the second harmonic chirp signal by reducing the range side lobe level. The problem of spectral overlap between the fundamental component and second harmonic component (SHC) was also investigated. Therefore, two methods were proposed: method I for the non-overlap condition and method II with the pulse inversion technique for the overlap harmonic condition. In both methods, the performance of the NLFM chirp was compared with that of the reference LFM chirp signals. Experiments were performed using a 2.25 MHz transducer mounted coaxially at a distance of 5 cm with a 1 mm hydrophone in a water tank, and the peak negative pressure of 300 kPa was set at the receiver. Both simulations and experimental results revealed that the peak side lobe level (PSL) of the compressed SHC of the NLFM chirp was improved by at least 13 dB in method I and 5 dB in method II when compared with the PSL of LFM chirps. Similarly, the integrated side lobe level (ISL) of the compressed SHC of the NLFM chirp was improved by at least 8 dB when compared with the ISL of LFM chirps. In both methods, the axial main lobe width of the compressed NLFM chirp was comparable to that of the LFM signals. The signal-to-noise ratio of the SHC of NLFM was improved by as much as 0.8 dB, when compared with the SHC of the LFM signal having the same energy level. The results also revealed the robustness of the NLFM chirp under a frequency-dependent attenuation of 0.5 dB/cm·MHz up to a penetration depth of 5 cm and a Doppler shift up to 12 kHz. (E-mail: m.arif@faculty.muet.edu.pk or https://sites.google.com/site/mdotarif/) © 2017 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Ultrasound, Nonlinear chirp, Pulse compression, Pulse inversion, Harmonic imaging.**

INTRODUCTION

In recent years, ultrasound harmonic imaging has become prevalent in commercial medical ultrasound imaging systems. Ultrasound harmonic imaging relies on second- or higher-order harmonic components. In tissue harmonic imaging, these non-linear harmonics are produced by finite-amplitude distortion of ultrasound waves propagating through biological tissue (Duck 2010), whereas in ultrasound contrast imaging, these harmonics are produced by the non-linear scattering from contrast microbubbles (de Jong et al. 2002; Maresca et al. 2014). Ultrasound images based on the non-linear second harmonic component (SHC) provide improved spatial resolution with reduced reverberation artifacts when compared with conventional (fundamental) B-mode imaging (Jensen 2007; Wells 2006).

Coded excitation techniques were originally introduced in radar communication and now are widely used in medical ultrasound imaging systems to provide improved signal-to-noise ratio (SNR) (Chiao and Hao 2005; Cook and Bernfeld 1967). Coded excitation with long-duration linear frequency-modulated (LFM) chirp signals offer the potential to improve the SNR of the SHC. This can be done without increasing the peak excitation pressure or mechanical index (MI) and without reducing the system frame rate (Cobbold 2007). However, on the receiving side of the system, harmonic matched filters are typically used to extract and compress the SHC and to recover signal axial resolution (Arif et al. 2010a; Kim et al. 2001). The SNR of a chirp signal depends on

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the time–bandwidth product (TBP) and can also be improved by extending the signal bandwidth. However, in ultrasound harmonic imaging applications, the signal bandwidth extension is restricted by the finite bandwidth of the ultrasound transducer to accommodate both the fundamental and the SHC and the spectral overlap between the fundamental and the SHC (Averkiou 2000).

The power spectrum of an unweighted LFM chirp is approximately rectangular and yields a sinc-like function after pulse compression. The compressed chirp signal contains a peak side lobe level (PSL) at approximately −13 dB. This higher value of PSL will mask out the main lobe width (MLW) from the weak scatterer and will potentially degrade the image contrast by appearing as false echoes. Therefore, the higher values of the PSL are unacceptable in modern medical ultrasound imaging systems operating at a dynamic range of more than 60 dB (Johnston and Fairhead 1986; Misaridis and Jensen 2005b).

To reduce the higher PSL of the compressed chirp signal, a strong weighting function is applied either on the transmitting signal or on the received matched filter; the latter case is termed a *mismatched filter*. Windowing on the excitation signal causes a reduction in the transmitting energy and Hence. penetration depth, whereas windowing on the matched filter results in reduced gain in the SNR and axial resolution. Therefore, a trade-off between the MLW and PSL exists in the pulse compression process of the LFM signal (Adams 1991; Milleit 1970).

Non-linear frequency-modulated (NLFM) chirp signals provide an alternative means to modify the rectangular power spectrum of the LFM chirp into a desirable shape. The NLFM chirp can be designed to optimize the signal transmitting energy and the shape of the power spectrum so that it matches spectrally the transfer function of the transducer. This results in transmission of more energy though the transducer, which potentially improves the SNR and penetration depth. Also, a reduced PSL will be obtained after pulse compression without using any additional windowing function on the matched filter (Arif et al. 2010b; Gran and Jensen 2007; Harput et al. 2013; Pollakowski and Ermert 1994).

The effects of shaping the transmitting spectrum using the NLFM chirp for improved spectral matching with the transmitter were first studied by Brandon (1973). He designed the non-linear pulse compression system for radar to obtain high resolution with reduced loss in the SNR. The NLFM chirp was designed using the least-squares optimization method for synthetic transmit aperture B-mode imaging (Gran and Jensen 2007). The NLFM signal with the quadratic instantaneous frequency function was designed and implemented for tissue harmonic imaging (Song et al. 2011).

In the study described here, NLFM chirp coding was investigated as an excitation scheme in ultrasound harmonic imaging. The aim was to reduce the PSL after pulse compression and to improve the SNR of the second harmonic chirp component.

The remainder of this article is organized as follows. In the next section, we describe the basic theory and design methods of NLFM and reference LFM chirp signals, followed by the proposed methods, the simulation and experimental procedures with the post-processing of non-linear received signals, the results of harmonic pulse compression and Doppler sensitivity evaluation of designed chirp signals, and finally, the performance of second harmonic pulse compression achieved using non-linear chirp coding.

THEORY AND SIGNAL DESIGN

Non-linear frequency modulated signals

In exponential form, the time domain chirp signal $x(t)$ can be expressed as Misaridis and Jensen (2005a)

$$x(t) = p(t)e^{j2\pi\phi(t)} \tag{1}$$

where $p(t)$ and $\phi\ (t)$ are the amplitude and phase modulation functions of the chirp signal, respectively.

The spectrum of the chirp signal given in (1) is expressed as

$$X(\omega) = \int_{-\infty}^{\infty} p(t)e^{j\{-\omega t+\phi(t)\}}dt \tag{2}$$

The integrand $[-\omega t+\phi(t)]$ in (2) is an oscillating function that is varying at the rate of (d/dt) $[-\omega t + \phi(t)]$. The major contribution to the chirp spectrum occurs when the rate of change of the oscillating function is minimal and is also referred to as the stationary phase point; this can be expressed as

$$\frac{d}{dt}[-\omega t+\phi(t)] = 0 \tag{3}$$

In (3), ω and t are two independent variables. Therefore, the value of t that can satisfy the condition given in (3) can be found by assuming the value of ω. In the case of an LFM signal with a quadratic phase modulation function, the integral in (2) can be solved analytically. However, in the case of non-linear phase modulation function, the second-order Taylor expansion of phase $\phi\ (t)$ around t_k, which is the solution to eqn (3) at ω_k, is used to reduce the integral in (2) to the Fresnel integral. Hence, after algebraic manipulation, the power spectrum of the chirp signal at ω_k is given by (Arif 2010; Collins and Atkins 1999; Cook and Bernfeld 1967)