CHAPTER 1

INTRODUCTION

Spatial resolution in ultrasonic imaging is one of many parameters that impact image quality. Therefore, mechanisms to improve system spatial resolution could result in improved ultrasound imaging and diagnostic performance including earlier cancer detection and screening, accuracy in tumor staging, and accuracy of thrombus detection and many other improvements to diagnostic imaging [1]. Spatial resolution in an ultrasonic imaging system is dictated by the beam and focal properties of the source (focal number, source bandwidth, etc.), tissue attenuation, nonlinearity of the medium, tissue inhomogeneity (phase abberation, spatial variations in the refractive index), and sound speed [1].

In ultrasound, axial resolution is improved as the bandwidth of the transducer is increased, which typically occurs for higher center frequencies. However, the attenuation of sound typically increases as frequency increases, which results in a decrease in penetration depth. Therefore, there is an inherent tradeoff between spatial resolution and penetration in ultrasonic imaging. One way to increase the penetration depth without reducing axial resolution is by increasing the excitation pulse amplitude. However, increased excitation amplitude results in increased pressure levels that could result in unwanted bioeffects, e.g., heating or damage to tissues [2]. Therefore, increasing the excitation pulse amplitude is not always a viable solution.

An alternate solution would be to increase the excitation pulse duration by using coded excitation which increases the total transmitted energy and allows for the minimization of the transmitted peak power [3, 4]. However, elongating the signal duration has the negative effect of decreasing the axial resolution of the ultrasonic imaging system. In order to restore the axial resolution after excitation with a coded signal, pulse compression is used. Pulse compression can be realized by using many filtering methods such as matched filtering, inverse filtering, and mismatched filtering. The main disadvantage of using coded excitation and pulse compression would be the introduction of range sidelobes that can appear as false echoes in an image. The introduction of range sidelobes is a detriment to ultrasonic image quality because it can reduce the contrast resolution [5]. The main advantage cited for using coded excitation is that it is known to improve the echo signal-to-noise ratio (eSNR) by increasing the time-bandwidth product (TBP) of the coded signal. This improvement in eSNR results in greater depth of penetration in the range of a few centimeters for ultrasonic imaging and improved image quality; i.e., increased eSNR can actually increase contrast resolution. Furthermore, this increase in penetration depth allows the possibility of shifting to higher frequencies with larger bandwidths in order to increase the spatial resolution at depths where normally it would be difficult to image.

1.1 Coded Excitation: Literature Review

Coded excitation and pulse compression techniques have been used successfully in radar since the early 1950s. Originally, radar work performed at Sperry Gyroscope Company [6] used an FM chirp to obtain a 10 dB increase in average signal power, all the while increasing the range detection by 78% with their coded excitation and pulse compression scheme. Other areas such as communications use spread spectrum techniques that utilized phase codes with a transversal filter for pulse compression.

In ultrasound, coded excitation (Golay code) and pulse compression was first tackled by Takeuchi [7, 8] in 1979. In this work, Takeuchi established the differences in signal processing between radar and ultrasound coded systems; specifically, clutter suppression vs. object detection, and TBPs on the order of 10^4 vs. 20, respectively. Takeuchi attributed the limitation in the TBP in ultrasonic imaging to the interaction of frequency-dependent attenuation in tissues and the imaging system time-gain compensator. Although not discussed in Takeuchi's research, a limited TBP results in a decrease of signal-to-noise ratio. In addition, ultrasound suffers from hardware complexity and implementation problems. As a result, coded excitation was not studied in the medical ultrasound community until the 1990s.

In 1992, O'Donnell [9] used a coded excitation (pseudochirp) and pulse compression (equalization filtering) technique to improve the eSNR of an ultrasound phased array imaging system by 15-20 dB. The coded excitation and pulse compression technique contained sidelobes around the -45 dB amplitude level. Nonetheless, the system developed by O'Donnell still had some stringent requirements for practical implementation and significant sidelobes levels.

By the late 1990s, a plethora of manuscripts regarding the subject of coded excitation and pulse compression in ultrasound had been published. In 1994, Rao [10] extended the work performed by Takeuchi by evaluating the effects of attenuation on a linear chirp, which resulted in eSNR degradation. Pollakowski and Ermert [11] evaluated the use of nonlinear coded signals that match the spectrum of the ultrasonic transducer. In 1996, Shen and Ebbini [12,13] developed a new approach for the compression using the pseudo-inverse operator. Moreover, Passmann and Ermert [14] developed a system that improved dermatological and ophthalmological ultrasound images by using a nonlinear frequency modulated chirp along with very high frequencies. Haider et al. [15] developed a pulse elongation and deconvolution scheme that used a stabilized inverse filter to reduce sidelobe artifacts.

In 2005, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* published a special issue on coded waveforms in ultrasonic imaging that included a comprehensive study on coded excitation and pulse compression by Misaridis and Jensen [5,16,17]. Misaridis and Jensen established the basic principles of pulse compression, evaluated design methods of linear FM signals and mismatched filters, and investigated methods to increase the frame rate in ultrasonic imaging when using modulated excitation signals. In 2006, Oelze [18] developed a coded excitation and pulse compression scheme that improves the axial resolution of an ultrasonic imaging system without introducing large range lobes. The technique developed by Oelze, which is known as resolution enhancement compression or REC, is the foundation of this dissertation; therefore, a more detailed explanation is provided in the following section.

1.2 REC: Resolution Enhancement Compression

REC [18] is a coded excitation and pulse compression technique that uses convolution equivalence (shown in Fig. 1.1) to improve the axial resolution and enhance the bandwidth of an ultrasonic imaging system. In REC, a desired pulse-echo impulse response, $h_2(t)$ (Fig. 1.1(d)), is synthetically generated so that time duration is less when compared to the true ultrasonic system pulse-echo impulse response, $h_1(t)$ (Fig. 1.1(a)). As a result, the corresponding bandwidth of $h_2(t)$ is larger than the bandwidth of $h_1(t)$. To obtain the desired impulse response for the imaging system, a pre-enhanced chirp, $v_{pre}(t)$ (Fig. 1.1(b)), is used to excite the source. The pre-enhanced chirp is obtained through convolution equivalence which is described by the following expression:

$$v_{pre}(t) * h_1(t) = v_{lin}(t) * h_2(t), \tag{1.1}$$

where $v_{lin}(t)$ is the linear chirp shown in Fig. 1.1(e). The pre-enhanced chirp is used to selectively excite an ultrasonic source with different energies at chosen frequencies. By exciting the transducer with the pre-enhanced chirp, the bandwidth can be enhanced due to the increase of energy in the frequency bands that normally would be filtered in some measure by the bandpass nature of the transducer. Conceptually, to obtain a constant eSNR per frequency channel across the desired bandwidth, the additional amount of energy required on transmit at the outer frequency bands will depend on the original transducer's bandwidth and the amount of bandwidth boost desired.

Once the source is excited with a pre-enhanced chirp, the received echo is compressed using a Wiener filter based on convolution equivalence. The resulting backscattered signal has an impulse response $h_2(t)$. Wiener filtering is described by the following equation:

$$\beta_{REC}(f) = \frac{V_{lin}^{'*}(f)}{|V_{lin}^{'}(f)| + \gamma \overline{eSNR}^{-1}(f)}, \tag{1.2}$$

where f is frequency, and γ is a smoothing parameter that controls the tradeoff between bandwidth enhancement (axial resolution), gain in eSNR, and sidelobe levels. $V_{lin}^{'}(f)$ is the Fourier spectrum of a modified linear chirp that is used to restore convolution equivalence as the signal is slightly altered and filtered by electronics. $V_{lin}^{'}(f)$ is defined as:

$$V_{lin}^{'}(f) = \frac{H_2^*(f)}{|H_2(f)|^2 + |H_2(f)|^{-2}} \cdot H_{out}(f), \tag{1.3}$$

where $H_2(f)$ is the Fourier spectrum of the desired response, $h_2(t)$, and $H_{out}(f)$ is the Fourier spectrum of an echo obtained from a planar reflector located at the focus upon excitation with a pre-enhanced chirp. $\overline{eSNR}(f)$ is the average eSNR [19] per frequency channel and is defined as:

$$\overline{eSNR}(f) = \frac{|H_{2c}(f)|^2 E\{|F(f)|^2\}_f}{E\{|\eta(f)|^2\}_\eta}, \tag{1.4}$$

where $|F(f)|^2$ is the power spectral density (PSD) of the object function, $|\eta(f)|^2$ is the PSD of the noise, and $|H_{2c}(f)|^2$ is the PSD of the echo signal over noise, $h_{2c}(t)$, which is defined as

$$h_{2c}(t) = E\{g(t)\}_{noise}, \tag{1.5}$$

where E is the expectation value of the argument and $g(t)$ is the echo signal over noise. To obtain $\overline{eSNR}$ experimentally, a measure of the noise per frequency channel is first obtained by estimating the mean of the PSD of a noise measurement from a water bath that contains no imaging target while using the same equipment settings. Thereafter, the signal (which contains noise) power is divided by the noise per frequency channel to get $\overline{eSNR}$.

Figure 1.2 illustrates the enhanced bandwidth of REC by displaying the PSD of the conventional pulsing (CP) and REC waveforms due to a reflection from a point scatterer in a simulated attenuating medium. In the simulation, the attenuation parameter α was set to 0.5 dB $\mathrm{MHz}^{-1}\mathrm{cm}^{-1}$. The simulated source has a center frequency of 10 MHz and the point scatterer is located at an axial distance of 50 mm. The bandwidths at -6 dB were 7.2 MHz and 12.1 MHz for CP and REC, respectively. The original source bandwidths at -6 dB before the inclusion of attenuation and scattering effects into the simulation were 7.9 MHz and 15.5 MHz for CP and REC, respectively. This result illustrated that with REC the bandwidth can be enhanced over conventional ultrasonic imaging methods.

1.3 Outline of Research Topic

A proof of concept for the REC technique has been developed by Oelze [18]. However, the impact that the REC technique may have in improving the diagnostic capabilities of conventional and quantitative ultrasound (QUS) imaging has not been established. Therefore, the overall goal of the studies in this dissertation were classified into two categories:

1. Characterization of the REC technique: The REC technique allows the bandwidth and the axial resolution of an ultrasonic imaging system to be enhanced. An important piece of information regarding the use of the REC technique in diagnostic imaging would be to establish the practical limitations of the technique. To characterize the technique, some imaging quality metrics must be used to quantify the improvements obtained or to establish potential tradeoffs. The effects of nonlinear distortion and frequency-dependent attenuation on the pre-enhanced chirp were evaluated. The potential of transducer heating by excitation of a pre-enhanced chirp was evaluated. Finally, the effects of the spatially varying nature of a transducer's impulse response and the spatial dependence of the eSNR throughout the image were evaluated. These studies represent an in-depth examination of the limitations of coded excitation for ultrasound imaging in general and for the REC technique specifically.
2. Exploration of potential applications where REC could be beneficial: Three applications were evaluated where the improved axial resolution and increased bandwidth available from REC could be beneficial. First, REC was evaluated in combination with frequency compounding to extend the tradeoffs between axial resolution and improved contrast. In the second application, REC was assessed for improving contrast and spatial resolution in QUS imaging.

This dissertation is organized into five parts: introductory remarks (Chapter 1), characterization of the REC technique (Chapter 2), applications where the larger bandwidth obtained using REC helped to improve ultrasound images (Chapter 3), the spatially varying Wiener filter (Chapter 4), a brief summary of the findings (Chapter 5).

1.4 Figures

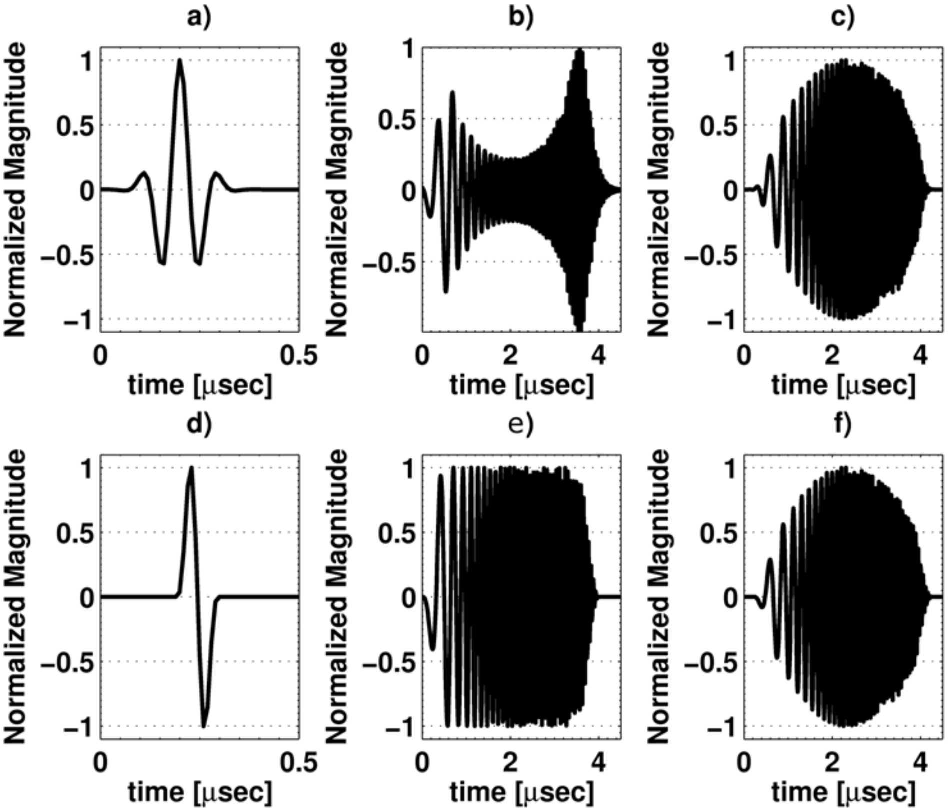

Figure 1.1: Convolution equivalence scheme from a MATLAB simulation: (a) pulse-echo impulse response for a source with an 80% -6-dB bandwidth, (b) pre-enhanced chirp used to excite the 80% bandwidth source, (c) convolution of 80% source with pre-enhanced chirp, (d) pulse-echo impulse response of a desired source with a 150% -6-dB bandwidth, (e) linear chirp used to excite the 150% bandwidth source, (f) convolution of 150% source with linear chirp.

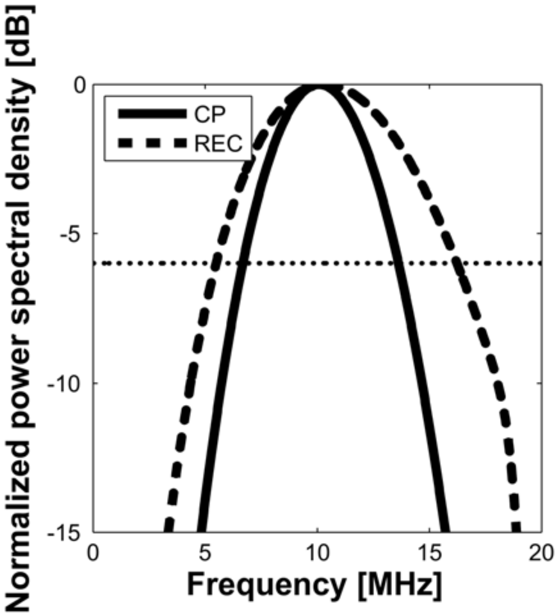

Figure 1.2: Simulated power spectrum of CP and REC (compressed) from a point scatterer in an attenuated medium with $\alpha = 0.5$ dB MHz^{-1}cm^{-1} using a 10 MHz source. The frequency shift for REC and CP were insignificant as the shape of the frequency response was not symmetrical.