Improved Axial Resolution Using Pre-enhanced Chirps and Pulse Compression

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Abstract— **Improving the resolution of an ultrasound imaging device can have broad clinical impact. A novel pulse compression technique is developed that improves the axial resolution of an ultrasound imaging system and provides a boost in the echo signal-to-noise ratio (eSNR). The new technique, called the resolution enhancement compression (REC) technique, was validated with simulations and experimental measurements. The technique relies on exciting the source with a pre-enhanced frequency-modulated (FM) chirp that is found from application of convolution equivalence. Convolution equivalence is used to equate the pre-enhanced FM chirp convolved with the impulse response of the source of finite bandwidth with a linear FM chirp convolved with the impulse response of a source of larger bandwidth. The REC technique uses the linear chirp to compress the excitation waveform resulting in an impulse response with a bandwidth larger than the impulse response from conventional pulsing methods. Simulations and experimental measurements were conducted to validate the REC technique. Image quality was examined in terms of three metrics: the eSNR, the bandwidth, and the modulation transfer function (MTF). The simulations were conducted with a weakly-focused single-element ultrasound source with a center frequency of 5 MHz. The experimental measurements were carried out with a single-element transducer (f/3) with a center frequency of 2.25 MHz. Measurements were taken from a planar reflector and wire targets. In simulations, the axial resolution of the ultrasound imaging system was almost doubled using the REC technique versus conventional pulsing techniques. The axial resolution measured from MTF curves was 0.14 mm and 0.27 mm, respectively. The -3-dB bandwidth was almost doubled from 47% to 96% and maximum range sidelobes were -50 dB. Experimental measurements conducted using the single-element transducer also revealed an improvement in axial resolution using the REC technique versus conventional pulsing. The axial resolution from the MTF curves was 0.31 mm and 0.44 mm, respectively. The -3-dB bandwidth was doubled from 56% to 113% and maximum range sidelobes were observed at -45 dB. In addition, a significant gain in eSNR (9.2 to 16.2 dB) was achieved in both simulations and experiments. Improvement in axial resolution, doubling of the system bandwidth, and a gain in eSNR were achieved with the REC technique with range sidelobe levels compatible with ultrasound imaging systems.**

Coded excitation; pulse compression; resolution enhancement; chirps; axial resolution

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I. INTRODUCTION

Coded excitation and pulse compression were first used in radar to significantly improve the echo signal-to-noise ratio (eSNR) over conventional pulsing techniques [1, 2, 3]. The increase of eSNR through pulse compression comes about by increasing the time-bandwidth product (TBP) through longer time signals than conventional pulsing techniques. The increase in eSNR increases the detection range of radar without appreciable loss in resolution.

Pulse compression techniques have been adapted successfully to ultrasonic imaging for the purpose of increasing the eSNR without increasing the acoustic pressure [4, 5]. The improvement of eSNR allows for deeper penetration of ultrasonic waves and improved image quality.

Increasing the eSNR, spatial resolution and bandwidth of an imaging system may be accomplished through specialized frequency-modulated (FM) chirps and pulse compression. Raman and Rao [6, 7] suggested that specialized FM chirps could be formulated, which under pulse compression could yield improved axial resolution and increase the -3-dB bandwidth of the imaging system. In that study, the frequency response of the source was assumed to be approximately Gaussian. An inverse Gaussian boost function (inverse of the frequency response) was used to create a pre-enhanced FM chirp that could be used under pulse compression to effectively increase the -3-dB bandwidth of the received signal. The pre-enhanced FM chirp was created by weighting a linear FM chirp function with the inverse of the approximate frequency response of the system. Pulse compression was accomplished by taking the autocorrelation of the measured waveforms (a matched filtering approach). The technique increased the -3-dB bandwidth of the source by 40-50% but with some increase in the sidelobe levels.

The present study examines the use of pre-enhanced FM chirps to improve the axial resolution and effectively increase the -3-dB pulse/echo bandwidth and the useable bandwidth of the ultrasonic imaging system. A technique is developed to construct optimal pre-enhanced FM chirps. Further, the new technique, called the resolution enhancement compression (REC) technique, enables the enhancement of axial resolution in the imaging system without large sidelobe levels. The REC technique offers four distinct novelties over the techniques introduced by Raman and Rao [6, 7]. First, the pre-enhanced chirps are constructed using convolution equivalence and the impulse response of the actual source. Second, pulse compression is accomplished through mismatched filtering in the frequency-domain as opposed to autocorrelation of the measured waveforms. Third, the REC technique makes use of convolution equivalence to decrease sidelobe levels over the approach by Raman and Rao. Finally, by using the convolution equivalence, the shape of the compressed waveform can be better controlled and to a limited degree shaped to the user's application.

II. THEORY

The total shift-varying impulse response of the imaging system is the convolution of the impulse response of the source and the voltage waveform used to excite the source,

$$h(nT,x) = \sum_{m=-\infty}^{\infty} v_1[n-m]h_1(mT,x) = \{v_1 * h_1\}(mT,x), \quad (1)$$

where $v_1[n]$ is the voltage waveform and $h_1(nT,x)$ is the pulse-echo impulse response of the system. The total shift-varying impulse response is not unique to a particular pulse-echo impulse response of the system. There may exist some pulse-echo impulse response for an imaging system, $h_2(nT,x)$, that when convolved with a different voltage waveform, $v_2[n]$, is equivalent to (1) or,

$$\{v_1 * h_1\}(mT,x) = \{v_2 * h_2\}(mT,x), \quad (2)$$

for some spatial location. Equation (2) implies convolution equivalence between two different impulse responses convolved with the appropriate voltage waveforms. An example of convolution equivalence is illustrated in Fig. 1. Two different impulse response functions (Fig. 1a, b) are convolved with two FM chirps (Fig. 1c, d) to yield an equivalent convolved waveform (Fig. 1e).

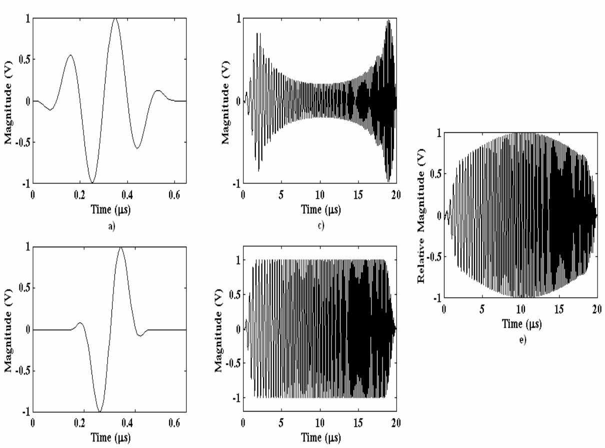

Figure 1. a) Pulse with approximately 47% -3-dB pulse/echo bandwidth, b) pulse with approximately 96% -3-dB pulse/echo bandwidth, c) modified chirp used to excite the 47% bandwidth source, d) linear chirp used to excite the 96% bandwidth source, e) convolution of the pulses with their respective chirps sequences.

Suppose that the voltage waveform used to excite the source with impulse response, $h_2(nT,x)$, is given by the linear FM chirp sequence, $v_2[n] = v_{Lin-chirp}[n]$. If a different FM chirp sequence (we denote as the pre-enhanced FM chirp or $v_{P-chirp}[n]$) is used to excite the source with impulse response, $h_1(nT,x)$, such that,

$$v_1[n] = v_{P-chirp}[n] = v_{Lin-chirp}[n] * \beta[n], \quad (3)$$

then $\beta[n]$ is some undetermined weighting function that can be found through application of convolution equivalence. From (3),

$$v_{P-chirp}[n] * h_1(nT,x) = v_{Lin-chirp}[n] * h_2(nT,x). \quad (4)$$

Rearranging the terms yields

$$\begin{aligned} v_{P-chirp}[n] &= v_{Lin-chirp}[n] * h_2(nT,x) * h_1^{-1}(nT,x) \\ &= v_{Lin-chirp}[n] * \beta[n] \end{aligned}, \quad (5)$$

where $\beta[n] = h_2(nT,x) * h_1^{-1}(nT,x)$.

III. EXPERIMENTAL METHODS

A. Experimental Setup

A single-element weakly-focused (f/3) transducer (Panametrics; Waltham, MA) was used in the experimental measurements. The transducer had a center frequency of 2.25 MHz and a 56% -3-dB pulse/echo bandwidth. Chirp waveforms were excited with an arbitrary waveform generator (Lecroy LW 400A; Chestnut Ridge, NY) with a sampling frequency of 400 MHz. The chirp signals were created with Matlab (The Mathworks Inc., Natick, MA) and downloaded to the arbitrary waveform generator. The signal was amplified with a 2100L RF power amplifier (ENI; Rochester, New York). The amplified signal (50 dB) was connected to the transducer through a diplexer. The received echo signal was connected to a Panametrics 5800 (Waltham, MA), which in turn was connected to an oscilloscope (Lecroy 9354 TM; Chestnut Ridge, NY).

Three sets of experiments were conducted to assess the ability to improve axial resolution and bandwidth. The first experiment consisted of measurements from a Plexiglas® reflector at the focus of the transducer. The second experiment consisted of taking measurements from a tungsten wire of 250 μm diameter. The third experiment consisted of taking measurements from 4 tungsten wires of 250 μm diameter spaced approximately at 0.535, 0.535, and 0.355 mm apart.

B. Implementation of Compression Algorithms

The impulse response of the transducer was measured from a Plexiglas® reflector located at the focus of the transducer excited with the Panametrics 5800 pulser/receiver. A new impulse response function with double the bandwidth of the actual impulse response of the source was constructed by placing a Hanning window half the length of the impulse response of the source at the center of the gated impulse response. The impulse responses are described by the functions $h_1(nT,x)$ and $h_2(nT,x)$, respectively.

The new pulse of larger bandwidth, $h_2(nT,x)$, was convolved with a linear FM chirp, $v_{Lin-chirp}[n]$. The -3-dB bandwidth of $v_{Lin-chirp}[n]$ was approximately 1.14 times the -3-dB pulse/echo bandwidth of $h_2(nT,x)$ in order to minimize sidelobe levels [8]. In addition, $v_{Lin-chirp}[n]$ was weighted with a Tukey-cosine window with 8% taper to further reduce sidelobe levels. From the convolved excitation waveform, (5) was used to find a pre-enhanced FM chirp that would be used to excite the transducer except that β was replaced with,

$$v_{P-chirp}[n] = v_{Lin-chirp}[n] * \mathcal{F}^{-1}\left\{\beta_{\exp}(u \mid x)\right\}, \quad (6)$$

where $\beta_{\exp}(u \mid x)$ is a Wiener-type filter given by,

$$\beta_{\exp}(u \mid x) = \frac{H_2(u \mid x) H_1^*(u \mid x)}{\left|H_1(u \mid x)\right|^2 + \left|H_1(u \mid x)\right|^{-2}}. \quad (7)$$

The resulting pre-enhanced FM chirp was tapered with a Tukey-cosine window with an 8% taper.

By tapering the pre-enhanced FM chirp, the convolution equivalence no longer holds. Furthermore, the actual pulse/echo impulse response of the transducer is only approximately known. The pulse/echo impulse response of the transducer was measured by exciting the transducer with the Panametrics 5800 pulser/receiver and recording the reflection off of a Plexiglas® reflector. To obtain the actual pulse/echo impulse response of the transducer, the transducer would need to be excited with a delta function of infinite bandwidth. In reality, the transducer is pulsed with a voltage spike that is not a true delta function and has a finite bandwidth. Therefore, exciting the transducer with the pre-enhanced FM chirp may not yield an equivalent waveform to the new impulse response function convolved with a linear FM chirp.

To reestablish convolution equivalence, a new linear FM chirp was calculated. The transducer was excited using the pre-enhanced FM chirp. The resultant waveforms were measured with the same transducer (pulse/echo) and recorded from the oscilloscope for post-processing. The waveform was initially measured from a planar Plexiglas® reflector located at focus of the transducer oriented normal to the propagation axis. The measured waveform was then deconvolved (not compressed) with the filtering function,

$$\beta_{h2}(u) = \frac{H_2^*(u \mid x)}{\left|H_2(u \mid x)\right|^2 + \left|H_2(u \mid x)\right|^{-2}}. \quad (8)$$

The resulting waveform, $v'_{Lin-chirp}[n]$, was used in the subsequent compression filter.

Implementation of the REC technique consisted of constructing the pre-enhanced FM chirp, recording the measured RF signal (from the impulse response of the transducer excited with the pre-enhanced FM chirp) from some scattering object, constructing the appropriate filter, and filtering the signal for compression. In the experimental measurements, the REC technique filter was given by,

$$\beta_{REC}(u) = \frac{V'^*_{Lin-chirp}(u)}{\left|V'_{Lin-chirp}(u)\right|^2 + \gamma\overline{\text{eSNR}}^{-1}(u \mid x)}, \quad (9)$$

where γ = 1 and $\overline{\text{eSNR}}$ is the echo signal-to-noise ratio per frequency channel.

IV. Results

The graphs of Fig. 2 indicate that the improvement in axial resolution due to the REC technique was significant when reflected from a Plexiglas® reflector. The graphs of the envelopes of the reflected signal are displayed in Fig. 2a. The width of the envelope at -6-dB is almost two times smaller using the REC technique over conventional pulsing techniques (the impulse response of the source). Range sidelobes occured at about 6 mm out from the mainlobe and are -45 dB down from the mainlobe. Comparison of the REC technique and conventional pulsing techniques (Fig. 2b) reveal that the REC technique outperformed the conventional pulsing technique in terms of axial resolution as defined from the MTF. The MTF value at which *k*-value fell to 0.1 corresponded to 10300 and 7500 m^{-1} for the REC technique and conventional pulsing technique, respectively. The MTF values corresponded to axial resolutions of 0.305 and 0.420 mm, respectively.

Another important consideration in using the REC technique is to quantify the subsequent -3-dB pulse/echo bandwidth and the $\overline{\text{eSNR}}$ of the compressed waveform. Fig. 3 displays the -3-dB pulse/echo bandwidth and the $\overline{\text{eSNR}}$ of the compressed waveform from reflections off a planar reflector located at the focus. The -3-dB pulse/echo bandwidth of the waveform compressed using the REC technique (Fig. 3a) was 113% and almost double that of the system impulse response (56%). The plots of $\overline{\text{eSNR}}$ (Fig 3b) reveal that the useable bandwidth was larger with the compressed waveform with a significant boost to signal-to-noise ratio through compression.

The second set of measurements was from a single tungsten wire located at the focus. Graphs of the envelope and MTF curves from the wire with conventional pulsing techniques and with the REC technique are displayed in Fig. 4. Both the

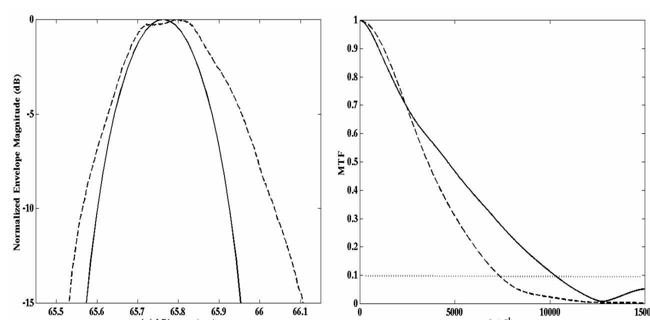

Figure 2. a) Envelopes of waveforms reflected from planar reflector located at focus and b) the MTF curves of the resulting waveforms (--, conventional pulsing technique; —, the REC technique).

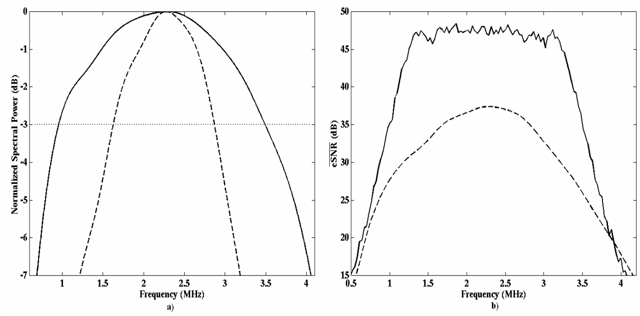

Figure 3. a) Power spectra of the measured waveforms from the planar reflector and (b) the resulting $\overline{\text{eSNR}}$ of the measured waveforms (--, conventional pulsing technique; ─, the REC technique).

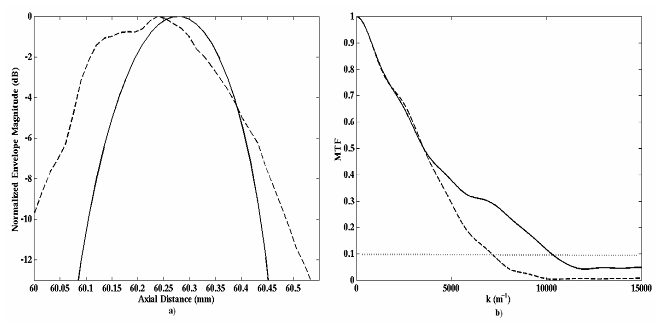

Figure 4. a) Envelopes of waveforms reflected from tungsten wire located at focus and b) the MTF curves of the resulting waveforms (--, conventional pulsing technique; ─, the REC technique).

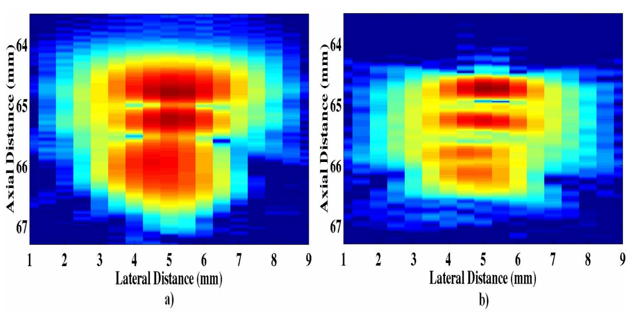

Figure 5. Figure 11: B-mode images of four tungsten wires with a) impulse response of transducer and b) from the compressed waveforms using the REC technique.

graphs of the envelopes and the MTF curves indicate the axial resolution of imaging system was improved with the REC technique. The *k*-values at which the MTF curves fell to 0.1 occurred at values corresponding to axial resolution values of 0.440 and 0.310 mm for the conventional pulsing technique and the REC technique, respectively.

The final set of experimental measurements was taken from a series of four tungsten wires. The wires were spaced at 0.535, 0.535 and 0.355 mm apart. According to the axial resolution predicted by the MTF curves for a single tungsten wire, the conventional pulsing technique should not be able to resolve the last two wires whereas the REC technique should be able to resolve the last two wires. Fig. 5 shows B-modes images of the four wires after compression with both conventional pulsing techniques and with the REC technique. The B-mode image (Fig. 5b) from the REC technique reveals that the last two wires could be resolved. Use of conventional pulsing techniques did not allow the last two wires to be resolved (Fig. 5a).

The TBP product of the linear chirp used in the compression filter corresponded to a predicted gain in eSNR of 16.9 dB [9]. The actual gain was less than the predicted gain. The maximum achieved gain in eSNR was 16.2 dB.

V. Conclusions

A pulse compression technique (REC) was used to enhance the axial resolution and bandwidth of an imaging system while also providing a significant boost in the eSNR. The technique made use of pre-enhanced FM chirps to excite more energy in frequency bands with decreasing spectral power in the bandwidth as compared to the center frequency. Mismatched filters were used to make use of the additional energy in the frequency bands. The mismatched filters were designed based on convolution equivalence (the pre-enhanced FM chirp convolved with the source impulse response was equal to a linear FM chirp convolved with a pulse approximately twice the bandwidth of the impulse response of the source).

Experimental measurements revealed that the REC technique significantly improved the axial resolution of the imaging system and the subsequent bandwidth. The axial resolution was improved to 0.305 mm from 0.420 mm, respectively. The -3-dB bandwidth was doubled from 56% to 113% and maximum range sidelobes were observed at -45 dB.

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