An Ultrasonic Imaging Speckle Supression and Contrast Enhancement Technique by Means of Frequency Compounding and Coded Excitation

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Abstract— **A method for improving the contrast resolution of B-mode images is proposed by combining the speckle reduction technique of frequency compounding (FC), and the coded excitation and pulse compression technique called resolution enhancement compression (REC). FC suppresses speckle but at the expense of a reduction in axial resolution. Using REC the axial resolution and bandwidth of the imaging system was doubled. Therefore, by combining REC with FC (REC-FC), the trade-off between axial resolution and contrast enhancement was extended significantly. Simulations and experimental measurements were conducted with a single-element transducer (f/2.66) having a center frequency of 2.25 MHz and a -3-dB bandwidth of 50%. Simulations and measurements of hyperechoic (+6dB) tissue-mimicking targets were imaged. Two FC cases were evaluated: full-, and half-width of the true impulse response bandwidth. The image quality metrics used to compare REC-FC to conventional pulsing (CP) and CP-FC were: contrast-to-noise ratio (CNR), speckle signal-to-noise ratio and histogram percent overlap. Increases in CNR of 121%, and 230% were obtained in experiments when comparing REC-FC for the full-, and half-width cases to CP. Improved lesion detectability was observed by using REC-FC.**

Coded excitation; pulse compression; contrast; frequency compounding; frequency diversity; speckle

I. INTRODUCTION

Speckle, the granular structure in ultrasonic images, reduces the ability to detect low-contrast targets. Speckle is formed by subresolution scatterers that cause constructive and destructive interference of backscattered ultrasonic signals within the resolution cell volume of an ultrasonic source [1]. Furthermore, speckle is considered to be a deterministic process because when an object is imaged under the same operating conditions no changes in the speckle pattern occur. It is because of this nature, speckle is not reduced by signal averaging. Therefore, a considerable amount of work and effort has been spent over the last few decades in developing techniques to reduce speckle in ultrasound images.

Frequency compounding (FC) is as a post-processing speckle reduction technique that divides the spectrum of the radio-frequency (RF) echoes into subbands to make separate images [2]. The latter instance is also known as frequency diversity [3], or split spectrum processing [4]. The main disadvantage introduced by using frequency compounding is the inherent tradeoff between axial and contrast resolution. Consequently, if the axial resolution and the bandwidth of an ultrasonic imaging system could be increased these tradeoffs between axial and contrast resolution could be extended.

A coded excitation and pulse compression technique was recently developed, resolution enhancement compression (REC), which allow the axial resolution and bandwidth of the imaging system to be enhanced [5]. In addition to improvements in terms of axial resolution, the REC technique has the typical coded excitation and pulse compression benefits, such as deeper penetration due to improvement in echo signal-to-noise ratio (eSNR). Therefore, the goal of this study is to combine the REC technique with FC, which will be described as REC-FC, to extend the tradeoff of loss in axial resolution versus enhancement in contrast.

II. PROBLEM FORMULATION

The driving force behind the REC technique is the capability to shape and select to a limited degree certain desired characteristics of an ultrasonic imaging system through coded excitation and pulse compression. Consequently, the characteristics of the impulse response of the imaging system could be tailored to have useful properties for particular imaging applications. In this case, the useable bandwidth of the imaging system will be doubled using REC. This increase in bandwidth could be used with FC to improve target contrast while retaining the original axial resolution of the imaging system.

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The objective of using FC is to reduce the speckle noise and enhance the contrast in ultrasonic B-mode images. In FC, the received wideband RF spectrum is partitioned into N subbands by using Gaussian band-pass filters of smaller bandwidth than the original spectrum. These narrowband subbands create separate images that make partially uncorrelated speckle patterns, up to 60% decorrelation [6]. Typically, improvements in speckle signal-to-noise ratio and contrast-to-noise ratio are proportional to $\sqrt{N}$; however, because the images are partially correlated the improvements are going to be proportional to a factor less than the square root of the sum of independent images [1]. These separate images can then be added together to reduce the speckle by reducing the image intensity variance. However, the axial resolution deteriorates because the compounded image was generated by averaging smaller subband images.

By using REC, a larger bandwidth is available, which would allow an increase in the number of subbands that can be applied for a particular desired axial resolution. Accordingly, a parameter of interest would be the bandwidth of these subbands. Therefore, for simulations and experiments, there were two cases evaluated in terms of the subband bandwidth when applying FC to the REC technique. The first case consists of using subbands that are full-width of the true impulse response bandwidth. This will gauge the true benefits of utilizing the REC-FC technique as the axial resolution of the compounded image will be the same of that for CP methods and the contrast resolution will improve due to FC. The second case consists of using subbands that are half-width of impulse response bandwidth and will be applied to REC and CP (CP-FC) for comparison purposes. Other filter bank parameters that were considered when applying FC to the RF spectrum were subband center frequency separation, first subband center frequency starting point, and the number of sub-bands. The values of these parameters were chosen that optimize the image quality metrics, which are defined in the following paragraphs.

To evaluate the performance of the REC-FC technique compared to CP and CP-FC the following image quality metrics were used:

1. *Contrast-to-noise ratio (CNR):* CNR [7], also known as contrast-to-speckle ratio, is a quantitative measure that will assess image quality and describe the ability to perceive a target from the background region. CNR is defined as

$$\mathrm{CNR} = \left| \frac{\mu_B - \mu_T}{\sqrt{\sigma_B^2 + \sigma_T^2}} \right|, \tag{5}$$

where μ_B and μ_T are the mean brightness of the background and the target lesion and σ_B^2 and σ_T^2 are the variance of the background and target, respectively. To avoid possible errors in the calculations due to attenuation, the evaluated regions of interest in the background and the target lesion will be of the same size and are located at the same depth.

2. *Speckle signal-to-noise ratio (sSNR):* sSNR [8] is a measure of the fluctuations in the speckle of a particular region of interest and is defined as

$$\mathrm{sSNR} = \frac{\mu}{\sigma}, \tag{6}$$

where μ and σ are the mean and the standard deviation of the region of interest, respectively. Specifically, sSNR will be evaluated for same-sized regions in the target lesion and the background adjacent to the target. For Rayleigh statistics, sSNR is equal to 1.91.

3. *Histogram percent overlap (HO):* Histograms display the distribution of pixels amongst the 256 grayscale intensity values of B-mode images. The percent overlap of target and background region were obtained from histograms that were made for same-sized regions for the target lesion and the background adjacent to the target. Ideally, for superior target detectability, there is no overlap present between the target histogram and the background histogram.

III. COMPUTER SIMULATIONS AND RESULTS

Computer simulations were carried out in Matlab (Mathworks, Natick, MA) to characterize the performance of the REC-FC technique. The simulations used a received pulse-echo pressure field model [9] described as

$$g'[n] = h_1(nT, x) \underset{t}{*} f(x) \underset{r}{*} h_{pe}(nT, x), \tag{7}$$

where $h_1(nT, x)$ is the pulse-echo impulse response of the transducer, $f(x)$ is the scattering function, and $h_{pe}(nT, x)$ is the modified pulse-echo spatial impulse response that takes into consideration the geometry of the transducer to the spatial extent of the scattered field (beam diffraction). The pulse-echo impulse response, $h_1(nT, x)$, for CP was generated by gating a sinusoid of four cycles with a Hanning window

$$w(n) = \begin{cases} 0.5 \cdot \left(1 - \cos\left(\frac{2\pi\pi}{N-1}\right)\right), & 0 \le n \le N-1 \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

where n is an integer and N is the number of samples in the window. The window and sinusoid parameters where chosen to match the transducer used in experiments. As a result, the pulse-echo impulse response generated was located at the focus of a 2.25 MHz single-element transducer (f/2.66) with a fractional bandwidth of 50% at -3-dB, which would correspond to a window length of N = 128. For the REC, the impulse response function, $h_2(nT, x)$, was constructed to have double the fractional bandwidth or 100% at -3-dB, compared to CP method; therefore, a Hanning window of size of half the length, N = 64, was used. The spatial response for a circular focused piston source can be simulated as a circular Gaussian beam which is defined as

$$h_{pe}(nT, y) = e^{-y^2/2\cdot\sigma_y^2}, \tag{9}$$

where y represents the lateral spatial coordinate and σ_y, which is equal to 1.28 mm, is the nominal lateral beamwidth of the source.

The received RF backscatter data were sampled at a rate of 100 MHz and the transducer was translated laterally in increments of 0.1 mm. The received RF data have a size of

4096 x 300. The object being imaged was a 30 mm x 30 mm x 1.92 mm simulated phantom. A cylindrical target with a radius of 7.5 mm was located at the center of the phantom. To generate a hyperechoic target with a contrast of approximately +6-dB, the density of point scatterers for the cylindrical volume was four times the density of the remaining volume of the phantom, which will be described throughout as the background. Specifically, to generate fully developed speckle, the cylinder had an average of 20 point scatterers per resolution cell volume and the background had an average of five point scatterers per resolution cell volume. The point scatterers in the phantom were uniformly distributed but the amplitude of the backscattered ultrasound from each scatterer was set to unity. Furthermore, to avoid clustering, the placement of the point scatterers was limited to a minimum distance of 50 μm from each other.

A total of 50 phantoms were simulated and evaluated with the image quality metrics discussed in section II. Attenuation and noise were not modeled in the simulations in order to examine the relationship of FC to speckle effect only. The B-mode images representing these results are displayed in Fig. 3.

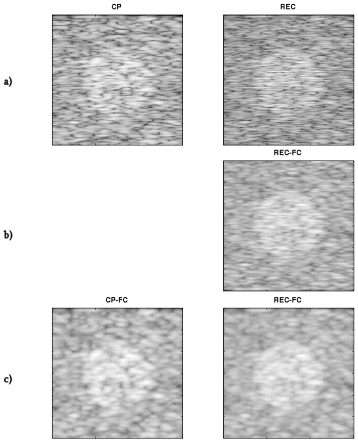

Figure 3: B-mode images of simulated results for: a) CP and REC reference scans, b) REC-FC full-width case, and c) CP-FC and REC-FC half-width cases. Image dynamic range = -50 dB.

Examination of the reference scans in Figs. 3a reveals that by using the REC technique the speckle size is finer when compared to CP. This smaller speckle size obtained by using REC means that the object boundaries would be more defined because there is more detail compared to CP. This axial resolution boost was then traded away to improve contrast by applying FC with subbands that have the same bandwidth as CP (full-width) as shown in Fig. 3b. For the full-width case, the CNR, $sSNR_B$, and $sSNR_T$ improved by a factor of 66%, 40%, and 47% when compared to CP. Essentially, a gain of CNR and sSNR was achieved while maintaining the same axial resolution that would be obtained by using CP methods. The HO of the target and background regions for the CP and REC reference scan were 26% and 25%, respectively. By using FC, the overlap was reduced to 23% for the full-width case.

The next case evaluated was half-width of CP impulse response, which would translate into a reduction by a factor of two in terms of axial resolution. The half-width case was applied to both CP and REC as shown in Fig. 3c. For the half-width case using REC-FC, the CNR, $sSNR_B$, and $sSNR_T$ improved by a factor of 134%, 95%, and 113% when compared to CP. Furthermore, the CNR, $sSNR_B$, and $sSNR_T$ improved by a factor of 29%, 23%, and 33% when compared to CP-FC (half-width). The HO for the half-width for CP-FC and REC-FC were 24% and 16%, respectively.

IV. EXPERIMENTAL SETUP AND RESULTS

Experiments were performed to validate the simulated results. A single-element weakly-focused (f/2.66) transducer (Panametrics, Waltham, MA) with a center frequency of 2.25 MHz and a 50% (at -3-dB) fractional bandwidth was used. There were two different experimental setups utilized; one for CP methods and another one for REC experiments. These setups would contain different noise levels due to the use of different excitation systems; therefore, the noise levels were normalized to an eSNR of 28 dB. Normalization of eSNR was accomplished by adding zero mean Gaussian white noise to the CP RF echo waveform. The two experimental setups are described as follows:

1. *Conventional pulsing experimental setup*: The transducer was excited by a pulser-receiver (Panametrics 5800, Waltham, MA) and the receive waveform was displayed on an oscilloscope (Lecroy 9354 TM, Chester Ridge, NY) for visual verification. The echo signal was recorded at a rate of 100 MHz by a 12-bit A/D (Strategic Test Digitizing Board UF3025, Cambridge, MA) for further processing by a PC.

2. *REC experimental setup*: The preenhanced chirp was generated in Matlab (The Mathworks Inc., Natick, MA) and downloaded to an arbitrary waveform generator (Tabor Electronics W1281A, Tel Hanan, Israel). The excitation signal was sampled at a rate of 100 MHz and amplified by an RF power amplifier (ENI 3251, Rochester, NY). The amplified signal (50 dB) was connected to the transducer through a diplexer (Ritec RDX-6, Warwick, RI). The echo signal was received by a pulser-receiver (Panametrics 5800, Waltham, MA), which was displayed on an oscilloscope (Lecroy 9354 TM, Chester Ridge, NY) for visual verification. The echo signal was recorded at a rate of 100 MHz by a 12-bit A/D (Strategic Test Digitizing Board UF3025, Cambridge, MA) for further processing by a PC.

A tissue-mimicking phantom (ATS Laboratories Model 539, Bridgeport, CT) was used to assess the performance of REC-FC with the image quality metrics described in section II. The material from the tissue-mimicking phantom consisted of urethane rubber which has a speed of sound of 1450 m/s ± 1.0% at 23°C and an attenuation coefficient of 0.5 dB/cm/MHz ± 5.0%. A +6-dB echogenic gray scale target structure with a 15-mm diameter at a depth of 4 cm was imaged for all four cases in addition to the reference signals. All measurements were conducted at room temperature in a tank of degassed water. The B-mode images representing these results are displayed in Fig. 4.

Examination of the reference scans in Fig. 4a reveal that by using the REC technique the speckle size was finer when compared to CP, which was evident in the simulations. Next, FC was applied with subbands corresponding to the bandwidth of the original impulse response of the source under CP methods (full-width) to improve contrast as shown in Fig. 4b. For the full-width case, the CNR, $sSNR_B$, and $sSNR_T$ using REC-FC improved by a factor of 121%, 41%, and 57% when compared to CP. An increase in CNR and sSNR was obtained while maintaining the same axial resolution that would be obtained by using CP methods. As was observed in the simulations, the smaller speckle size obtained by using REC leads to better definition of the object boundaries because there is more detail compared to CP. Therefore, when applying REC-FC this extra information can enhance the results obtained when compared to CP. The HO of the target and background regions for the CP and REC reference scan were 35% for both cases. By using FC, the overlap was reduced to 33% for the full-width case.

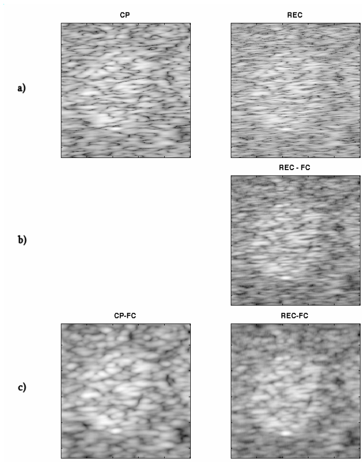

Figure 4: B-mode images of experimental measurements for: a) CP and REC reference scans, b) REC-FC full-width case, and c) CP-FC and REC-FC half-width cases. Image dynamic range = -50 dB.

A comparison of experimental results against simulations reveals the improvement for the full-width case in terms of $sSNR_B$ and $sSNR_T$ remained approximately the same, while the improvement in terms of CNR was almost doubled in the experiment (121%) when compared to simulations (66%). The next case evaluated was half-width of CP impulse response, which consisted of subbands that use half of the bandwidth of the impulse response of the source under CP methods. The half-width case was applied to both CP and REC as shown in Fig. 4c. For the half-width case, the CNR, $sSNR_B$, and $sSNR_T$ improved by a factor of 230%, 98%, and 104% when using REC-FC compared to CP. Furthermore, the CNR, $sSNR_B$, and $sSNR_T$ improved by a factor of 55%, 38%, and 50% when using REC-FC compared to CP-FC (half-width). Comparing experimental results to simulations the improvement for the half-width case in terms of $sSNR_B$ and $sSNR_T$ were quite similar, while the improvement in terms of CNR was larger in the experiment (230%) when compared to simulations (134%). The HO for the half-width for CP-FC and REC-FC were 33% and 28%, respectively.

V. DISCUSSION AND CONCLUSIONS

A pulse compression and coded excitation technique, REC, was used to double the axial resolution, which translated into an increase in system bandwidth. The speckle reduction technique known as FC utilized this larger available bandwidth to improve image contrast in ultrasonic B-mode images. FC partitions the useable bandwidth by using subbands that are smaller than the system bandwidth to improve image contrast and reduce speckle noise but at the expense of axial resolution. Therefore, the major objective of this study was to establish the benefits of doubling the axial resolution by utilizing REC and then applying FC to take advantage of the larger useable bandwidth to increase the number of subbands.

Simulations and experimental measurements were used to establish the usefulness of the REC-FC technique in enhancing image contrast and reducing speckle noise. Simulations and experimental measurements suggest that REC-FC was a useful tool to obtain substantial improvements in terms of image contrast and to enhance the boundaries between the target and the background speckle noise. CNR, $SSNR_B$, and $SSNR_T$ were increased in both simulations and experiments for all cases. In simulations and experiments, the HO between the background and the target regions was significantly reduced as the size of the subbands decreased. In general, it was observed that REC-FC was always a step ahead of CP/CP-FC. This was due to the doubling of the axial resolution of the ultrasonic imaging system by using REC which allowed an increase in the number of subbands.

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