EXPERIMENTAL STUDY ON REDUCTION OF POST-COMPRESSION ERROR IN CODED EXCITATION IMAGING USING ORTHOGONAL GOLAY CODES

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Abstract: Coded excitation, which employs pulse compression techniques, improves SNR by increasing average power without affecting instantaneous peak power [1-4]. It has been known that the transmitted energy can be increased up to 15-20 dB by coded excitation before reaching particular intensity limits (Isppa, Ispta) [1]. Hardware complexity of coded excitation imaging systems can be greatly reduced by carrying out pulse compression after receive beamforming, which introduces, however, compression error because of the irregular arrangement of input samples due to dynamic focusing delays. We present a post-compression coded excitation technique using orthogonal Golay codes with reduced compression errors by employing transmit multi zone focusing with dynamic aperture control. To prevent the frame rate reduction, the multi zone focusing is done by transmitting orthogonal Goloay codes for different transmit foci at the same time. The performance of the proposed scheme was verified through computer simulations and actual experiments.

Introduction

Coded excitation can improve the signal-to-noise ratio (SNR) of ultrasound imaging, by using long transmitted pulses without sacrificing the axial resolution [5]. In a coded ultrasound imaging, coded waveforms with long duration are transmitted and the reflected waves are compressed into a short pulse with a high amplitude gain. Ideally, pulse compression should be done before receive beamforming, which is called pre-compression [6]. This requires a compression hardware at each channel, resulting in huge increase in system complexity, since pulse compression generally requires correlating the received signals with transmitted compression waveforms with long duration.

Therefore, post-compression, which is to perform pulse compression on focused rf data, is a very attractive approach to reduce the hardware complexity. In this case, only one compression hardware is required. Post-compression can be modeled as summing the pre-compressed signals where at each channel the received signals are rearranged irregularly according to the focusing delays and then fed to the corresponding correlator. Therefore, post-compression introduces compression error and accompanying degradation in axial resolution.

Recently, authors have investigated a simultaneous transmit multi-zone focusing (STMF) method using mutually orthogonal Golay codes, which can achieve multiple transmit focusing with no accompanying decrease in the imaging frame rate [7-9]. The purpose of the present work is to investigate the compression error in the STMF method using Golay codes and to design a post-compession based imaging system with reduced compression error.

Analysis of post-compression error was performed theoretically and verified through computer simulations.

Post-compression in STMF

In order to achieve a high lateral resolution, low f-numbers should be used in real-time dynamic focusing. In low f-number imaging, focal points should be updated frequently since the depth of focus decreases with decreasing f-number. On the other hand, the compression error in post-compression method can be eliminated if the code length is limited to one focal range. Therefore, post-compression method is generally inadequate for low f-number imaging.

The focal range is defined as the range over which the phase of the outside element differs by less than π from the phase center [1]. This limits the transmitted code duration to be :

$$T < 16(\text{f/num})^2 / f_0 \qquad (1)$$

where T is the transmitted code duration, f/num is the instantaneous f-number which is the ratio of the focal range R_0 to the diameter D of the transmitting aperture, and f_0 is the center frequency of the ultrasound pulse. For typical far-field imaging with a real time array imaging system, the f/num of the static transmit aperture is about 2 and hence the duration T_{code} of the code cannot exceed 8.53μsec when a highest center frequency is 7.5MHz,.

An error is introduced in post-compression, when dynamic receive focusing is employed [5-6]. To evaluate the error due to dynamic focusing, consider the dynamic focusing delay:

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$$\tau_n = \frac{z - \sqrt{z^2 + x_n^{\ 2}}}{c} \approx -\frac{x_n^{\ 2}}{2cz}$$
$$\left(\because \sqrt{z^2 + x_n^{\ 2}} \approx z + \frac{x_n^{\ 2}}{2z} \right) \quad (2)$$

where c is the velocity of ultrasound, z is the distance from the aperture center to the desired focal point and d is the interelement spacing as shown in figure 1.

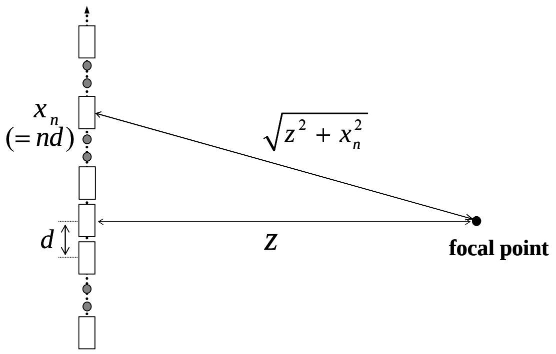


Figure 1: Geometry of focusing situation

The error depends on the change in the shape of the delay profile. More exactly the error comes from the rate of change in the curvature of time delay τ_n when changing the depth, which is given by the range derivative of τ_n:

$$\frac{\partial \tau_n}{\partial z} = \frac{x_n^2}{2cz^2} = \frac{1}{8c}\left(\frac{2x_n}{z}\right)^2 = \frac{1}{8c}\frac{1}{f_n^{\ 2}} \quad (3)$$

where f_n is the f-number for element x_n. The delay profile changes more rapidly near the transducer than far away. Thus, the error increases with smaller f-number, and the phase center channel at $x_n = 0$ does not have any distortion but the outer-most channels of the active aperture have the maximum distortion. To minimize the error one should measure far away from the transducer and naturally keep the distance between focal points small. Fortunately, coded excitation is needed primarily in the deeper regions of the image in which the f-number is larger and noise can cover any range sidelobes below -50 dB [6].

To give a quantitative insight of the size of the rate of change in τ_n, figure 2 shows a plot of $\partial \tau_n / \partial z$ as function of depth into tissue z for different f-number using x_n (n=3,10,20,30). In this simulation, we used a 7.5MHz linear array transducer with 192 elements and 0.2mm pitch and assumed the number of active channels to be 64. The rate of change in τ_n decreases with larger f-number (or smaller aperture size) and rapidly decreases with depth into tissue near the transducer. $\partial \tau_n / \partial z$ converges to 0 at 2cm depth regardless of the f-number.

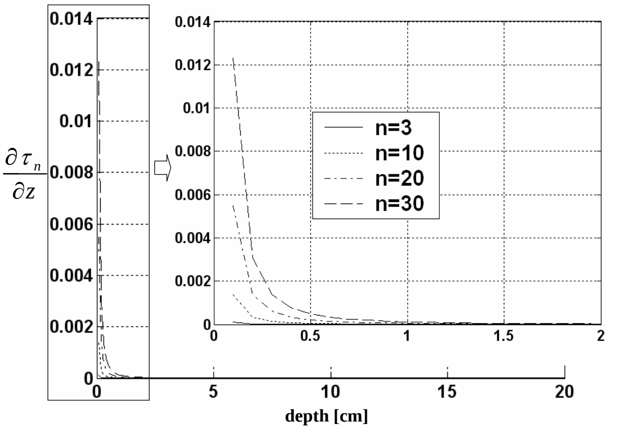
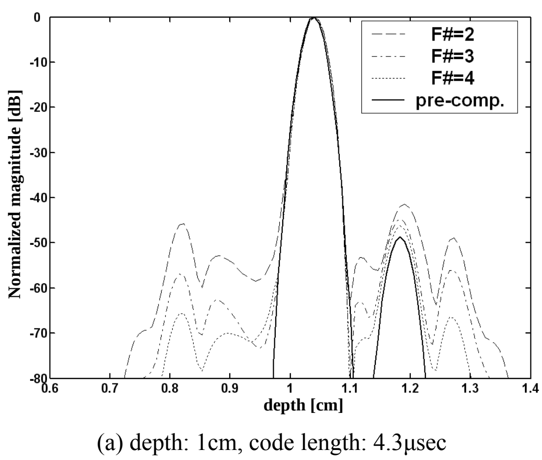


Figure 2: The size of the rate of change of in τ_n as function of depth for different aperture size.

The post-compression scheme is attractive because of reduced compression filtering. As discussed earlier, one drawback of the post-compression is the decoding error due to dynamic focusing. The error investigated here decreases with larger depth and smaller code length. Coded excitation with conventional Golay codes is used primarily for obtaining information of the deeper region. It provides 12~15dB improvement in SNR when Golay codes, with duration 8 to 16 times longer than the conventional on-off pulse, are used (1.1μsec to 2.2μsec for 7.5MHz center frequency) [8].

Conventional Golay code requires two firings to transmit the code pair, which reduces the frame rate by a factor of two. STMF method using orthogonal Golay codes can be used to recover this frame rate loss [7-12].

Figure 3 compares the range sidelobe level (RSLL) of decoded Golay signals, which is caused by dynamic focusing, for different f-numbers and code lengths: (a)~(b) 4.3μsec and (c)~(d) 1.1μsec. Figure 3 shows, in post-compression, Golay coded signal is sensitive to dynamic focusing with RSLL increasing as f-number decreases or as code length increases. Figures 2 and 3 show the error as a function of depth decreases rapidly at greater depths. Moreover, we can see the error may be ignored after 2cm depth.



(a) depth: 1cm, code length: 4.3μsec

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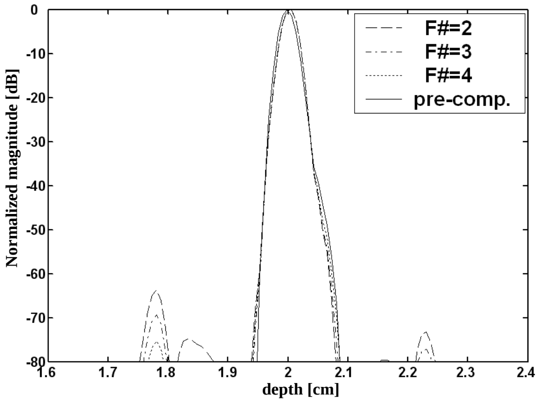
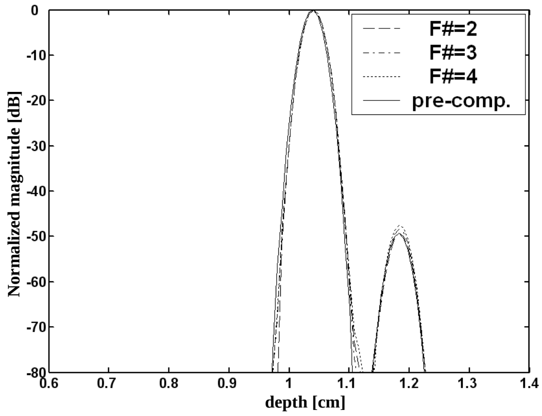
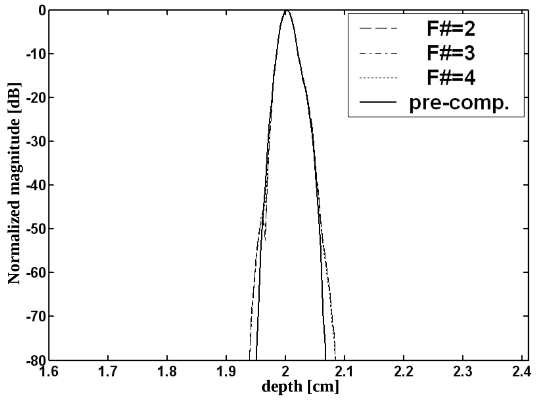


(b) depth: 2cm, code length: 4.3μsec



(c) depth: 1cm, code length: 1.1μsec



(d) depth: 2cm, code length: 1.1μsec

Figure 3: Axial point-spread function of decoded Golay signals in post-compression and pre-compression for different f-numbers and code lengths at two depths.

Figure 4 shows the block diagram of a receiver architecture for post-compression based STMF method using mutually orthogonal Golay codes, $[a_{11}(n), a_{12}(n)]$ and $[a_{21}(n), a_{22}(n)]$. The mutually orthogonal codes $a_{11}(n)$ and $a_{21}(n)$ are simultaneously transmitted, which are focused at two different focal depths. The orthogonal codes received with each array elements are separated by correlating with each transmitted codes after beamforming. The same transmit/receive (T/R) event is performed along the same scan line with the complement set of the previously transmitted ones, $a_{12}(n)$ and $a_{22}(n)$. Then, the two focused signals for each focal zone can be combined into a short pulse by simply adding them together. Finally, by aggregating the two focused and compressed signals for two focal zones and by repeating the same procedure for all scan lines, a frame of image is obtained with the same frame rate as that of single zone transmit focusing using Golay codes. Compared to the pre-compression scheme, the post-compression scheme can save 2(N-1) (N is the number of active channels) correlators.

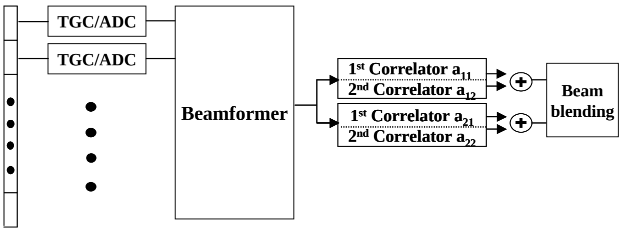
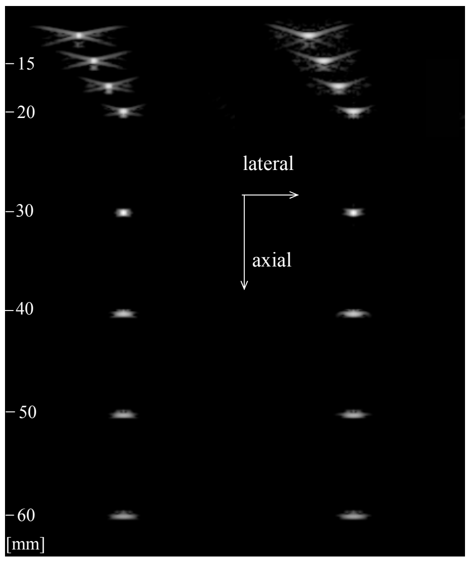


Figure 4: Block diagram of the presented post-compression coded excitation imaging.

Results and Discussion

Figure 5 shows computer generated B-scan images of several point targets for (a) pre-compression scheme and (b) post-compression scheme. The compression error is larger at shallow depths and decreases with depth. This near field error can be reduced by employing dyanmic aperture control, which in turn degrades the near field lateral resolution. This problem can be mitigated in the presented method, because near field is independently focused without decrease in frame rate.



(a) pre-compression (b) post-compression

Figure 5: Computer generated B-scan images.

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The images in figure 5 were obtained using 64 elements of a 7.5MHz array with two transmit foci at 20mm and 50mm. In the near zone imaging, f-number was chosen to be 4 and aperture size is controlled according to the following formula:

$$x_n = \frac{z}{2(\mathrm{f/num})} \qquad (6)$$

where x_n represents the off-axis distance of n-th element from the array center. On the other hand, all 64 active elements were used for all depth.

Figure 6 shows B-scan images of a tissue-mimicking phantom for (a) pre-compression scheme and (b) post-compression scheme. The error is too small to recognize in experimental results because any RSLL below -40dB is covered by noise.

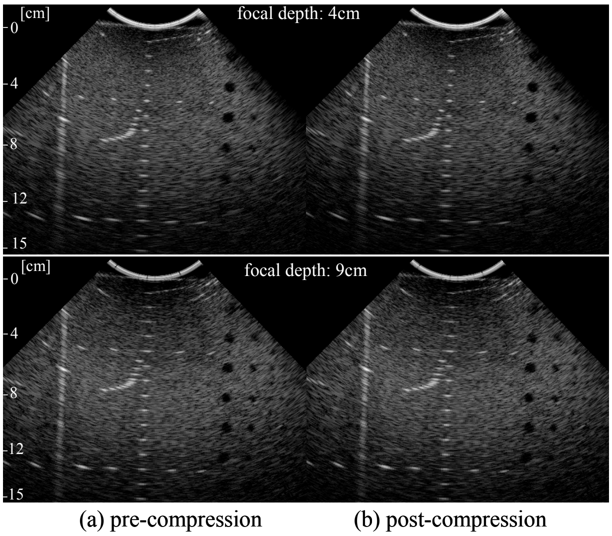

Figure 6: B-scan images of a tissue-mimicking phantom.

Figure 7(a)~(c) show A-scan and B-scan images of a tissue-mimicking phantom for the following cases: (a) fixed transmit focusing at 6cm with the conventional pulse-echo method using a short pulse of duration 0.26[μsec], (b) fixed transmit focusing at 6cm using the pre-compression method with conventional Golay codes of length 16 and (c) two-zone focusing (at 4[cm] and 9[cm]) with the presented post-compression STMF method using modified orthogonal Golay codes of length 16 (i.e., of duration 2.1[μsec]) with a low peak voltage of 10Vp. Figures 7(a)~(c) show that both the contrast resolution and SNR are much improved with the presented post-compression STMF method: the cysts and wire targets are defined much more clearly in figure 7(c), particularly at the far field.

Conclusions

The error introduced by the post-compression scheme is addressed and investigated in theory and by simulations and actual experiments. The experimental results show that the post-compression STMF method using orthogonal Golay codes can provide high resolution and SNR without noticeable errors compared to the conventional pre-compression coded excitation imaging with Golay codes. Moreover, the presented method requires a pulse compression circuit with 2 correlators as opposed to 2N correlators in the pre-compression scheme, which is suitable for use in portable ultrasound scanners.

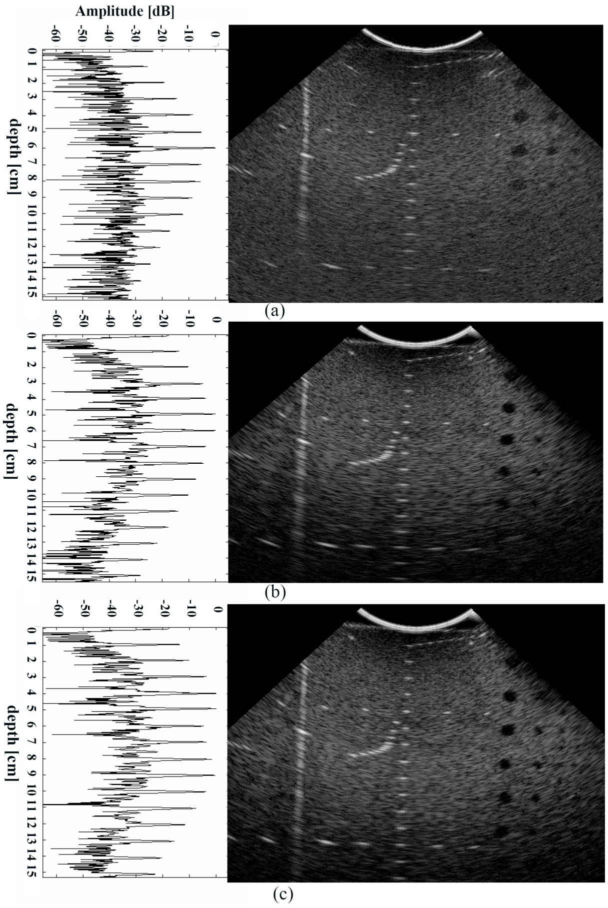

Figure 7: A-scan(left) and B-scan images(right) of a tissue-mimicking phantom.

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