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Delay-encoded Transmission in Synthetic Transmit Aperture (DE-STA) Imaging

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***Abstract*—Synthetic transmit aperture (STA) ultrasound imaging offers dynamic focusing in both transmission and receiving, leading to high image resolution. The major problem of this technique is the low signal to noise ratio (SNR) compared to the conventional B-mode ultrasound method. Hadamard encoded transmission is an approach to overcome this difficulty, but it requires transducer array to transmit a pulse in some array elements and the inverted pulse in the other elements simultaneously, which is not compatible with many commercial scanners. In this paper, we propose delay-encoded synthetic transmit aperture (DE-STA) imaging to encode the transmission elements to increase the SNR of the radiofrequency (RF) echo signals. In this technique, selected transmitting elements are encoded with half period delay and then a decoding process is applied to the acquired RF signals to obtain the equivalent traditional STA signals with a better SNR.**

The proposed protocol (DE-STA) was tested with both simulated data using Field II and experimental data acquired with a commercial linear array imaging system (Ultrasonix RP). The results from both the simulations and the experiments demonstrated improved image quality compared with the traditional STA images with the same amount of measurement noise in the RF data. This SNR improvement in the RF data is comparable with the Hadamard encoded method.

Keywords—Coded excitation; Synthetic Transmit Aperture Imaging; Beamforming methods

I. INTRODUCTION

Synthetic transmit aperture (STA) ultrasound imaging is a novel imaging technique which can offer near-ideal resolution over the entire image. One of the limitations that hinder STA being widely used in clinic is the low signal-to-noise-ratio (SNR) of the RF signals compared with the conventional B-mode ultrasound method [1]. This is caused by the fact that in STA imaging only one or a small number of elements are selected for each transmission.

The SNR of the RF signals can be increased by using encoded transmissions, spatially, temporally, or combined [2]. Chiao et al. introduced a spatially-encoded method which uses Hadamard matrix to encode the transmission scheme to increase the SNR and uses its inverse to decode the received RF signals [3, 4]. In this method, part of the array elements transmit a positive pulse while the others transmit a phase inverted (negative) version of the same pulse simultaneously. The sequence and order of the pulses are determined by the Hadamard coding matrix, which is a matrix with element either 1 or -1. 1 refers to positive pulses and -1 refers to negative pulses. After multiple transmissions, the backscatter signals received from all the transmissions can be processed in a decoding step by multiplying the inverse of Hadamard coding matrix to obtain the equivalent traditional STA data. The SNR of the RF signals can be increased by $\sqrt{I}$ times (I is the total number of active transmitters) compared with the traditional STA. Later this Hadamard spatially encoding method was combined with temporal encoding such as using chirped signals [2] or orthogonal Golay codes [5].

However, these Hadamard based approaches require driving elements with positive and negative pulses in one transducer array at the same time. This cannot be implemented in most commercial ultrasonic scanners. In addition, any mismatch in the shape between the pulse and the phase inverted pulse may compromise its performance. S-sequence spatially-encoded method has been proposed to avoid the phase inversion requirement as in Hadamard encoding. However, in each transmission, only half of the elements are activated [6, 7].

In this paper, we propose another Hadamard based encoding method called delay-encoded synthetic transmit aperture (DE-STA) imaging to increase the SNR. In each transmission of this technique, all elements are excited instead of a single element excitation, which leads to a greater transmission power. Selected transmission elements are encoded with a delay of a half period rather than reversing the polarity. Then the acquired RF signals are decoded to obtain the equivalent traditional STA signals with a better SNR. This approach can provide comparable SNR improvement with Hadamard encoding and can be implemented in commercial scanners.

In section II, the theory of the DE-STA imaging will be explained and then the implementation of DE-STA in both simulations and experiments will be described. The quantification parameters for image quality will be introduced as well. In section III, the results in both simulations and experiments will be shown and the image qualities will be assessed in different ultrasound imaging methods. In section IV, the results of performance measurement will be discussed and the conclusion will be drawn.

II. Methods

A. Theory

The DE-STA transmission protocol is similar to the Hadamard encoding protocol except that it replaces the inverted transmission pulses with positive pulses delayed by a half period at the central frequency of the probe. Elements were delayed according to an encoding matrix $\mathbf{A}$. Each row of $\mathbf{A}$ represents the coding for one transmission event and the index of each column represents the position of an active transmitting element. In this paper, the encoding matrix $\mathbf{A}$ is a 128 by 128 matrix which stands for 128 active transmit elements in each excitation and 128 transmission events to acquire one complete data set for one image. $\mathbf{A}$ is constructed in frequency domain by replacing element -1 in Hadamard matrix with $e^{-j\pi\frac{f}{f_0}}$ (f is the temporal frequency and f_0 is the central frequency). Hence, in encoding matrix $\mathbf{A}$, the elements are either 1 or $e^{-j\pi\frac{f}{f_0}}$, where 1 refers to no delay will be applied to the corresponding transmitting element and $e^{-j\pi\frac{f}{f_0}}$ refers to a half-period delay will be applied.

Equivalent signals to the standard STA transmission can be obtained by multiplying a decoding matrix $\mathbf{D}$ with the signals received in DE-STA in the frequency domain. Both $\mathbf{A}$ and $\mathbf{D}$ are frequency dependent and the decoding process was applied to each frequency component independently. It is worth noting that when f equals to 0 or $2f_0$, the coding matrix will be an square matrix with all the elements equaling to 1, which cannot be inversed stably. To deal with this, since the central frequency is 5 MHz, the received RF data were processed by a 4-th order Butterworth filter with the pass-band ranging from 3.5MHz to 6.5MHz (the frequencies corresponding to half-maximum of the filter) to stabilize the decoding step. Then the decoding process was implemented in the frequency range of 2MHz to 9MHz, in which the above filter has a non-zero weight. Afterwards, the decoded signals in the frequency domain were transformed into time domain and ultrasound images were obtained using the standard delay and sum reconstruction method in STA imaging [1].

B. Methods in simulations and experiments

1) Simulation and Experimental system details

The simulation was performed using FIELD II program [8, 9] in standard STA imaging without and with -10dB noise and DE-STA imaging under the same amount of noise. The probe was simulated as a 4 cm wide linear array probe with 128 elements, 5 MHz central frequency, 0.3 mm pitch, 0.02 mm kerf and 1 cm height. The sampling frequency was 40 MHz.

The experimental phantom images were acquired using an Ultrasonix RP research platform equipped with the parallel channel acquisition system SonixDaq (Ultrasonix, CA). The ultrasound probe was L14-5, which is a 4 cm-wide flat linear array probe with 128 elements that could be used as both transmitters and receivers. The transmission scheme was controlled by Texo. The central frequency of the transducer was 5 MHz and data was sampled at 40 MHz as well.

2) Simulation phatom (wire phantom)

The simulated medium was a 4 cm × 1 cm × 5.5 cm (lateral × azimuthal × axial) phantom which contained seven wire targets located at 5 mm intervals from 15 to 45 mm in depth. The diameter of the wire targets was 200 μm.

3) Experimental phatom (tissue mimicking phantom)

The experimental RF data were acquired in the B-mode, STA and DE-STA from a 4 cm × 4 cm tissue mimicking phantom which contained two 1.2-cm-diameter inclusions (left: hypo, right: hyper echoic) and one 0.05-cm-diameter wire inclusions at 2.4 cm depth. The phantom was made of degassed water, gelatin powder, polyethylene oxide (scatter) and formaldehyde. In the background of phantom, the scatter concentration was 1% of the total weight whereas inside the hyper-echoic inclusions the scatter concentration was twice of that and the hypo-echoic inclusions had no scatters. The transducer was fixed on the top of the phantom surface to ensure that the images were taken from exactly the same section. The beamformed signals were processed by Hilbert transform followed by the logarithm compression and were then displayed as log-enveloped images.

C. Quantification parameters

In this paper, the SNR of backscattered RF signals in the simulation was characterized using (1).

$$\mathrm{SNR}_{\mathrm{dB}} = 20\log_{10}[\mathrm{norm(signal)/norm(noise)}] \quad (1)$$

The noise was obtained by using noiseless STA signals (Fig.1 (a)) as a reference.

Image qualities were quantified using lateral resolution, peak signal to noise ratio (PSNR), and contrast to noise ratio (CNR) among three different imaging techniques: conventional B-mode imaging, traditional STA imaging and DE-STA imaging. The lateral resolution was determined from the full-width at half-maximum (FWHM). The image PSNR was quantified by the point targets as defined in (2) [10].

$$\mathrm{PSNR}_{\mathrm{dB}} = 20\log_{10}[\max\{\mathrm{S}_{\mathrm{target}}\}/\sigma_{\mathrm{noise}}] \quad (2)$$

where $\max\{\mathrm{S}_{\mathrm{target}}\}$ is the wire target peak signal and σ_{noise} is the root mean square (rms) of the noise at the same depth as the wire.

The CNR of inclusions to the background was calculated using (3) [10].

$$\mathrm{CNR} = \frac{\left|\langle \mathrm{S_{ROI}}\rangle - \langle \mathrm{S_{background}}\rangle\right|}{\sqrt{\sigma_{\mathrm{ROI}}^2 + \sigma_{\mathrm{background}}^2}} \quad (3)$$

where $\langle \mathrm{S_{ROI}}\rangle$ and $\langle \mathrm{S_{background}}\rangle$ donate the mean values of log-enveloped region of interest (ROI) and background at the same depth, respectively. σ_{ROI}^2 and $\sigma_{\mathrm{background}}^2$ are the standard deviation of log-enveloped ROI and background, respectively.

III. Results

A. Simulation Results

Fig. 1 indicates the channel RF signals (without beamforming) of STA without (a) and with noise (b), and restored RF signals after decoding in DE-STA with noise (c). The SNR of the RF signals in DE-STA was improved by 21dB over those in standard STA. This value is nearly identical to the theoretical value in Hadamard encoding ($10\times\log_{10} I$ dB, I is the total number of transmitting elements).

Fig. 2 displays the images produced by STA without (Fig. 2 (a)) and with noise (Fig. 2 (b)) and DE-STA (Fig. 2 (c)) with the same amount of noise. As seen in Fig. 2 (b) and (c), the noise level after delay encoding and decoding processes has been significantly reduced.

Fig. 3 shows a detailed comparison of image PSNRs between STA and DE-STA images under noise by assessing the seven wire targets locating at different depths. The average image PSNR improvement by using DE-STA was around 11dB.

Fig. 4 presents the lateral resolution comparison of the wire targets in both STA and DE-STA. It can be observed that when the PSNR of the wire targets is relatively high, DE-STA and STA can provide almost identical lateral resolution results (as seen for wire targets located at 1.5, 2, 2.5, 3, 3.5 and 4.5 cm depths). However, when the PSNR is relatively low, DE-STA technique can significantly improve the resolution (as seen for wire target located at 4 cm depths). This is in agreement with the images in Fig. 2 as the wires at 4 cm depths have very poor detectability using standard STA (Fig. 2 (b)).

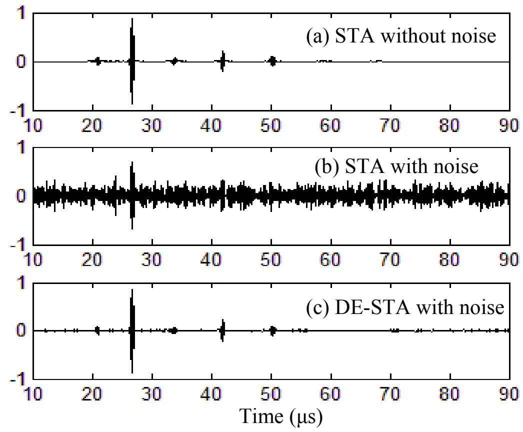

Figure 1. Line plots of a simulated raw RF signal obtained from: (a) the standard STA without noise, (b) the standard STA with noise and (c) the restored RF signals after decoding the DE-STA signals with the same amount of measurement noise as in (b).

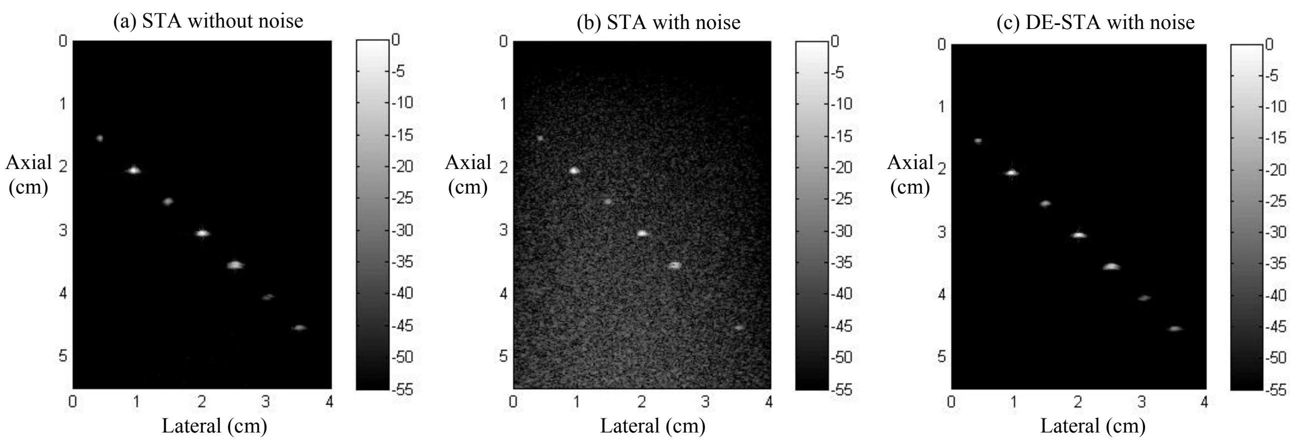

Figure 2. Simulated images from: (a) standard STA without noise, (b) standard STA with noise and (c) DE-STA with noise.

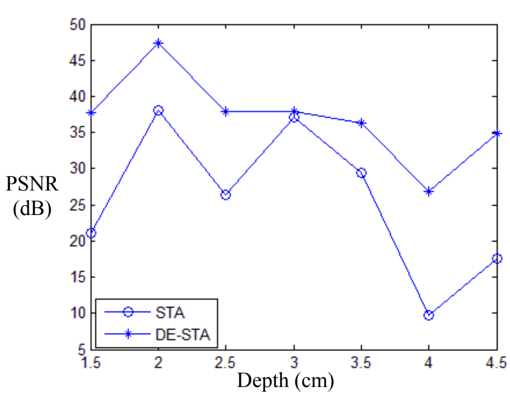

Figure 3. PSNR of seven point targets in STA and DE-STA under the same amount of noise.

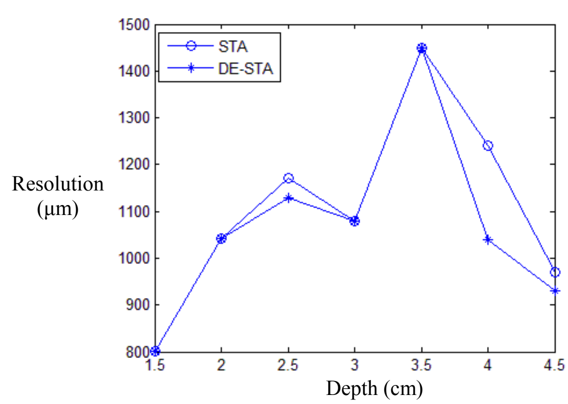

Figure 4. Lateral resolution of seven point targets in STA and DE-STA under the same amount of noise.

B. *Phantom Experimental Results*

Fig. 5 shows the reconstructed images of B-mode (a), standard STA (b) and DE-STA (c) from the tissue mimicking phantom. The lateral resolution (as assessed by the FWHM of the wire) of DE-STA image is improved by 40% and 28% and the PSNR of the wire at 2.4 cm depth is increased by 21.3 dB and 7 dB, compared with the B mode and the standard STA images, respectively (shown in TABLE I). DE-STA image has the best contrast property for the hyper inclusion as well (TABLE I).

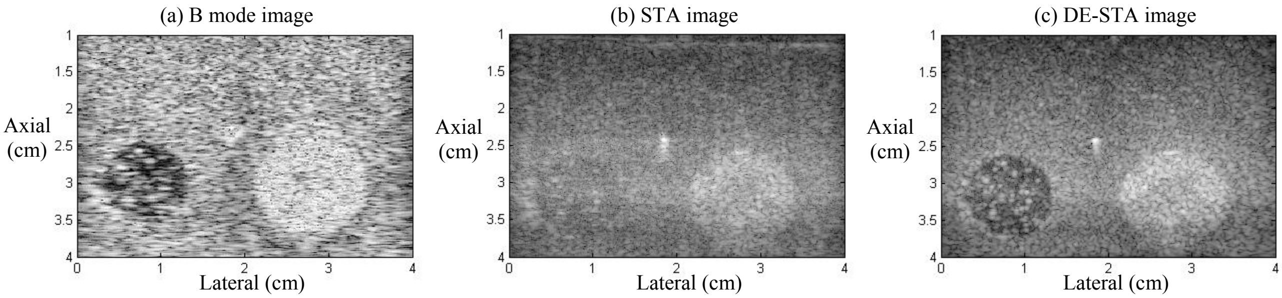

Figure 5. Experimental images from: (a) B mode, (b) standard STA and (c) DE-STA.

TABLE I. PSNR, resolution and CNR comparison among B mode, STA and DE-STA images of experimental phantom.

Mode	PSNR [dB]	$FWHM_{lat}$ [mm]	CNR (hyper)
B mode	16.7	1.00	0.9186
STA	31.0	0.72	1.1725
DE-STA	38.0	0.60	1.4229

IV. Discussion and Conclusion

From simulation and experiment results, we have demonstrated that the image qualities can be improved by delay-encoded synthetic transmit aperture (DE-STA) imaging in terms of PSNR, resolution and CNR. Based on this encoded multi-element transmission, more transmitting energy can be transmitted into the medium, resulting in higher SNR of the decoded RF signals. Therefore, the image PSNR and CNR can be increased as well. The enhancement of resolution (Fig. 4 and 5) of wires is due to the fact that with a better SNR of the RF signals in DE-STA imaging, the high resolution in the STA technique can be attained.

The implementation of Butterworth filter before decoding as mentioned in Method section is a crucial step of DE-STA technique as the half period delay is calculated at the central frequency (5 MHz). As the frequency component moving further away from it, the decoding matrix **A** is getting more and more instable to be inversed and SNR improvement performance is getting worse as well. Therefore, to avoid this problem, the band-pass Butterworth filter is applied here to cut off the frequencies leading to instable inversion. This can also be combined with regularization methods to further stabilize the coding matrix inversion.

In conclusion, DE-STA can improve the SNR of RF signals, and therefore the image qualities are improved over the traditional STA imaging. The improvement is comparable to that in the Hadamard encoded transmission and this technique can be implemented in most commercial scanners.

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