10.1109/ULTSYM.2014.0301

Comparison of Different Image Reconstruction Algorithms for Synthetic Transmit Aperture Imaging using Sparse Receiving Array

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***Abstract*—Hadamard encoded Synthetic transmit aperture (H-STA) ultrasound imaging was proposed to provide RF signals with high signal-to-noise ratio (SNR). In this paper, the Hadamard encoded transmission was applied to designing a low-cost ultrasound imaging system by reducing the number of receiving channels and eliminating the delay circuit for transmission. However, reducing the receiving channels compromised the image qualities. To improve the image qualities, we proposed a reconstruction method: synthetic aperture sub-array compounding (SASC). We compared the performance of three image reconstruction methods: regular synthetic aperture (SA) reconstruction, synthetic aperture compounding (SAC) and SASC. SASC presents a good balance between SA and SAC in terms of contrast-noise-ratio and contrast ratio of the hypo-echoic inclusion.**

Keywords—Sparse Receiving Array; Low-cost; Image Reconstruction Algorithm; Synthetic Transmit Aperture Imaging; Sub-array Compounding

I. INTRODUCTION

Synthetic transmit aperture (STA) imaging with ultrasound can provide more uniform lateral resolution and less shadowing artifacts compared with B-mode ultrasound imaging. However, the standard STA imaging suffers from a low signal-to-noise ratio (SNR) [1] which is unacceptable in medical ultrasound imaging. Different approaches have been proposed to overcome this difficulty [2-5]. One of them is using Hadamard matrix encoded transmission, which increases the SNR by encoding the transmission process with positive and inverted/negative pulses and then using its inverse to decode the received data [6, 7]. However, this approach requires that various elements of the transducer probe must be driven by both positive and negative pulse sequences in each transmission. This is not compatible with many commercial ultrasonic systems (e.g. Ultrasonix RP). Even in systems that allow simultaneous transmission of both positive and the inverted pulses, it is challenging to assure that the negative pulse is an exact inverted copy of the positive one. Any mismatch in the waveform might compromise the performance of the Hadamard matrix encoding. This problem can be solved by separating the Hadamard transmission scheme into two steps: first, elements driven by positive pulse are activated; and then the ones driven by negative pulse are excited. Afterwards, a complete data set can be obtained by combining the received signals from both steps together [5].

Because of the high cost of each receiving channel, reducing the number of receiving channels can significantly reduce the ultrasound system complexity/cost, especially in 3D ultrasound imaging. Here H-STA was applied to designing a low-cost ultrasound imaging system by reducing the number of receiving channels and the resulting image quality degradation was compensated by a proposed reconstruction method, synthetic aperture sub-array compounding (SASC). In this paper, we decreased the number of receiving channels to ¼ of the original number and we compared the performance of three reconstruction methods: regular synthetic aperture (SA) reconstruction, synthetic aperture compounding (SAC) and synthetic aperture sub-array compounding (SASC). SASC has been demonstrated to provide a well-balanced contrast ratio (CR) and contrast noise ratio (CNR) values compared with SA and SAC.

In the next section, the detailed theory and experiment setup for Hadamard encoded STA (H-STA) imaging are described. Different reconstruction methods (SA, SAC and SASC) are introduced. In section III, the experimental results with sparse receiving array and detailed quantification of CR and CNR are shown. We discuss the performance of these reconstruction methods in section IV. The conclusions are drawn in section V.

II. METHODS

A. Hadamard encoding implementation

Generally, we assume there are L transmission events in the Hadamard encoding transmission scheme to form one high-resolution image. In each transmission I elements (the same I elements for all the L transmissions) are fired with either positive or negative pulses following a L-by-I Hadamard coding matrix $\mathbf{H}$. The column index ($i, i = 1 \cdots I$) of $\mathbf{H}$ corresponds to a particular transmission element position, and each row index ($l, l = 1 \cdots L$)) stands for the index of a transmission event. In the coding matrix $\mathbf{H}$, the elements are either 1 or -1. Thus, if $\mathbf{H}_{li} = 1$, the i-th element in the l-th transmission is driven by a positive pulse and if $\mathbf{H}_{li} = -1$, the element is driven by a negative pulse.

In our implementation of the Hadamard encoded STA imaging, all the transmission elements in one transmission are grouped into two categories [5]: the elements in the group $\mathbf{N}^{+}$ are driven by positive pulses and the elements in the group $\mathbf{N}^{-}$ are driven by negative/inverted pulses. We can first excite group $\mathbf{N}^{+}$ elements in L transmissions and acquire the signal s_{lk}^{+} (the RF signal from the k-th ($k = 1 \cdots K$) receiver in the l-th transmission event); then we excite group $\mathbf{N}^{-}$ elements with the same pulse for another L transmissions and acquire the signal s_{lk}^{-}. Lastly the equivalent RF signal s_{lk} to that acquired in standard Hadamard-encoded transmission can be obtained by (1).

$$s_{lk} = s_{lk}^{+} - s_{lk}^{-} \tag{1}$$

Assume $\mathbf{s}$ is the matrix with elements of s_{lk}, which stands for equivalent standard Hadamard-encoded RF signals in a full set of acquisition. Hence, a full $\mathbf{s}$ data set can be achieved with $2L$ transmissions in total. Then the equivalent RF signals as in the traditional STA imaging **p** can be obtained by a decoding process [6, 7]:

$$\mathbf{p} = \mathbf{Hs}\,. \tag{2}$$

Then a standard delay-and-sum beamforming process can be applied to signal **p** as in the traditional STA [1].

B. Experiment setup

The Hadamard encoded STA and traditional STA data were acquired using an Ultrasonix RP commercial system equipped with the SonixDaq acquisition system (Ultrasonix, CA). We selected a 4cm-wide flat linear array probe (L14-5) with 5MHz central frequency. The array probe has 128 elements which can be used as both transmitters and receivers. The transmission scheme was controlled by Texo, a development toolkit provided by Ultrasonix that allows for lower level control of ultrasound system using programs written in C/C++. The sampling frequency was 40 MHz. The tissue mimicking phantom (images were shown in Fig. 1) was made of degassed water (93.85% of total weight), gelatin powder (4.69%), polyethylene oxide (scatter) (1%) and formaldehyde (0.46%). In the background of phantom, the scatter concentration was 1% of the total weight and the hypo-echoic inclusions had no scatters. The 4 cm by 6.5 cm phantom contained 3 hypo-echoic inclusions with a diameter of 1.2cm, 0.7cm and 1.2cm, from the top to the bottom of the phantom, respectively.

RF data were processed for traditional STA and H-STA with full and simulated sparse receiving channels. In the H-STA image reconstruction, we used 32 receiving channels to simulate a sparse receiving array by uniformly selecting one from every four elements in the transducer array. The beamformed signals were then displayed as log-enveloped images.

C. Image Reconstruction Methods

The data acquired from H-STA imaging with sparse receiving aperture were reconstructed in three ways for comparison. Usually, each low-resolution image is reconstructed for each transmission in the standard STA imaging [1]. In this paper, each low-resolution image was reconstructed by coherently summing all the L time-domain signals from one receiver when each transmitter was excited consecutively in L transmissions. Therefore, we obtained K low-resolution images corresponding to K receivers. After that, the low-resolution images were combined to form a high-resolution image by using each of the following methods:

- Synthetic aperture (SA): All the low-resolution images are summed up coherently before envelope-detection;
- Synthetic aperture compounding (SAC): All the low resolution images are summed up incoherently after envelope-detection;
- Synthetic aperture sub-array compounding (SASC): A sub-array with M receiving channels was randomly selected within the sparse receiving aperture. All the beamformed low-resolution images from the sub-array were summed coherently into one intermediate image. Then this process was repeated for N times with different sub-arrays leading to N intermediate images. These intermediate images were then added incoherently to form a high-resolution image. ($M = 10$; $N = 40$ in this paper.)

III. Results

Fig. 1 shows the log-enveloped images of standard STA (a), H-STA with 128 receiving channels (b) and H-STA with 32 receiving channels reconstructed by SA (c), SAC (d) and SASC (e), respectively. It illustrated that the contrast properties (CR and CNR) of all H-STA images with either full or sparse receiving aperture are much greater than that in traditional STA (Fig. 1 (a)) image. This result is in agreement with the vertical line plots (Fig. 2) through the center of the three hypo inclusions from: standard STA (a), H-STA with 128 receiving channels (b) and H-STA with 32 receiving channels reconstructed by SA (c), SAC (d) and SASC (e) methods. The clutter inside H-STA image reconstructed by SASC (Fig 1 (e)) was suppressed better than the one in Fig 1 (b) and (c).

Table 1 shows the detailed comparison of CNR and CR values in the three hypo-echoic inclusions from top to the bottom in the different methods. The contrast property of H-STA image reconstructed by SASC has a good balance between the ones reconstructed by SA or SAC. It reduced the background variance as using SAC while still retained the comparable CR values as the SA approach.

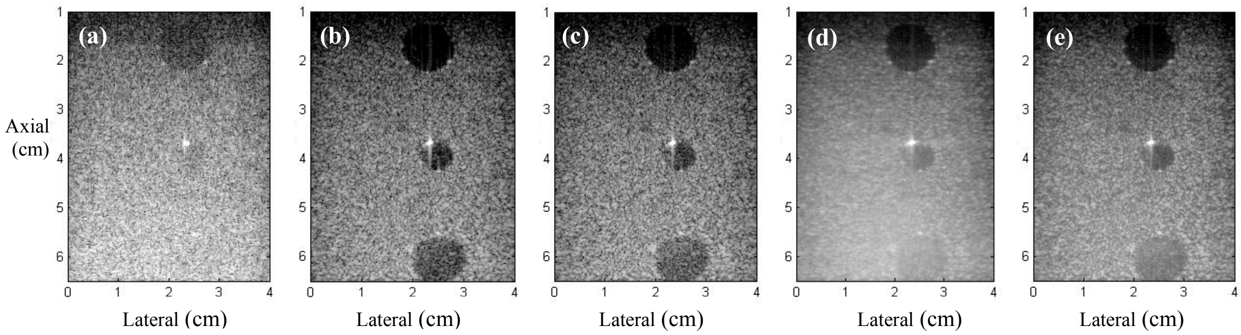

Figure 1. Experimental images obtained in: standard STA (a), H-STA with 128 receiving channels (b) and H-STA with 32 receiving channels reconstructed by SA (c), SAC (d) and SASC (e).

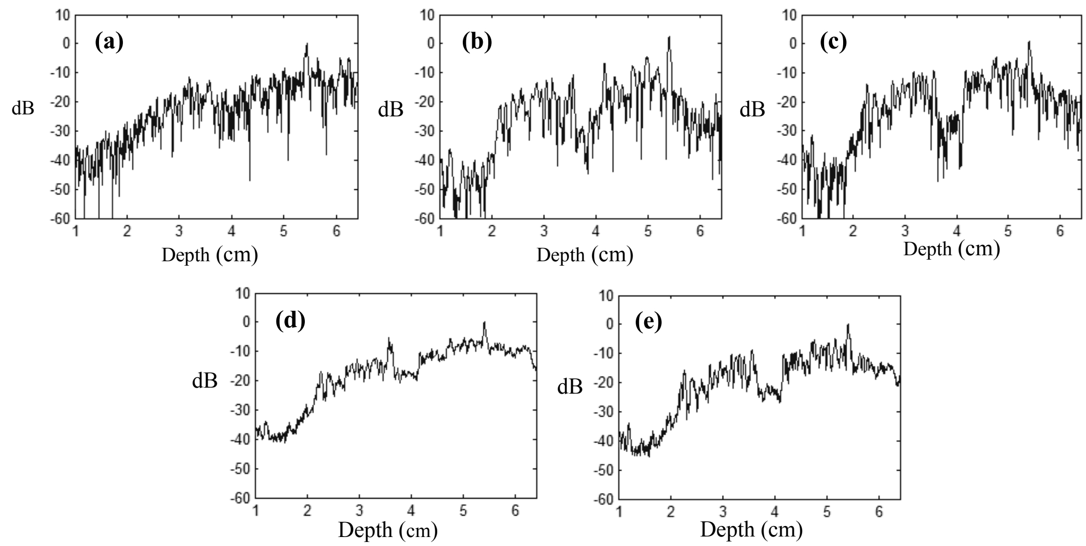

Figure 2. Line plots through three hypo inclusions at 2.5cm vertically from: standard STA (a), H-STA with 128 receiving channels (b) and H-STA with 32 receiving channels reconstructed by SA (c), SAC (d) and SASC (e).

TABLE I. CNR and CR values of three hypo-inclusions in the images of: standard STA (a), H-STA with 128 receiving channels (b) and H-STA with 32 receiving channels reconstructed by SA (c), SAC (d) and SASC (e).

Method	1st Hypo Inclusion		2nd Hypo Inclusion		3rd Hypo Inclusion	
	CNR	**CR (dB)**	**CNR**	**CR (dB)**	**CNR**	**CR (dB)**
STA	0.6954	5.9797	0.4945	3.9526	0.2006	1.6230
H-STA$_{128}$	1.6196	15.1222	1.9212	15.6933	1.7032	13.2633
H-STA$_{SA}$	1.3879	12.8622	1.7050	13.6137	1.3205	10.3544
H-STA$_{SAC}$	1.8913	8.7643	3.5104	7.3515	1.6428	3.2507
H-STA$_{SASC}$	2.0286	11.7278	2.6794	10.1387	1.6678	6.1850

IV. Discussion

Increased contrast properties of H-STA over traditional STA images are demonstrated (Fig. 1 and 2, Table 1) in this paper. This can be explained by the improvement of SNR in H-STA. Because of higher SNR, the RF signals in H-STA are contaminated by less noise which resulted in better contrast properties of all hypo inclusions. Moreover, with reduced receiving channels, H-STA still provides better image quality over traditional STA image. This characteristic of the approach can potentially significantly decrease the complexity/cost of the system by reducing the number of receiving channels especially for 3D ultrasound imaging system.

The SASC reconstruction method is a combination of coherent and incoherent summation. Hence, it inherits some features from both SA and SAC methods resulting in comparable CR values with SA method and comparable CNR values with SAC. The sub-array was selected randomly to evenly distribute the probability of each element being chosen. The length of the sub-array and repeating times in this paper were selected as 10 and 40 as an example to evaluate the performance of SASC. In the future, both parameters can be adjusted to optimize the image contrast property.

The implementation of H-STA in this paper sacrificed the theoretical SNR improvement of standard Hadamard encoding by 2 times and it also increases transmission number by 2 times. However, it can still potentially be implemented in real time (~25frames/s). H-STA decoding and SASC image reconstruction could also be optimized in real time because of high parallelism. Therefore, future work may focus on the optimization of H-STA and SASC to speed up the decoding process and image reconstruction. In addition, delay encoded synthetic aperture imaging [8] can replace the Hadamard encoding transmission in SASC to reduce the transmission number per image frame.

V. Conclusion

An alternative way of implementing Hadamard encoded synthetic transmit aperture (H-STA) imaging is presented in this paper to increase the SNR of RF signals in traditional synthetic transmit aperture (STA) imaging. The number of receiving channels is reduced to decrease the system cost and the image degradation is compensated by synthetic aperture sub-array compounding (SASC). Different STA reconstruction methods are compared and SASC demonstrates the best contrast properties. This method can be extended to 3D ultrasound imaging as well.

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