

Improving the Computational Complexity of Artificial Ultrasound Imaging Using a Combination of Independent Component Analysis and Adaptive Filter

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Abstract

Purpose: The artificial aperture imaging method owns a good contrast in the data recording and imaging process. However, this method is very time consuming that prevents its practical implementation.

Materials and Methods: In this paper, the separated waveforms are sent by two elements together, instead of a single element, and the combination of the methods of independent component analysis and adaptive filtering both are used to extract different components in the received echoes. The obtained result illustrates that the imaging is performed in less time, and the computational complexity of this method is declined.

Results: The proposed algorithm has been evaluated on two sets of simulated data and experimental data. The results indicate that the proposed method in the point phantom mode is only 1.5% worse in the resolution than the conventional artificial aperture method. Also, from the contrasting viewpoint, the proposed method has made the CR parameter worse by about 1.34dB than the conventional artificial aperture method. These adverse points of resolution and contrast in the proposed method are neglected than the conventional artificial aperture method because of a slight decrease in image quality than the artificial aperture method.

Conclusion: However, the proposed method improves the computational complexity by 45% than the conventional artificial aperture method. As a result, it has brought the researchers closer to the practical implementation of artificial aperture imaging.

Keywords: Medical Ultrasound Imaging; Computational Complexity; Artificial Aperture Method; Independent Component Analysis; Adaptive Filter.

1. Introduction

In an aperture imaging system, the elements of the array send ultrasound pulses in sequence, and all the elements simultaneously receive recursive echoes. Applying the appropriate delay to the recursive echoes result in a low-resolution output image. If it is assumed that the array used has an N element, then a low-resolution image was formed by stimulating each of the array elements. Eventually, the sum of the low-resolution images will result in a high-resolution image [1].

In a study in [2], ultrasonic (ultrasound) imaging with artificial aperture improved the low resolution of images to an appropriate extent, but the time-consuming imaging process limited its use in practice [2]. In recent years, researchers in this field have focused more on increasing the frame rate and thus performing real-time imaging. Although this method can completely collect the information from recursive echoes, it is a time consuming and slow process. Although enormous research has been done to reduce the complexity of the artificial aperture method, only in a study in [3], the method of blind source separation has been used to improve the beam formation. Rostami *et al.* used an adaptive filter to form a virtual signal, and this signal, along with the signal of the received array, were used as inputs in the blind-source separation method [3]. After separation by the blind source separation method, the retrieved signals were delayed to form the image and the output image was formed with this method. One of the problems of the proposed method in the study in [3] was its use only for point phantoms, which according to this texture in simulation is considered as a phantom cyst, and in volume λ^3 there is at least 10 scatters in which λ is the wavelength, so it was virtually impossible to use this method [4].

Zhou *et al.* used a two-stage artificial aperture method for 3D imaging [5]. Because the two-stage Synthetic Aperture Sequential Beamforming (SASB) method is an independent method of imaging depth, the resolution does not depend on the depth. Nonetheless, with an increase of imaging depth, resolution declines in the Dynamic Receive Focusing (DRF) method. Besides, from the point of view of computational complexity, the two-stage artificial aperture method has less computational complexity than the conventional

artificial aperture method. The two-stage artificial aperture method consists of two consecutive imaging methods. The first step involves fixed focus and the second step involves a proportional delay for dynamic focus in the image. In the mentioned work in [5], a two-stage artificial aperture method was used for three-dimensional imaging. Also, the effect of reducing the number of transmission and reception elements was studied separately on 3D image quality. Their result showed that reducing the number of reception elements from 64×64 to 32×32 and from that to 16×16 , has not affected the resolution or the image quality; however, the reduction in the number of elements from 32×32 to 16×16 has ruined the efficiency of the two-stage artificial aperture method. This low quality in image may lead to increased sub-lobes due to low radiant wave energy, which results in reduced image quality [5, 6].

Ping *et al.* used four consecutive perpendicular signals for imaging [7]. The time lag between each waveform was half the pulse length. Then in the output of the coding method using the characteristics of vertical signals and time delay in the form of retrieving the desired echoes was used. The main problem of their method was the intense decrease in the quality of output images compared to the conventional artificial aperture method [7, 8].

Loksh *et al.* improved the artificial aperture imaging method to improve the computational complexity. They performed the imaging using 8 or 16 active elements and proved that their method does not significantly affect the image quality of the artificial aperture. Their method was to use 8 or 16 array elements in each step to send a divergent wave to the imaging medium and record the return of echoes with all array elements. Then, to delay the recursive echoes in forming the image, the distance of the virtual source from the focal point and the distance of the focal point from the reception array was calculated and it was considered as a delay related to the focal point. By doing this, only 8 or 16 elements were stimulated instead of stimulating each transmission with all the elements of the transmission array. Their results indicated that the lateral resolution for their method and the artificial aperture method in transmission mode is 0.38 mm and 1.03 mm, respectively. Thus, their method has led to better lateral resolution than the artificial aperture in the transmission mode; however, this improvement has only

been proved efficient for a high number of transmission and reception elements [9, 10].

Mikkel *et al.* used the adaptive spatial filter method to solve the problem of the two-stage artificial aperture (SASB) method [11]. The two-stage artificial method greatly improved the difficulty of calculating the artificial aperture method. Their method was an ideal method for use in manual tools because of the good resolution and also the isolation of image quality from the depth of the image. One of the problems that have challenged their method is that it has more sub-lobes compared to the DRF method, which results in a deterioration of the contrast of this imaging method. In the study in [11], an attempt has been made to improve the contrast of the two-stage 7dB aperture method in $F\#=0.5$ by replacing the second stage of the SASB method with the spatial adaptive filter method. The application of the spatial adaptive filtering methods was such that for each location point of the RI within the desired area, the convolution related to the waveforms caused by the fixed focus with the time-reversal of that waveform was obtained, and in the next steps, it was used to extract the required information. Their results indicate that the use of spatial adaptive filtering instead of dynamic delay in the second stage of two-stage beam formation can increase the contrast by 7dB and 6dB at depths of 20 and 30mm, respectively [11, 12].

Lucas *et al.* developed two-dimensional imaging using screen waves in the space-time domain. They proved that mapping space-time space information to wavelength-frequency space can reduce the complexity of calculations related to delay and sum beam well. Accordingly, they implemented the image method in the wavelength frequency domain and were able to develop two-dimensional images related to the texture in real-time. They then implemented 3D ultrasound imaging in the wavelength-frequency domain and proved that reconstructing the image matrix in the wavelength-frequency domain could reduce the computational complexity by 18 times [13].

In this paper, two stimulus elements are used simultaneously instead of sending through one element, and each element sends a separator chirp signal to the environment. Then, independent component analysis is used to isolate the combined echoes. Additionally, an adaptive filter is utilized to improve the signal to noise

of these isolated echoes. These result in two images in output and the frame rate of the proposed method improves by 45%. Nonetheless, a slight drop in the image quality is in the presented method than the conventional aperture method.

2. Materials and Methods

2.1 Independent Component Analysis Method

The Independent Component Analysis (ICA) method is a powerful tool in the field of blind separation of composite signals and the efficiency of this method has been proven in extracting components independent of the combined signal, without prior information. This method has been widely used in separating ECG, EEG, etc. [14-16]. The word "blind" means that there is no information about the signal of the sources and how they are combined, and only this method reconstructs the signal of the sources using a set of observations. This method uses two assumptions to reconstruct the combined signal:

- the resource signal must be independent of each other.
- their combination should be done linearly.

As can be seen from Figure 1 (block diagram of the ICA algorithm) this algorithm consists of two blocks of mixing system and separation. The purpose of the mixing system is to combine the S_i together. The output of this block is an observation that each observation may be a combination of all sources. The second block is the separation block which is the purpose of the ICA algorithm. So, there will be Y_i in output that results in all the same resources while maintaining their statistical properties. V_i inputs, in which added to observations, are often unwanted inputs that are known as noise signals. In some cases, before the application of the separation system, pre-processes are applied to the

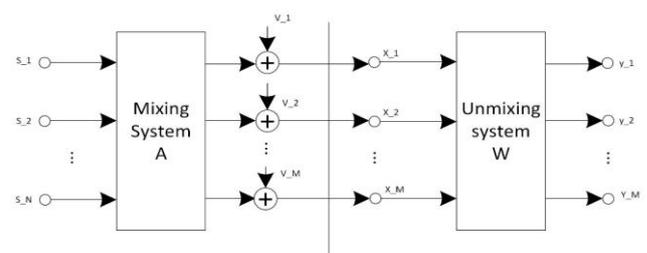


Figure 1. Block diagram of the ICA algorithm

observation signals to reduce the effects of these noises. These pre-processes. can include filtering or even whitening the observations.

A simple model of this method is described below [14]:

$$X = A.S \quad (1)$$

Where S is the vector of the source signal, A is a composition matrix that contains the weights (representing the contribution of each source forming the composition signal) and X is the vector of observations (composition). The goal of the ICA method is to estimate the W matrix which is the opposite of A :

$$Y = W.X = W.A.S = \hat{S} \quad (2)$$

Depending on how the W estimate is accurate, \hat{S} gets closer to S . In this paper, the ICA method is used to separate the combined signals. The input is attached to the separator system, the combined signal, and the virtual signal while the output is the signals of the transmission array. Ultimately, the separated signal is utilized to apply the delay and thus the formation of the output image.

2.2. Adaptive Filter Theory

Adaptive filtering is used in array signal processing to maximize signal to noise of output. If it is assumed that the retrieved signal is displayed by the ICA method with $x(t)$, then the adaptive filter is defined as convolution $x(t)$ with its inverse time $x^*(-t)$. The output of the adaptive filter in the frequency domain can be rewritten as follows [17]:

$$m.f = \text{ifft}(X(f).X^*(f)) \quad (3)$$

Where $X(f)$ is Fourier signal transform of $x(t)$, the multiplication symbol, $X^*(f)$ represents the Fourier signal transform conjugate of $X(f)$ and the IFFT represents the reverse Fourier transform. In the proposed method, an adaptive filter is used to improve the signal-to-noise isolated signals by the ICA method. Figure 2 shows the output of the adaptive filter to the experimental ultrasonic (ultrasound) time signal.

As can be seen in Figure 2, the application of an adaptive filter has increased the signal to noise of the ultrasonic signal by 10 times. Improving the signal to noise in the ultrasound field improves the contrast. Improving the contrast increases the distance between

the black and white of the ultrasound image, thus making the edges of the cyst in the texture more pronounced.

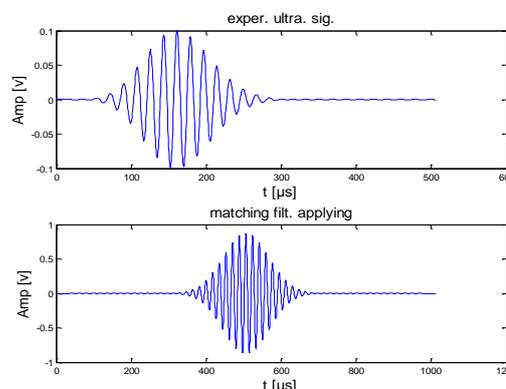


Figure 2. Application of adaptive filter to ultrasound time signal

3.2. The Proposed Method for the Image Formation in Phantom Cysts

According to the mentioned definitions, the steps of the image formation for phantom cysts in the proposed method are summarized as follows:

1. Using 2 chirp signals perpendicular to each other to simultaneously stimulate the two elements of the transmission array.
2. Utilizing the signal of adjacent elements as a second observation.
3. Applying the observations by ICA to separate the combined echoes.
4. Benefiting an adaptive filter to improve the signal to noise of the retrieved signals by the ICA algorithm.
5. Employing a good delay to form two images per transmission to double the improvement of the frame rate.

In the following, more description of the proposed method and also 2 chirp signal is presented.

To implement the proposed method, a linear array of 64 elements with a width of 0.95 pitch per element in which the distance between the centers of the two consecutive elements in the array are used. The height of each array element is considered to be 5mm, and one array is used as a transmission and reception transducer. In order to simulate the imaging environment,

a phantom is utilized containing a black cyst with a radius of 4mm at a depth of 45mm. Also, **Field II** software is employed to build phantoms and stimulations [18]. Moreover, the system of echo pulse in ultrasound is simulated. Two sending elements are active at any one time and as in **Figure 3**, each sends a distinct signal to the imaging environment. For this purpose, two chirp signals are used which must have the following characteristics: their time span is the same, their (B) bandwidth are equal together, and they should not share the same frequency bands.

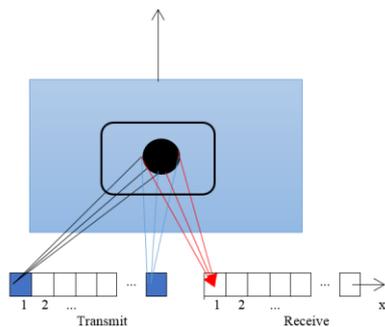


Figure 3. Imaging system in the proposed system

The two chirp signals are defined as follows:

$$S_1(t) = \exp(j2\pi(f_1 t + \frac{B}{2T t^2})) \tag{5}$$

Assuming $-\frac{T}{2} \leq t \leq \frac{T}{2}$.

Where $f_1 = 3$ MHz, B is the bandwidth and its value is equal to 4 MHz and T is defined as the signal length and its value is equal to 6.2 μ s [19]. The second chirp signal is also defined as follows:

$$S_2(t) = \exp(j2\pi(f_2 t - \frac{B}{2T t^2})) \tag{6}$$

Assuming $-\frac{T}{2} \leq t \leq \frac{T}{2}$.

Where $f_2 = 7$ MHz, B is bandwidth and its value is equal to 4 MHz, and also T is the signal length and its value is equal to 6.2. The frequency band of these two signals is shown in **Figure 4** in the result section.

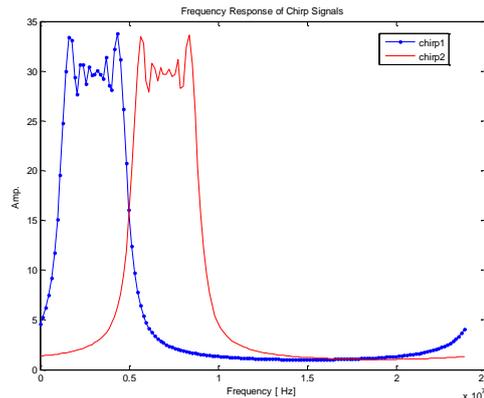


Figure 4. Frequency response of chirp signals $s_1(t)$ and $s_2(t)$

3. Results

3.1. Validation for a Cyst Simulated Phantom

Figure 4 shows a comparison between the frequency response of the two chirp signals. The main reason for equality of the time span and the bandwidth of the two signals is that the time length of signal and bandwidth is proportional to the signal energy and the axial resolution, respectively. Using signals with different lengths of time and bandwidth may create a heterogeneous state in the image. Furthermore, the essential reason to satisfy the condition of independence results in why their frequency bands are unsubscribed.

Figure 5 (A) illustrates the combined signal of the first element of the reception array, **Figure 5 (B)** shows the combined signal of the second element of the receiver array, and **Figure 5 (C)** and **(D)** show the retrieved signals by ICA algorithm.

Figure 6 shows the output of ordinary delay and sum algorithms and the proposed combination method in this paper, respectively.

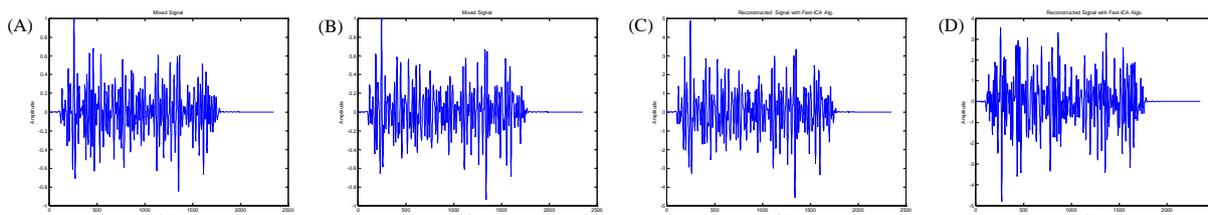


Figure 5. (A) The combination signal of the first element of the reception array, (B) the combination signal of the second element of the reception array, (C) and (D) Retrieved signals by ICA algorithm (Two independent Chirp signals are used for stimulating the elements)

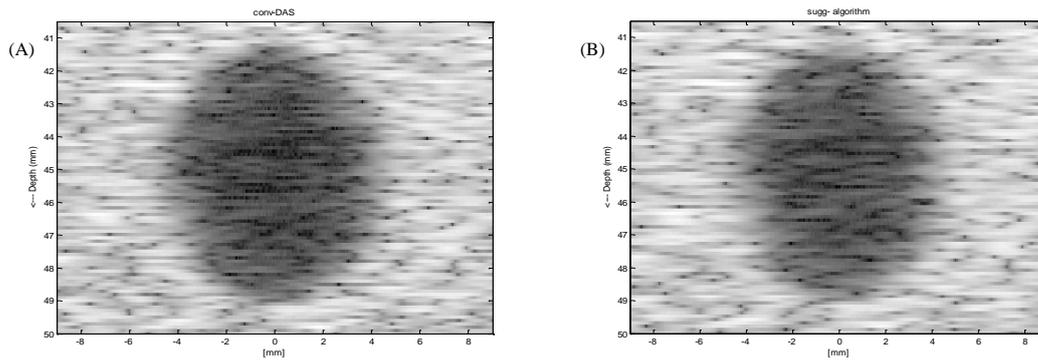


Figure 6. (A) Delay algorithm and ordinary sum (conventional artificial aperture method), (B) The proposed method (the combination of the methods of separating blind sources and adaptive filter to recreate the output image)

Figure 7 shows a comparison between the program runtime of the proposed method with the conventional artificial aperture method. For better differentiation, the times are normalized to the time of running the artificial aperture method.

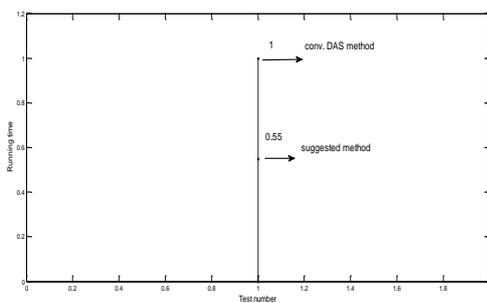


Figure 7. The comparison between the runtime of the proposed method and aperture ordinary artificial method

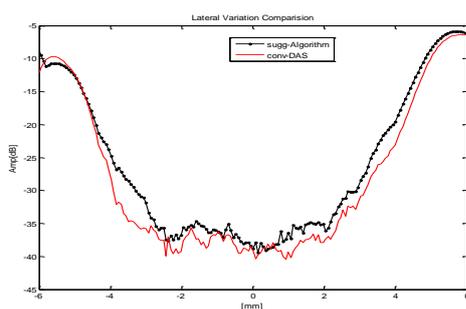


Figure 8. Comparison between lateral changes of delay and ordinary sum method with the proposed method in the middle of the black cyst

3.2. Validation for the Experimental Phantom of the Geabr

In order to validate and compare the purposed algorithm to the conventional artificial aperture method on the experimental data sample, the Geabr

experimental data of a real texture sample was used which recorded the Medical Ultrasound Laboratory at the University of Michigan. This raw data is recorded by a linear array with 64 elements, length of 15.4 mm and central frequency 3.33 MHz. This raw data is the output information of the received array, which is provided to users in the form of time signals and is called "scan lines".

Researchers in the field of science and knowledge have recorded appropriate delays in scanning data lines and retrieved the brightness of each pixel of the image, eventually forming the Geabr experimental phantom image. Accordingly, the contrast and resolution of the output image may differ depending on the type of delay application algorithm and the proposed method in general.

The light intensity both inside the cyst and outside looks whiter in the proposed method compared to the delayed method and the ordinary sum which proves a decrease in the average light intensity inside and outside the cyst. This decrease is proportional to the obtained results in Table 2. Table 2 shows the study of CR and CNR parameters for the experimental phantom of Figure 9. Compared to the results of Table 1, it can be seen that although the average light

intensities inside the cyst have slightly decreased, the difference between the light intensities inside and outside the cyst compared to the simulated data state is almost constant. Therefore, the proposed method reduces the computational complexity of the artificial method by 45% while maintaining the approximate contrast and image quality, and the frame rate of this method in medical imaging has proportionally doubled.

Table 1. Comparison of conventional artificial aperture method and proposed method in terms of contrast

Algorithm	Average Light Intensity Inside of the Cyst (dB)	Average Light Intensity Outside of the Cyst (dB)	Parameter CR	Std Outside of the Cyst	Parameter CNR
Conv-DAS	-41.87	-13.45	28.41	5.55	5.11
Sugg-Algori.	-39.88	-12.81	27.07	5.50	4.92

Table 2. Comparison of conventional artificial aperture method and proposed method in terms of contrast for Geabr experimental phantom

Algorithm	Average Light Intensity Inside of the Cyst(dB)	Average Light Intensity Outside of the Cyst (dB)	Parameter CR	Std Outside the Cyst	Parameter CNR
Conv-DAS	-40.33	-14.12	26.21	5.45	4.81
Sugg-Algori.	-37.22	-12.33	24.77	5.30	4.67

Figure 9 shows the output of the proposed algorithm and the typical artificial aperture method on the Geabr experimental data. This Figure also proves the obtained results in Figure 6. It is clearly shown in the Figure that the proposed algorithm on the actual data is consistent with the conventional artificial aperture method, and the image quality is partially affected.

Geabr experimental data is available on the University of Michigan Ultrasound Laboratory website at:

[mailto:\(http://www.bme.umich.edu/labs/bul/newBULsite\)](mailto:(http://www.bme.umich.edu/labs/bul/newBULsite))

3. Discussion

In general, the purpose of this study is to use beamforming methods along with independent component analysis methods to improve the efficiency of beamforming methods. Considering that the

beamforming methods and the independent component analysis have the same goal of retrieving the desired signal from the combined signal, which uses spatial and frequency information for this purpose, respectively. As a result, the idea of using these two methods is simultaneously formed to further improvement in the quality of the output images in the artificial aperture beamforming method. Additionally, the Independent Component Analysis (ICA) method is used to isolate the combined echoes at the array output, and consequently, the complexity of the artificial aperture beamforming method is reduced by 45%.

As previously reported, Figure 4 shows a comparison between the frequency response of the two chirp signals. The slope of frequency increase or decrease in the chirp signal is defined as follows:

$$\mu = \frac{B}{T} \tag{7}$$

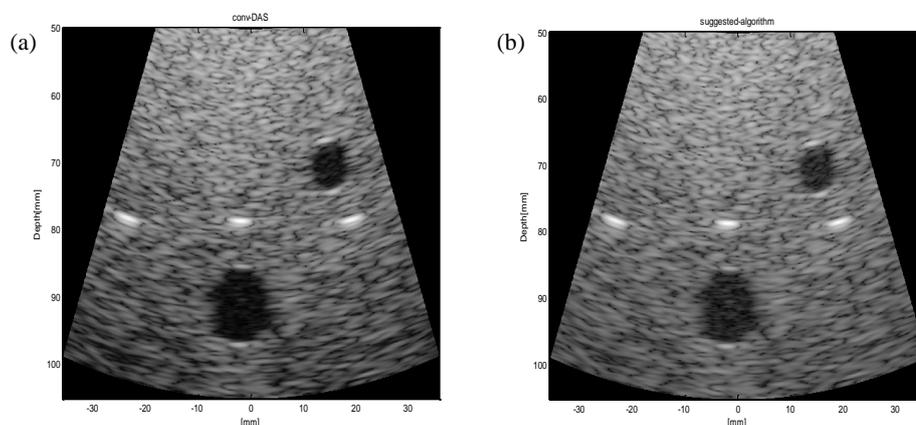


Figure 9. Validation of the proposed algorithm on the Geabr experimental data (a) for the ordinary delay and sum algorithm (conventional artificial aperture method), (b) the proposed algorithm

Where B represents bandwidth and T indicates the length of time in the chirp signal. It can be proved that the use of slopes with different sign reduces cross-correlation by 12 dB. And separating their frequency bands reduces the value to around -60 dB. The results mean that the two signals can be separated from each other with this accuracy [20].

Figure 5(A) shows the composition signal for the first element of the receiving array. This signal is obtained by applying the chirp S1 (t) signal to the first element and the chirp S2 (t) signal to the 64th element of the array. The ICA method for separating the combined echoes from the two chirp signals requires two observations for each of the receiving array elements. Since among the signals of the receiving array elements, the signals of the adjacent elements have the highest correlation with each other. As a consequence, the signal from adjacent elements was used as the second observation for each receiving array element to apply the ICA method. Figures 5(A) and 5(B) show the observations related to the first element of the receiving array. Figure 5(C) and 5(D) are used for retrieving the combined echoes and the output of the ICA method is shown.

To compare the contrast of the proposed method than the delay method and the ordinary sum method (conventional artificial aperture method), a phantom containing a black cyst with a radius of 4mm at a depth of 45mm is used. The reason for placing the target phantom at this depth is that the ultrasound imaging is usually performed in a close field, and also the tissues of the body are practically at the same depth. In **field II** software, the Gaussian distribution is used to define the amplitude of the scatter points. Figure 6 shows the output of the ordinary delay and sum algorithms as well as the proposed method in this paper, respectively. Because in the proposed method, the number of submissions that are halved towards the environment, it has less computational complexity than the conventional artificial aperture method and is obtained an improvement of 45% in the computational complexity.

In order to quantify the difference between the proposed method and the conventional artificial aperture method, Contrast Ratio (CR) and Contrast to Noise Ratio (CNR) parameters are used. The CR parameter is defined as the absolute value of the

subtraction of light intensity inside the black cyst relative to the average light intensity outside the black cyst [21]. Also, the CNR parameter is the result of dividing the CR parameter on the standard deviation of light intensity outside of the black cyst [21]. It can be seen from Table 1 that the method of combining the adaptive filter and the analysis of independent components make the CR and CNR parameters worse than the conventional delay and sum method by 1.34 dB and 3.7%, respectively. The proposed method has reduced the computational complexity of the artificial aperture method by about 45% which is a very important advantage and can help scientists in the practical implementation of the conventional artificial aperture method. However, there is a little degradation of contrast than the other mentioned methods. Also, the runtime of the program for the artificial aperture modes is compared with the proposed method in the phantom cyst mode. For better differentiation, the time is normalized to the running time of the conventional artificial aperture method. As it is shown in Figure 7, the runtime of the program in the phantom cyst mode has been reduced to 0.45% for the proposed method than the artificial aperture method.

Figure 8 shows a comparison of the beam patterns of the two delay and ordinary sum algorithms (conventional artificial aperture method) and the proposed method in the middle of the black cyst. It is clear from the Figure that the proposed method has three advantages over the other methods to reduce the complexity of the artificial method, which are:

- In the proposed method, the cyst retains its actual size.
- The proposed method follows the changes in light intensity inside the cyst almost like a conventional artificial aperture method.
- The proposed method follows changes in light intensity outside the cyst almost like a conventional artificial aperture method.

Figure 9 shows a comparison between the proposed method and the conventional artificial aperture method for the experimental phantom. As can be seen, the proposed method can precisely follow the changes of the conventional artificial aperture method and restore the edges of the cyst with the background noise. Table 2 shows the comparison between the CR

and CNR parameters for the experimental phantom in both the conventional artificial aperture method and the proposed method. As it turns out, the proposed method withstands a slight contrast drop of 1.44dB and improves the computational complexity of the conventional artificial aperture method by 45%. This slight decrease in contrast of the proposed method compared to the conventional artificial aperture method is due to the simultaneous use of the two methods (ICA and adaptive filter) to separate the combined signals and increase the signal to noise.

In the end, using the proposed method will have two advantages. First, imaging can be done in less time, because the computational complexity of the artificial aperture method is less, and also getting closer to real-time imaging. Second, this proposed method can form the completed information from the recursive echoes, so the resolution is less affected.

4. Conclusion

In this paper, simultaneous stimulation of two array elements was used instead of stimulating by one element. Since the receiving array elements received the combination of transmitted signals, there is a need for another auxiliary signal to separate the combined signals by ICA. To this end, the composition signal of the adjacent array was used. By doing this, the proposed method can completely form the information from recursive echoes to minimize the effects of the quality and contrast in the proposed method.

In general, the steps of image formation in the proposed method of this research is summarized as follows:

1. Using 2 chirp signals perpendicular to each other to stimulate the two elements of the array simultaneously.
2. Utilizing the signal of adjacent elements as a second observation.
3. Applying ICA to separate the combined echoes
4. Employing an adaptive filter to improve the signal to the noise of the recovered signals.
5. Benefiting a good delay to form two images per transmission to double the frame rate.

The obtained results indicated that regarding the contrast, the parameters of CR and CNR were degraded by 1.34dB and 3.7%, respectively, in the proposed method compared to the conventional artificial aperture method. Although the slight decrease of resolution and contrast was in the proposed method, an improvement of 45% was made in the computational complexity by the proposed method than the conventional artificial aperture method. As a result, the complexity of calculation in the artificial aperture method was reduced to half with the proposed algorithm.

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