Parallel Beamformation Method to Enhance Ultrasound Images

S. M. Sakhaei*, A. Mahloojifar**, H. Ghassemian**

Abstract: Contrast resolution and detail resolution are two important parameters in ultrasound imaging. This paper presents a new method to enhance these parameters, simultaneously. A parallel auxiliary beamformer has been employed whose weightings are such that an estimation of the leaked signal through the main beamformer is obtained. Then the output of main beamformer is modified according to the estimated leaked signal. The efficiency of our adaptive method is demonstrated by applying it over an experimental data set and provided an enhancement of about 22 percent in lateral resolution and 15-20 dB in contrast resolution. This method also has the advantages of simplicity and possibility of real time implementation.

Keywords: Beamforming, Contrast Resolution, Ultrasound imaging.

1 Introduction

In diagnostic ultrasound, contrast resolution and detail resolution are two main measures of the image quality providing the ability to detect deep lying, low contrast lesion in the body, such as tumors [1]. In order to increase the detail resolution, the beam width in the focal point should be decreased. For the contrast resolution, the beam intensity should diminish quickly outside the focal point.

A simple and common way to control the beam properties and image quality is weighting of the array elements [2-12]. However, weighting decreases the sidelobe level at the price of widening the mainlobe width and consequently the detail resolution is sacrificed to enhance the contrast resolution [2]. In addition, the point spread function (PSF) of an ultrasound imaging system is generally spatial shift variant [13] and enhancing the resolution in all points needs changing the weights continually, which is computationally expensive [6], [8], [9]. On the other hand, properties of the PSF are related to the characteristics of the medium to be imaged and preset weightings cannot provide the desired PSF. Therefore, adaptive weighting may be a choice [10-12], but it is time consuming, needing high computational load. In addition, performance of adaptive methods is usually degraded with system errors (such as errors in location of elements of the array), uncertainty in the characteristics of the medium (such as speed of sound) and transducer noise.

Another adaptive method to enhance the ultrasound image is the nonlinear processing of the received echo data [14-17]. These techniques try to estimate the signal leaked through the sidelobes and then correct the amplitude of main signal by scaling it according to the estimation of leaked signal. In [16-17], a filter called null filter is introduced in which the steering operator is mathematically applied to the received data and signals obtained in some null directions are computed. Then estimation of leaked signal is considered as rms value of the computed signals. The significance of this type of methods is the enhancement of detail and contrast resolution, simultaneously.

In this paper, a new method to enhance the ultrasound image through estimation of leaked signal is presented. In this method, an auxiliary beamformer parallel to the main beamformer is employed. Weighting in auxiliary beamformer is such that an estimation of the leaked signal through the main beamformer is obtained. We demonstrate that our method is an efficient adaptive technique to enhance the ultrasound image through both simulation and experimental data. Also, it yields a filter which outperforms the null filter and is easier to implement in real time.

The paper is organized as follows. In Section 2, the new method is described. In Section 3, the method is evaluated through simulation and the results obtained by applying it over an experimental data set are compared to conventional and null filter methods. Section 4 represents discussions and Section 5 gives conclusions and further works for improving performance of the proposed method.

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2 Theory

Suppose that S(l,t) is the output signal of array at time t when reading l'th line and $S_{leak}(l,t)$ is leaked signal through sidelobe which interferes with the main signal S(l,t). It is possible to decrease the effects of interference in the main signal by scaling as:

$$S_f(l,t) = \frac{S(l,t)}{1+\gamma\left(\frac{S_{leak}(l,t)}{S(l,t)}\right)^{\beta}} \tag{1}$$

where β and γ are constants. Let us call the filter described by Eq. (1) as the leak filter. The filter is similar to that used in [16] and [17]. The filter inputs are the RF channel data for each depth/time after applying the beamforming delays. The filter behaves as follows: if the leaked signal is negligible, then the filter input is transferred to the output without attenuation; otherwise, the output is scaled down, according to the ratio of the leaked signal level to the main signal.

To calculate $S_{leak}(l,t)$, the weighting of the elements is selected in a way that the obtained beam pattern has negligible value about the mainlobe of primary beam pattern and the same values at sidelobes. We call the new beam pattern as leak BP. To design leak BP, we define an optimization problem whose main objective is to minimize the energy of error between primary BP and leak BP at sidelobes with constraining the value of the leak BP at the main axis to be zero. Hence, the problem may be expressed as:

$$\underset{v}{\text{Min}} \quad \Delta E(\theta_s+\delta,\pi)+\Delta E(-\pi,\theta_s-\delta) \tag{2-1}$$

$$\text{subject to:} \sum_{n=1}^{N} v_n = 0 \tag{2-2}$$

where v_n denotes the weightings used for leak BP, λ_c is excitation wavelength, d the array element spacing, N the number of elements and ΔE the energy of error between primary and leak BP, $\theta_s = 2\pi d\sin\Phi_s/\lambda_c$, $\delta = 2\pi d\sin\Phi/\lambda_c$, Φ_s is steering angle and Φ is the deviation of observation angle from steering angle (see Fig. 1). Region outside the interval $(\theta_s - \delta, \theta_s + \delta)$ is considered as sidelobe region and so the relation (2-1) tries to equalize the primary and leak BP at sidelobes. The constraint (2-2) forces the leak BP at the main axis to zero.

The energy of a BP in the interval θ_1 and θ_2 for an array with weighting vector w can be calculated by:

$$E(\theta_1,\theta_2) = w^T M(\theta_1,\theta_2)\, w^* \tag{3}$$

where M is the energy matrix and symbols * and T represent complex conjugate and transpose operators, respectively. For an array having N elements equally spaced, energy matrix may be calculated as [18]:

$$\begin{aligned} M(\theta_1,\theta_2) &= \int_{\theta 1}^{\theta 2} \underline{e}\cdot\underline{e}^{*T} du \\ \underline{e} &= [1, e^{ju}, e^{j2u}, ..., e^{j(N-1)u}]^T\, e^{-j\frac{N}{2}u} \end{aligned} \tag{4}$$

and the component (m,n) of matrix M is equal to:

$$M_{mn}(\theta_1,\theta_2) = \begin{cases} \frac{j}{m-n}\left[e^{j(m-n)\theta_1} - e^{j(m-n)\theta_2}\right]; m \neq n \\ \theta_2 - \theta_1 \qquad ; \quad m = n \end{cases} \tag{5}$$

Using Eq. (3), the energy of error may be expressed as:

$$\Delta E(\theta_1,\theta_2) = (v-w)^T M(\theta_1,\theta_2)(v-w)^* \tag{6}$$

and the optimal v may be obtained by applying Lagrange multiplier method on Eq. (2) as:

$$v = w - \frac{1_w^T w}{1_w^T\left(S^*+S^T\right)^{-1} 1_w}\left(S^*+S^T\right)^{-1} 1_w \tag{7}$$

where l_w represents an N by 1 vector whose all elements are 1 and S is calculated as:

$$S = M(\theta_s+\delta,\pi) + M(-\pi,\theta_s-\delta) \tag{8}$$

which results in:

$$S_{mn} = \begin{cases} -2\frac{\sin(m-n)\delta}{(m-n)} \; ; m \neq n \\ -2\delta \quad ; \quad m = n \end{cases} \tag{9}$$

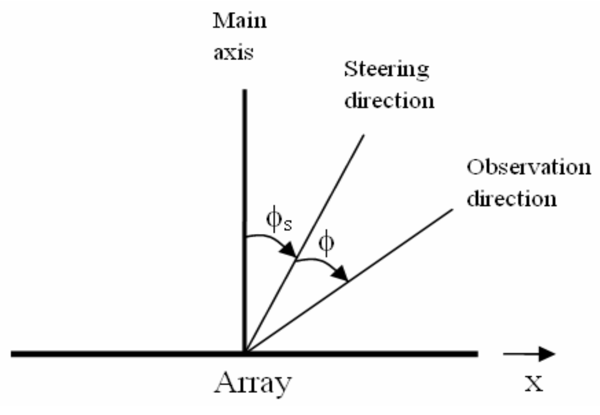


Fig. 1 The geometry showing steering and observation directions.

Therefore, S is a real symmetric matrix and the desired weighting may be calculated as:

$$v = w - \frac{1_w^T w}{1_w^T S^{-1} 1_w} S^{-1} 1_w \qquad (10)$$

The Eq. (10) gives the weighing of the auxiliary beamformer producing leak beampattern.

3 Simulation

To evaluate the performance of the new method, it is applied to some cases using ultrasound field simulation software, FIELDII [19]. A linear array having length 85mm and 128 elements, with only 64 elements used in receive, is considered. The transmit focal point is set to 60mm, the center frequency assumed to be 3.5 MHz, the pulse shape is given as:

$$p(t) = \exp[-(\omega_0 t / \sigma)^2] \cos(\omega_0 t) \qquad (11)$$

and σ determining the pulse length, is set to 2.5π.

Beamformation is applied to received RF signals in two ways; one with no weighting, resulting in the primary signal and another, with weighting calculated by Eq. (8), resulting in the leak signal. The two signals are combined according to Eq. (1).

Figure 2 shows the lateral point spread function of a point lying in depth 60mm by applying primary and leak beamformer. It is evident from the figure that the lateral PSFs are similar in sidelobe regions and leak PSF has small value around the mainlobe of primary PSF.

In Fig. 3, the lateral PSFs obtained by using different filter types have been compared. It demonstrates that the leak filter has better performance than that of the third-order null filter and its mainlobe width and sidelobe level are lower.

Another advantage of leak filter to null filter (and sidelobe filter) is the higher sensitivity. In null filter, the estimated leaked signal is contaminated by desired signal and, consequently, the scaling factor is less than one. This means that the signal is always attenuated by filtering, even in cases with no leakage.

Due to the nonlinearity, this attenuation is not the same at different points and may reduce the sensitivity of the system. However, in leak filter method, the attenuation is negligible, and the sensitivity of imaging system is higher than that obtained by null filter. It is confirmed by simulations adopted in Fig. 3, where values of attenuation are 6dB using a third-order null filter with $\gamma = 1$, 15dB using the same filter, but $\gamma = 5$ and only 1dB using a leak filter with $\gamma = 10$.

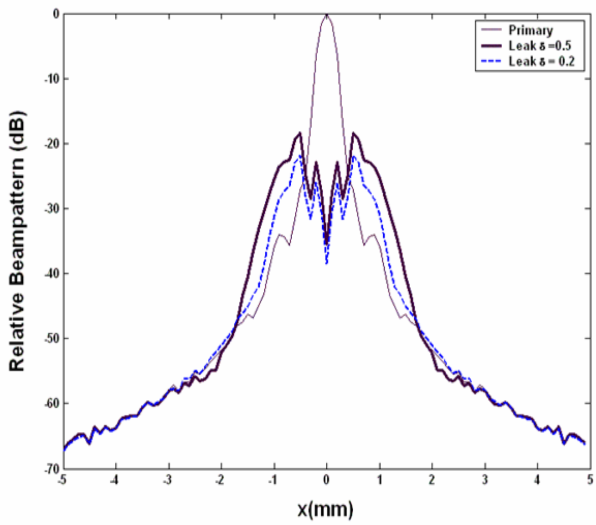


Fig. 2 Primary and leak beam pattern.

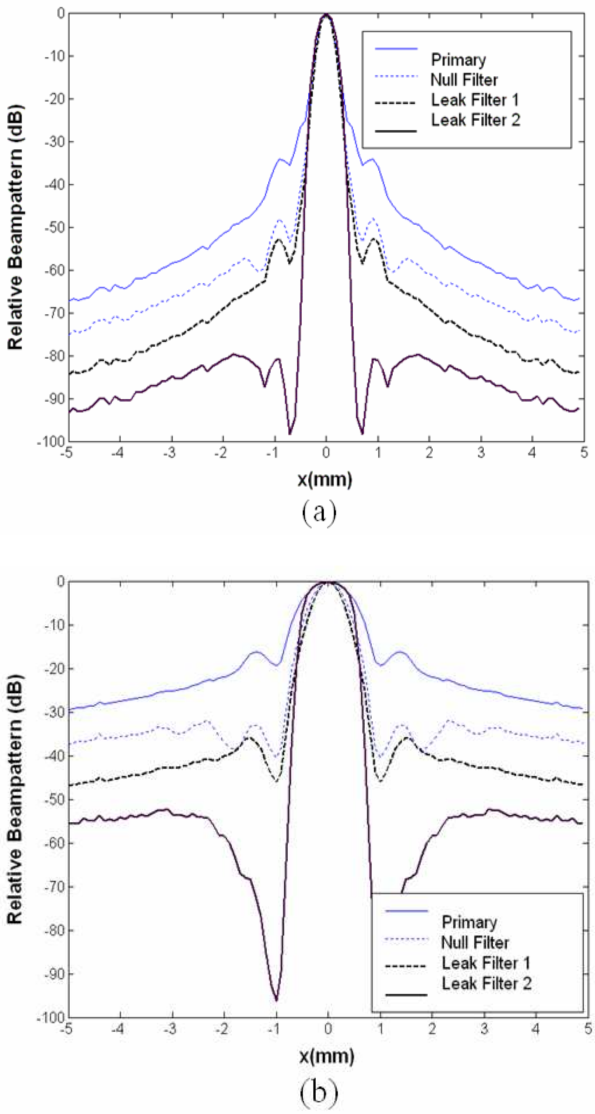


Fig. 3 Lateral point spread function at depths 60mm (a) and 90mm (b) The null filter is third order with γ=5, for leak filter1 δ=.2, γ=10, β=1 and for leak filter 2: δ=.5, γ=1, β=20.

In addition, the filter nonlinearity causes amplitude distortion in the obtained image and regions having different reflection coefficients may not produce acceptable contrast in the image. To evaluate this, three point reflectors lying in depth 60 mm and separated by 3λ are considered and assumed the left and right ones to have reflectivity of 20dB and 40dB below the central one, respectively. The simulation results are shown in Fig. 4. It is obvious that the leak filter detects the right point correctly, as well as conventional and null filter. However, the leak filter produces higher contrast than other types. The leak filter also distinguishes the left point from surrounding medium at the price of deviating linearity; where the other filters can not do the same. Hence, the distortion made by leak filter does not lose any useful information and may be acceptable.
The performance of our method in imaging of complex media is also verified. A speckle media is simulated and the images obtained by conventional and our method are evaluated. In Fig. 5, the autocorrelation functions of images, as indexes of detail resolution [20] are plotted. It shows an enhancement of 50 percent in lateral resolution.

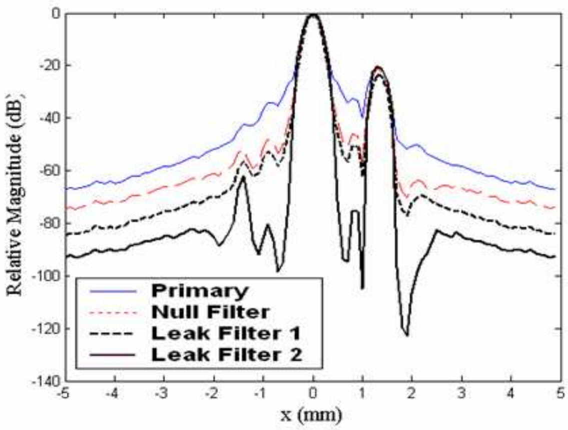


Fig. 4 Comparison of linearity in brightness for filter response to targets: reflectivity is 20 dB (right target) and 40 dB (left target) lower than center target. The filter parameters are described in Fig. 2.

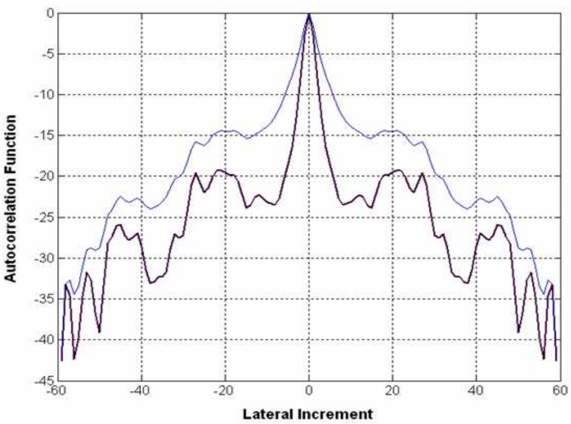
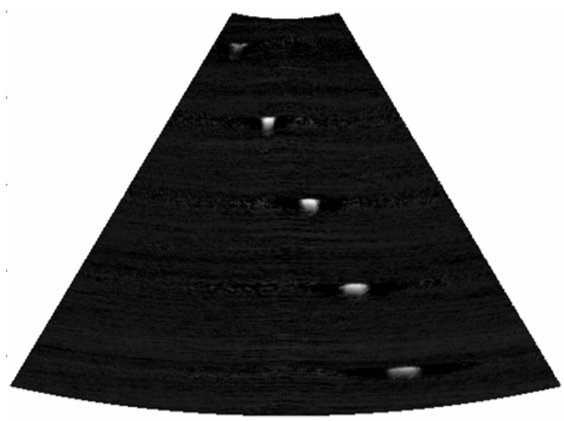


Fig. 5 Comparison of lateral resolution of conventional (thin line) and leak filter (thick line) for a speckle media. The leak filter parameters are: δ=0.5, γ=1, β=10.

To verify the performance of the proposed technique on real data, it is applied to "Acuson 17" data set, a complete data set gathered by the Biomedical Ultrasound Laboratory, University of Michigan [21]. The parameters are as follows: 128 channels, 13.8889 MHz sampling rate, 3.5 MHz transducer with 0.22mm element spacing, 2048 RF samples per line each represented in 2 bytes, and 8 averages. The data were acquired for a phantom with pins at different positions. We used the data to simulate an image in an arc of width 50o by a 64 elements phased array transducer. The results obtained by the conventional and leak filter methods are shown in Fig. 6. It is evident from the figure that the leak filter can highly enhance the resolution. To quantify the amount of enhancement, the lateral point spread function for one of the pins may be approximately calculated. To this end, a sector containing the fourth pin is considered and the maximum of the envelop signal in each lateral position considered as the amount of lateral point spread function [8]. The results are shown in Fig. 6-c. It is concluded from the figure that the lateral resolution at 10dB loss is enhanced by 22 percent and the contrast resolution about 15-20 dB.



(a)

(b)

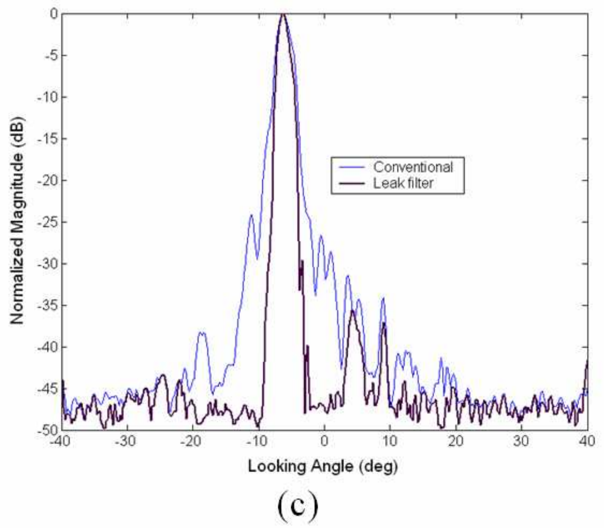


Fig. 6 The images obtained from a real data set by conventional method (a) and leak filter (b) Comparison of lateral distribution for fourth point is shown in (c).

4 Discussion

Since our objective is to reveal the ability of new technique to enhance the detail resolution higher than that obtained in no weighting cases, the primary beamformer is obtained by no weightings. If the weighting is applied to primary beamformer, the leak filter may improve the detail resolution.

To design a leak filter, as simulations have shown, suitable selection of filter parameters δ, β and γ are very important. Large γ causes the amplitude of lateral PSF at all regions to be more attenuated and the mainlobe width and the sidelobe level to be lowered, simultaneously. Conversely, the attenuation on main axis is increased and the nonlinear effects may be adverse. Increasing β means that in points where the signal to interference ratio is low, the scaling factor is much lower than in points where the signal to interference ratio is high. Therefore, by increasing β the value of lateral PSF about the main axis becomes smoother and then decreases quickly (Fig. 3-b). In addition, scaling factor becomes lower and nonlinear distortions may be decreased.

The value of δ is related to the angle of determining width of the beam pattern mainlobe and decreasing the value of δ narrows the mainlobe width of leak filtered signal. However, it inserts errors on estimation of interference. Also, very low value of δ causes the leak PSF to fluctuate about the main axis.

Therefore, suitable selection of parameters δ, β and γ can produce an enhanced image.

5 Conclusions

In this paper, we have introduced a new adaptive technique to enhance ultrasound images. The proposed technique is practical and efficient and may be implemented in real time, inexpensively. An important advantage of our method over weighting method is reduction of the sidelobe level and the mainlobe width, simultaneously. In addition, this method has advantages over similar methods based on nonlinear processing of received echoes, which are higher performance in reduction of the sidelobe level and higher sensitivity of the imaging system. The enhancement of lateral resolution for a real data set by the leak filter is about 22 percent and the contrast resolution, about 15-20 dB, as compared to the conventional method.

To improve performance of the method, it is possible to optimally calculate the values of δ, β and γ such that a predefined index of image e.g. CNR (Contrast to Noise Ratio) or autocorrelation function is optimized. Also, adaptive tuning may be applicable. For example, at any instant, the parameters may be selected such that the energy at the output of the leak filter is minimized subject to the soft constraints on the parameters: $\delta \geq \delta_0$, $\gamma \leq \gamma_0$, $\beta \geq \beta_0$ where the parameters labeled with zero are constants that avoid undesired results.

In addition, to calculate the weightings of auxiliary beamformer, the continuous wave beam pattern has been employed in this paper. However, better results may be obtained using wide band beam pattern or point spread function in each point.

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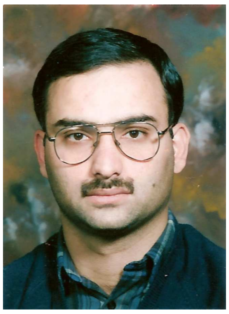

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