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Combined phase screen aberration correction and minimum variance beamforming in medical ultrasound

Mahsa Sotoodeh Ziksari, Babak Mohammadzadeh Asl *

Department of Electrical and Computer Engineering, Tarbiat Modares University, Tehran, Iran

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ABSTRACT

In recent years, applying adaptive beamforming to ultrasound imaging improves image quality in terms of resolution and contrast. One of the best adaptive beamformers in this field is the minimum variance (MV) beamformer which presents better resolution and edge definition compared to the traditional delay-and-sum (DAS) beamformer. However, in real situations, sound-velocity inhomogeneities cause phase aberration which leads to ambiguity in targets' location and degradation in resolution. This effect is a fundamental obstacle to utilize advantages of MV beamformer, although, in aberrating medium MV beamformer results in better performance compared to DAS.

In this paper, two different levels of phase screens have been applied to simulate aberrator layers located close to the transducer. Also, prior to beamforming process, a conventional correction technique based on phase screen model is used. Simulations are performed in majority resolution of MV which has the lowest robustness. The results demonstrate that applying this correction method can retrieve the efficiency of the MV beamformer. Moreover, the method improves the performance of the MV in both terms of resolution and contrast. As corrected MV achieved at least 22% improvement in sidelobe reduction and 24% increase in contrast to noise ratio (CNR) with respect to the DAS corrected data. Also, according to experimental dataset 17% enhancement in CNR is yielded by MV.

1. Introduction

Over the last few years, ultrasound imaging has become an efficient diagnostic tool in many areas of medicine. Therefore, improving the image quality in terms of resolution and contrast will significantly increase the clinical reliability of ultrasound imaging in many applications.

All ultrasonic imaging systems utilize a fixed velocity for imaging; however, there are differences between acoustic velocities in soft tissues. Actually, echoes are generated by scatterers which are made by these discontinuities in impedance. On the other hand, changes in sound speed cause phase errors in beamforming, that prevent convergence of all acoustic energy to focal point, resulting in additive off-axis response and degradation in resolution, contrast and image dynamic range [1]. In the aberrating medium, large and high frequency arrays could not be used to improve the resolution of images, as they make aberration more severe [2].

Since, beam properties have direct influence on image quality, the resolution is affected by main lobe beam width, while sidelobes specify image contrast. Beamforming techniques are used to reduce the sidelobe levels and the beam width.

The simplest beamforming used to reconstruct images in medical ultrasound is the delay-and-sum (DAS) method, which applies constant predetermined weights to received signals. DAS is a straightforward and fast method, but the suppression of interfering signals and also resolution of the results are weak. To achieve the desired results, several adaptive beamformers have been applied to ultrasound imaging that lead to higher resolution and contrast by updating the aperture weights. The minimum variance (MV) is one of these adaptive beamformers which improves lateral resolution and edge definition [3–7]. The MV weights are calculated by minimizing the power of the beamformer output subject to the constraint that the beamformer must exhibit the given response in the steering angle.

As adaptive methods are dependent on data, they are not robust enough in some realistic conditions such as aberrating environments. If the MV beamformer becomes more robust in the presence of aberration, it would be an efficient way to improve imaging resolution.

Previously, sensitivity of MV beamforming to aberration was studied [8] and shown that with proper spatial smoothing and regularization, the MV provides better or similar performance

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* Corresponding author.
E-mail address: babakmasl@modares.ac.ir (B.M. Asl).

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compared to DAS for typical aberration levels. The MV beamformer slightly diminishes the effect of aberration on image quality, however to achieve more desired quality, there is another group of correction methods which estimates the phase errors and restores coherence of signals [9].

There are several aberration correction methods, including cross correlation [10–12], speckle brightness [13], backpropagation of wavefront [14], and use of time reversal focusing [15,16]. All of these techniques are implemented on a common basis that attempts to measure arrival time or phase difference on receive aperture. Phase correction methods are done by estimating and compensating time delays along the aperture in both transmitted and received signals. To this end, in this paper, the nearest neighbor cross correlation (NNCC) algorithm is used which is one of the most common phase screen based techniques to estimate the aberration profile.

This paper shows the effect of different degrees of aberration layers on image quality. The parameters which control the balancing of MV performance are set to the condition of best resolution. Then, a correction algorithm is used to eliminate unwanted effects of aberration which leads to recovery of the efficiency of the MV beamformer in the presence of aberration.

The rest of the paper is organized as follows. In Section 2 the methodology of the present work is described. Section 3 illustrates the results of applying different aberrators and correction of them. The discussion is presented in Section 4. Finally, this paper is concluded in Section 5.

2. Method

2.1. Phase aberration correction

In the phase screen model of aberration profile, the most common class of aberration correction techniques is the nearest neighbor cross correlation (NNCC) as described by Flax and O'Donnell [10,11]. In NNCC, phase of each element is aligned with signal of adjacent element as a reference signal, and therefore the relative aberration delay is associated with the phase of prior calculated elements. The cross correlation operation, described in (1), is calculated between any two adjacent sampled signals $x(n)$ and $y(n)$ over a window of length N

$$A(k) = \sum_{n=-N/2}^{N/2-1} x(n)y(n+k), \tag{1}$$

where N is the total number of interpolated signals. As recommended by O' Donnell and Flax [17], the correlation function was computed over a segment length of 12 mm with center at transmit focus. The time shift between each two elements is calculated via maximization of the cross correlation function, then the relative aberration delay τ_n for each element $n > 0$ is given by unwrapping the time shifts across the aperture and eliminating undesirable components:

$$\tau_n = \sum_{m=0}^{n-1}\Delta t_m - m\left[\frac{\sum_{m=0}^{M-2}\Delta t_m}{M-1}\right], \tag{2}$$

where $\tau_0 = 0$ and M denotes the total number of elements on the aperture. The correction procedure is performed on both transmit and receive in order to improve focusing delays [18].

The simulation is done in two steps. The goal of the first step is to estimate the aberration profile. In order to obtain the aberration profile, the NNCC algorithm would be applied on received signals. In the second step, the estimated profile acquired from the first simulation is applied to compensate the aberration on transmit with the expectation of convergence of all acoustic energy to the accurate focal point. It is noteworthy to mention that the second step of simulation is done without transmit aberration, resulting in improved transmit focus, so more accurate estimates of aberration profile can be reached on received signals.

2.2. The minimum variance beamformer

Assume a linear array of M elements for which $x_i[n]$ is the observation of each element. The output signal of beamforming for each sample is given by [5]

$$y(n) = \sum_{i=1}^{M} w_i^*(n)x_i(n-\Delta_i) = \mathbf{w}(n)^H\mathbf{x}(n), \tag{3}$$

where w_i is a complex weight, and $(\cdot)^H$ expresses conjugate transpose. The time delay Δ_i is applied to channel i for focusing at a determined point in the image.

In the MV beamforming, the signals are delayed and summed with a unique set of weights, one set for each receiving direction and depth. The optimum weight vector are calculated by minimizing the power of the beamformer output under the constraint that the signals propagated from the steering angle have unity gain:

$$\begin{aligned}&\min\ \mathbf{w}(n)^H\mathbf{R}(n)\mathbf{w}(n),\\ &\text{subject to } \mathbf{w}(n)^H\mathbf{a} = 1.\end{aligned} \tag{4}$$

In this beamforming, spatial smoothing is used to estimate the covariance matrix $\mathbf{R}(n)$ and then diagonal loading is applied to make the estimation more robust [5]. The $\mathbf{w}(n)$ weights for the steering vector $\mathbf{a}$ is given by

$$\mathbf{w}(n) = \frac{\mathbf{R}(n)^{-1}\mathbf{a}}{\mathbf{a}^H\mathbf{R}(n)^{-1}\mathbf{a}}, \tag{5}$$

since the data have been delayed, the steering vector $\mathbf{a}$ can be a unity vector.

As mentioned above, there are two parameters to control robustness of MV. Subarray length L is the first parameter. In the case of $L = 1$, the results are similar to those of DAS, with no apparent increase in the resolution. As subarray length increases the resolution will be enhanced at the expense of robustness. Note that to have invertible covariance matrix, $M/2$ Z is the upper limit on L. The second parameter is diagonal loading with a constant value γ, to ensure the covariance matrix is stable [19]. To this end, by adding a spatially white noise to the recorded wavefield, the sample covariance matrix $\mathbf{R}(n)$ is replaced by diagonally loaded matrix $\mathbf{R}(n) + \gamma\mathbf{I}$. The loading value is proportional to the power in the received signals which is given by

$$\gamma = \Delta \cdot \mathrm{tr}\{\mathbf{R}(n)\}, \tag{6}$$

where Δ is a predetermined value and $\mathrm{tr}\{\cdot\}$ is the trace operator. Δ is typically (much) less than $1/L$ [6]. A high amount of Δ ensures a robust solution, however, leading to a loss in resolution. Therefore, using $\Delta = 1/100L$ comes close to a well-conditioned covariance matrix.

2.3. Simulation setup

The random electronic phase screens with zero mean are simulated as effect of sound velocity inhomogeneities on the beam and shown in Fig. 1. As described by Dahl et al. at [20] these aberrating layers are generated by convolving Gaussian random numbers with a Gaussian function. The root-mean-square (rms) of amplitude in nano-second (ns) expresses strength of screens, the typical values as measured in natural cases are 21 ns in weak aberration and 49 ns for strong case. The weak and strong levels of arrival time fluctuation were produced by the chest wall, and abdominal