

High Frame Rate Adaptive Imaging Using Coherence Factor Weighting and the MVDR Method

Shun-Li Wang

Department of Electrical Engineering,
National Taiwan University,
Taipei, Taiwan

Pai-Chi Li

¹Department of Electrical Engineering, National Taiwan
University, Taipei, Taiwan
²Graduate Institute of Biomedical Electronics and
Bioinformatics, National Taiwan University, Taipei,
Taiwan

Abstract—Adaptive imaging has been extensively studied. Although some success has been demonstrated, these approaches generally are not suitable for high frame rate (HFR) imaging where broad transmit beams are required. In this study, we propose an effective adaptive imaging method suitable for HFR imaging based on coherence factor (CF) weighting and the minimum variance distortionless response (MVDR) method. The CF is a focusing quality index estimated from receive-channel data. It is the ratio between the energy of the coherent sum to the total incoherent energy. This method is an adaptive weighting technique in which the amplitude of each image pixel is weighted by the corresponding CF such that the unwanted side lobes are reduced. Direct implementation of the CF weighting in HFR imaging does not provide satisfactory results because broad transmit beams required for HFR imaging affect accuracy of CF calculations. In this study, we overcome this problem by applying the MVDR method to the delayed channel data. Specifically, the MVDR method is used for angle of arrival estimation. The beam sum data are then weighted by the estimated CF. A synthetic transmit aperture method is used for HFR imaging. Only 8 firings are required to form an image. Both simulations and clinical breast imaging data are used. In the experiments, clinical breast data are acquired using a programmable array system. With the proposed method, the average contrast enhancement is 4.59 dB and the average CNR enhancement is 20.19%. The results demonstrated that the proposed method can improve image quality. Even for HFR imaging with only 8 firings per image, effective contrast enhancement and better lesion boundary can be achieved. Efficacy of the proposed method is clearly demonstrated.

Keywords: *high frame rate imaging ultrasound adaptive imaging; coherent factor; MVDR*

I. INTRODUCTION

Medical imaging systems are used to estimate properties of tissues and to assess pathological conditions of the tissues. Ultrasound imaging is an extensively used imaging method in clinics due to its advantages of real-time capabilities, noninvasiveness, safety, and cost effectiveness. Estimating properties such as regional wall motion and thickening using ultrasound requires a relatively short time between image frames. To shorten the image acquisition time, a high frame

rate (HFR) imaging method is essential. Since an ultrasound image is formed using the receive echo signals after the excitation pulses are transmitted. The round trip propagation time is the physical limitation of imaging frame rate. To shorten the image acquisition time, reducing the number of firings is a must to increase frame rate. In practice, an effective way to increase frame rate is to transmit a broad beam and to form several receive beams simultaneously. A broad transmit beam can be formed using a plane wave excitation (i.e., an unfocused transmit beam), a defocused beam, or a limited diffraction beam. Since in this case the insonifying energy is more distributed than a focused beam, parallel receive beams can be formed within the insonified area. Therefore, the frame rate of the imaging system is increased. Although the frame rate can be increased using broad transmit beams, the disadvantages of the broad transmit beams are low signal-to-noise ratio (SNR) and poor image qualities due to lacking of transmit focusing. Therefore, the image quality for high frame rate system is degraded inevitably in the presense of focusing errors, much like the case for conventional two-way focusing.

Many adaptive imaging methods have been proposed to correct focusing errors adaptively [1]–[5]. These methods are also known as phase aberration correction and are developed to compensate for sound velocity inhomogeneities in the human body. The near field phase screen model treats the focusing errors as a phase screen at the surface of the transducer. These methods can compensate for delay errors resulted from sound velocity inhomogeneities which are estimated by finding the peak of the cross-correlation function of the signals from adjacent channels [1], [2]. The displaced phase screen model considers not only the delay errors but also the energy-level fluctuations and waveform distortion. The displaced phase-screen model accounts for focusing errors as a phase screen positioned at some distance away from the transducer surface and compensate for the aberrations by back propagating the receive signals to an optimal distance where the phase screen is located. On the other hand, effective side lobe-reduction methods are also used to reduce focusing imperfections by suppressing the elevated side lobes resulted from focusing errors to improve image qualities. One method

is coherence factor (CF) [3]. The CF is a focusing index indicating the focusing quality of the corresponding image point. An image point with a high CF represents signal from main lobe region (i.e., coherent) and possesses good focusing quality. On the other hand, an image point with a low CF represents signal from side lobe region (i.e., incoherent) and possesses poor focusing quality. The purpose of signal processing of the CF method is to weight the image point with the corresponding CF. This coherence-based method shows good contrast enhancement, but also results in artifacts in the speckle pattern. Success has been demonstrated in that the coherence-based methods is feasible for imaging systems with transmit focusing [3]–[5].

Despite of the previous success, the existing adaptive imaging methods are generally not suitable for the imaging system using broad transmit beams. The coherence of the signals among the receive channels is degraded using broad beam than that using focused transmit beams. Therefore, to correct focusing errors for HFR imaging, alternative methods should be developed. In this paper, an adaptive imaging method combining the CF and minimum variance distortionless response (MVDR) method [6] is used to correct for these errors. Feasibility of the proposed method is investigated using simulation data and clinical breast data.

II. MATERIAL AND METHODS

A. Coherence Factor (CF)

Adaptive imaging techniques for side lobe reduction have been extensively studied. These methods estimate energies contributed by the on-axis and off-axis components from the receive data. Then the estimated on-axis components are preserved and the off-axis components are suppressed in the resultant image. The CF method [3] is one of the side lobe reduction methods. The CF is defined as the ratio between the estimated coherent energy (i.e., the on-axis component) to the received total incoherent energy. In other words, the CF is expressed as:

$$CF(t) = \frac{\text{coherent energy}}{\text{total coherent energy}} = \frac{\left| \sum_{n=1}^N x_n(t) \right|^2}{\sum_{n=1}^N |x_n(t)|^2}, \quad (1)$$

where N denotes the total number of array channels, x_n is the signal received at channel n , and t denotes the time which is corresponding to the depth of the image point. The CF is estimated using the delayed channel data prior to beam summation. The estimated CF value represents the coherence of the beam sum data and, hence, can be used to estimate focusing quality. In other words, a high CF value stands for good focusing quality, and a low CF value stands for poor focusing quality. The processing of the CF technique is to weight each image point (i.e., beam sum data) with the corresponding CF.

B. MVDR method

Conventionally, beamformers use delay-and-sum (DAS)

to form receive beams. Its procedure is to weight the receive channel data (i.e., apodization). Subsequently, the receive beam data are obtained after summation is done across the channels. Apodization function which can be viewed as spatial filtering in beam forming can control the width of the main lobe and amplitude of the sidelobes. In other words, the weighing function is used for beam shaping.

An adaptive beamformation approach using adaptive weighting has been proposed by Capon [6]. The weighting for each channel is chosen to minimize the output power of the array, subject to the constraint that the array gain should be unity in the desired look direction. The Capon's method is also known as MVDR method. Optimization of the array weights can be formulated as:

$$\begin{aligned} \min_{\mathbf{w}(t)} & \mathbf{w}^H(t) \mathbf{R}_{xx}(t) \mathbf{w}(t), \\ \text{subject to} & \mathbf{w}^H(t) \mathbf{a} = 1, \end{aligned} \quad (2)$$

where the $\mathbf{w}$ denotes the weighting vector, $\mathbf{R}$ is constructed from the received data, and steering vector $\mathbf{a}$ is a vector of ones in case the focusing delays are previously applied. Then, the optimum weighting solution of (2) is given as:

$$\mathbf{w}_{MVDR}(\theta, t) = \frac{\mathbf{R}_{xx}^{-1}(t) \mathbf{a}(\theta)}{\mathbf{a}^H(\theta) \mathbf{R}_{xx}^{-1}(t) \mathbf{a}(\theta)}. \quad (3)$$

where the $\{\cdot\}^{-1}$ denotes matrix inverse operation and steering vector $\mathbf{a}(\theta)$ is a vector that applies steering phase shift to each array element. The array output power $P(\theta, t)$ according to a weighting vector can be expressed as:

$$P(\theta, t) = \mathbf{w}(\theta, t) \mathbf{R}_{xx}(t) \mathbf{w}(\theta, t). \quad (4)$$

Combining (3) and (4), the estimated array output power along the steered beam using the MVDR weighting can be expressed as:

$$P_{MVDR}(\theta, t) = \mathbf{w}_{MVDR}^H(\theta, t) \mathbf{R}_{xx}(t) \mathbf{w}_{MVDR}(\theta, t) = \frac{1}{\mathbf{a}^H(\theta) \mathbf{R}_{xx}^{-1}(t) \mathbf{a}(\theta)}. \quad (5)$$

Therefore, the estimated array output power of the MVDR method is obtained and can be used in high-resolution angle-of-arrival estimation. As a comparison, the estimated output power of the aforementioned steered beam method is expressed as:

$$P(\theta, t) = |y(\theta, t)|^2 = \mathbf{a}^H(\theta) \mathbf{R}_{xx}(t) \mathbf{a}(\theta). \quad (6)$$

C. Adaptive imaging using CF weighting and MVDR method

In high frame rate imaging, broad transmit beams are used on transmit to increase frame rate. On the other hand, aberration correction techniques rely on the coherence of the receive data and hence need a focused beam (i.e., narrow beam) on transmit. Coherence, or correlation, of the receive signals determines accuracy in the estimation of time delay errors and affects performance of other adaptive imaging methods. Therefore, aberration correction is more challenging in high frame rate imaging using broad transmit beams due to the degraded coherence and SNR. To develop a phase aberration correction technique for high frame rate imaging, the technique should be developed against the degraded coherence and SNR. As a consequence, a coherence-based with high spectral resolution method is explored in this study

to estimate the coherence for imaging using broad transmit beams. In our method, spectral estimation (5) is used to estimate the coherent energy of the receive data, and the CF estimation in (1) is modified as:

$$CF_{MVDR}(\theta, t) = \frac{P_{MVDR}(\theta, t)}{\sum_{n=1}^N |x_n(t)|^2} = \frac{1}{\mathbf{a}^H(\theta) \mathbf{R}_{xx}^{-1}(t) \mathbf{a}(\theta)} \frac{1}{\sum_{n=1}^N |x_n(t)|^2}. \quad (7)$$

Hence, coherence factor estimation with high spectral resolution and low side lobe level is possible.

III. EXPERIMENTAL RESULTS

Experiments were performed to test efficacy of the proposed method in clinical breast imaging. The clinical female breast data were collected in the Taipei Veterans General Hospital with the assistance from Dr. Y.-H. Chou and patients' consent. A programmable imaging system (DiPhAS, IBMT, Fraunhofer Institutes, Germany) was used to acquire the channel data. The experimental setups are shown in Fig. 1. The transducer was a 128-elements linear-array transducer with a center frequency of 5 MHz and a pitch of 0.3 mm (L6/128, Sound Technology, Inc., State College, PA). A high-resolution image is synthesized using the STA method from the 8 original images. In other words, 8 firings were used to reconstruct 1 resultant high frame rate image. Effects of the number of firings are shown in Fig. 2. The corresponding frame rate can achieve 2400 frame/sec according to the imaging depth. All images are displayed over a 50 dB dynamic range and are shown in a linear scan format with a step size of 0.15 mm

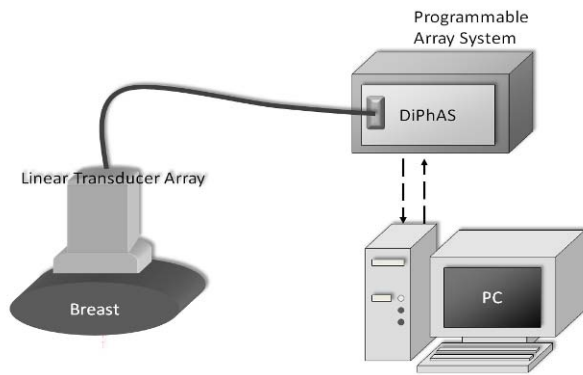


Fig. 1. Experimental setup

Fig. 3 shows images of a fibroadenoma (FA) lesion in a 42-year-old female patient. Fig. 3(a) shows the original image, and Fig. 3(b) shows the corrected images using the proposed weighting method. The CRs and CNRs were 15.25 dB and 2.42 for the original image, and 20.10 dB and 2.97 for the image with the proposed weighting method, respectively. The image quality improvement for CR and CNR were 4.84 dB and 22.56% with the proposed weighting method.

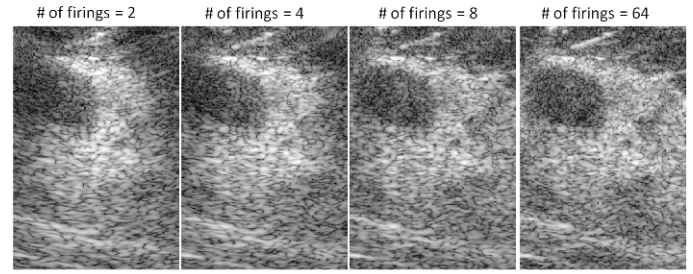


Fig. 2. Effects of the number of firings in the STA method.

Fig. 4 shows images of a carcinoma (CA) lesion in a 63-year-old female patient. Fig. 4(a) shows the original image, and Fig. 4(b) shows the corrected images using the proposed weighting method. The CRs and CNRs were 9.58 dB and 1.76 for the original image, and 12.41 dB and 2.07 for the image with the proposed weighting method. The image quality improvement for CR and CNR were 2.82 dB and 17.57% with the proposed weighting method, respectively.

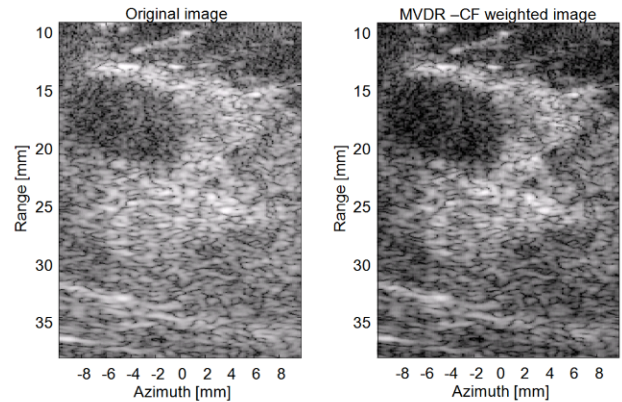


Fig. 3. Images of a fibroadenoma in a 42-year-old woman over a 50-dB dynamic range. (a) the original B-mode image, and (b) the image using the proposed weighting method.

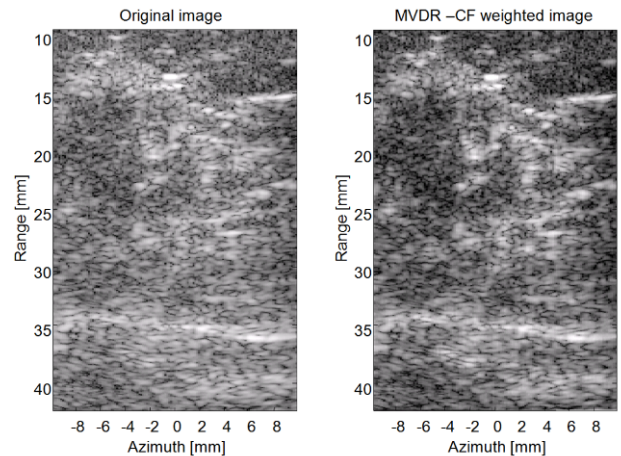


Fig. 4. Images of a carcinoma in a 63-year-old woman over a 50-dB dynamic range. (a) the original B-mode image, and (b) the image using the proposed weighting method.

Fig. 5 shows images of a cyst from a 66-year-old female patient. Fig. 5(a) shows the original image, and Fig. 5(b) shows the corrected images using the proposed weighting method. The CRs and CNRs were 21.22 dB and 3.41 for the original image, and 27.32 dB and 4.11 for the image with the proposed weighting method. The image quality improvement using the proposed weighting method were 6.10 dB and 20.43%, respectively.

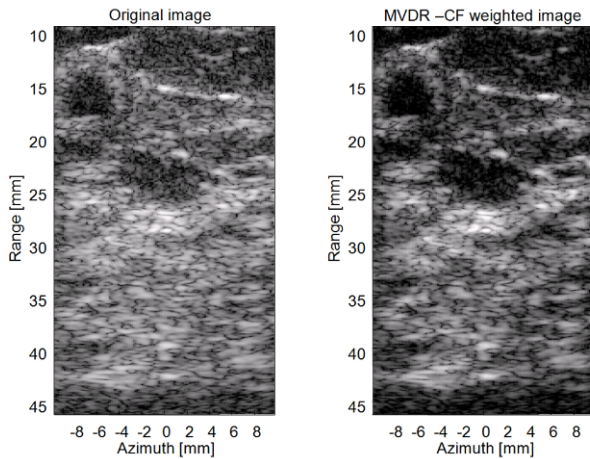


Fig. 5. Images of a cyst in a 66-year-old woman over a 50-dB dynamic range. (a) the original B-mode image, and (b) the image using the proposed weighting method.

IV. DISCUSSION AND CONCLUDING REMARKS

Recently, adaptive beamforming techniques such as MVDR method have been extensively studied and applied to ultrasound imaging. Due to the minimization of the interference power, the adaptive beamforming techniques can narrow the beam width of the main lobe and effectively suppress the side lobe level. Therefore, the adaptive beamforming methods possess the potential of high spatial and high contrast resolutions. Due to these advantages, the adaptive beamforming method is of great interests especially for high frame rate imaging. Fig. 6 shows a comparison between the conventional CF method and the CF_{MVDR} method with a simulated phantom data. The conventional CF method results in estimation errors for images using broad transmit beams. The results showed artificial black holes in the weighted image resulted from the conventional CF method.

In this study, we utilized the characteristics of the high spatial and contrast resolutions provided by the MVDR method to estimate the CF. The processing for the proposed method is to weight each image point with the corresponding CF. Unlike the adaptive beamforming method that weighting is done in the aperture domain as spatial filtering, the proposed method weights the estimated CF at each image point and also reduces the computational complexity compared to other adaptive beamforming method.

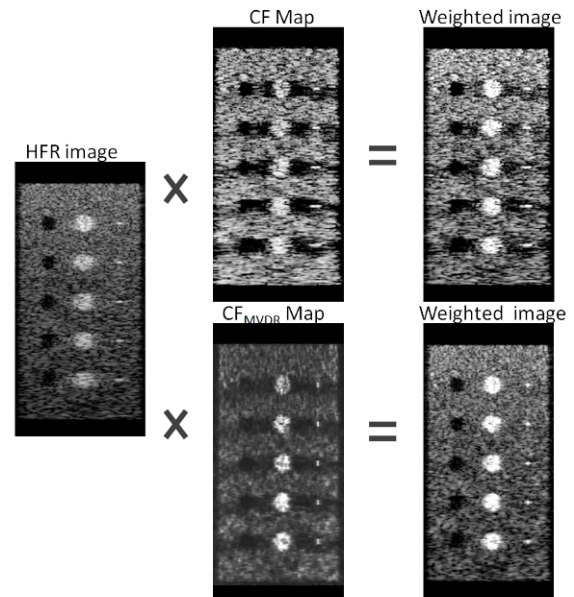


Fig. 6. Comparison of a HFR image weighted using the conventional CF method (top) and the CF_{MVDR} method (Bottom).

Finally, this paper proposes an adaptive weighting technique based on the CF and the MVDR method, to reduce focusing errors in ultrasound imaging, especially for the focusing errors resulted from sound velocity inhomogeneities. The proposed method was evaluated with both simulations and experimental data. The results demonstrate that the proposed method is effective, especially for HFR ultrasound imaging.

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