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Depth-of-field enhancement in Filtered-Delay Multiply and Sum beamformed images using Synthetic Aperture Focusing

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ABSTRACT

The Synthetic Aperture Focusing (SAF) technique makes it possible to achieve a higher and more uniform quality of ultrasound images throughout depth, as if both transmit and receive dynamic focusing were applied.

In this work we combine a particular implementation of SAF, called Synthetic Transmit Aperture (STA) technique, in which a single element in turn transmits and all the array elements receive the ultrasound wave, with the Filtered-Delay Multiply and Sum (F-DMAS) non-linear beamforming algorithm that we presented in a previous paper. We show that using F-DMAS, which is based on a measure of backscattered signal spatial correlation, B-mode images have a higher contrast resolution but suffer from a loss of brightness away from the transmit focus, when a classical scan with receive-only dynamic focusing is performed. On the other hand, when synthetic transmit focusing is achieved by implementing STA, such a loss is compensated for and a higher depth of field is obtained, as signal coherence improves. A drawback of SAF/STA however is the reduced signal-to-noise ratio, due to single-element transmission; in the paper we also analyze how this influences F-DMAS images. Finally, a preliminary investigation on the use of the classical monostatic SAF technique with F-DMAS beamforming is also carried out to evaluate its potential performances.

1. Introduction

In signal processing, beamforming can be considered as a form of spatial filtering [1] aimed at reinforcing the estimate of the signal received from the direction of interest, while rejecting as much as possible interferences coming from off-axis directions.

To accomplish this task, in ultrasound medical imaging systems, the receive beamformer unit is in charge of computing and applying a set of delays and weights to the echo signals received by the transducer elements in the probe, in order to focus and steer the beam towards the desired direction, while optimizing its shape.

The standard beamforming technique implemented by commercial ultrasound scanners is the simple Delay And Sum (DAS). However, the quality of ultrasound images remains still limited by the aperture size and operating frequency of the system, which are directly related to the achievable lateral/axial resolution, depth of field (DOF) and penetration depth. On the other hand, adaptive beamformers, such as the Capon/Minimum Variance (MV) beamformer [2,3], have been developed to obtain higher resolution and contrast by controlling the aperture apodization weights based on the spatial statistics of the received signals. Other ultrasound image formation techniques have also been recently developed to improve the lateral resolution and gain a higher contrast, as, for example, the Dual Apodization with Cross-Correlation (DAX) [4] or the Side Lobe Masking [5] techniques. Besides, non-linear beamformers were proposed in the past, mainly for direction of arrival estimation but also for beam formation [6,7].

In a previous work [8], we proposed and adapted a non-linear beamforming algorithm, called Delay Multiply and Sum (DMAS), for application to ultrasound B-mode image formation. That beamformer had been originally presented by Lim et al. in a paper on microwave image reconstruction for breast cancer detection [9]. By introducing several further processing steps in the beamformation chain, both working on the amplitude and frequency content of the echo signals, this improved DMAS algorithm, called Filtered-DMAS (F-DMAS), was shown to achieve higher contrast resolution than DAS, both in simulation and *in vivo* tests, and also when used jointly to other ultrasound imaging techniques [10–12]. The improved performance of the F-DMAS beamformer arises from the computation of the aperture spatial auto-correlation, on which this technique is based.

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Actually, a slight decrease of brightness can be observed in F-DMAS B-mode images at low (i.e. near to the probe surface) and high depths, as compared to DAS. A possible explanation of this phenomenon could be that the spatial correlation of backscattered signals is higher in correspondence of the transmit focal depth. In conventional B-mode imaging, in fact, a fixed focal depth is used during transmission and dynamic focusing (DF) is usually implemented only in reception, otherwise the frame rate would be drastically reduced. An acceptable trade-off between the required frame rate and an improved image quality could be achieved by acquiring images with different transmit focal depths and splicing them together [13]; anyway, even in this case the frame rate would be reduced.

In [14] we presented some preliminary results to validate the hypothesis that the intensity loss shown by F-DMAS images away from the transmit focus could be due to the decrease of echo signal coherence when DF is applied only in reception. As a matter of fact, backscattered signal coherence is expected to reach its maximum at the transmit focus based on the Van Cittert-Zernike (VCZ) theorem [15].

A similar problem affects also Short-Lag Spatial Coherence (SLSC) imaging [16], which is another recently proposed technique based on the spatial correlation of backscattered signals [17]. SLSC computation involves the coupling, multiplying and summing of the short-lag echo signals. However, differently from B-mode image formation techniques like DMAS, in this case such operations are used to generate images of the backscattered signal spatial coherence, and not images of echo magnitudes, whose influence is removed by normalizing the cross-correlation [17]. Therefore, being SLSC images a direct representation of backscattered signals coherence, in [16] they were shown to suffer from a reduced DOF away from the transmit focal depth, based on the VCZ theorem. The DOF was instead significantly improved by implementing Synthetic Aperture Focusing (SAF) [18].

In a classical SAF implementation, the aperture is synthetically built by activating one single element at each time to act as a transmitter and receiver. Instead, when a single element is used in turn to transmit the ultrasound pulse but reception is performed by all the array elements, this technique is referred to as Synthetic Transmit Aperture (STA) [19,20]. After the transmit-receive sequence has been repeated for all the elements in the array, beamforming can be performed by synthetically focusing the acquired signals a posteriori in each point of the image space, as if implementing both transmit and receive DF. Therefore, signals can be almost correctly realigned by compensating for the two-way propagation delays at all depths, yielding to an image with higher lateral resolution, improved DOF and more uniform quality, thanks to synthetic transmit focusing. However, a drawback of these techniques is that they generally suffer from a poor SNR and low penetration capability due to single-element transmission, and also from tissue motion artifacts, due to the higher number of transmit events required to generate an image [18].

In this paper we hypothesize that there are mainly two factors that cause the decorrelation effect which affects F-DMAS image intensity in standard B-mode scans with receive-only DF, i.e.: (i) the broadening of the transmit beam away from the transmit focus, and (ii) noise (including both electronic noise and other interferences related to the physics of the ultrasound beam). Thus, we aim to understand how F-DMAS images are influenced by different focusing strategies. This would also provide further insights on the impact of backscattered signal coherence on F-DMAS beamforming, widening the study presented in our previous work [8]. We thus implemented F-DMAS with or without STA and synthetic transmit focusing, in order to analyze decorrelation effects in F-DMAS beamformed images.

Finally, we also investigate if F-DMAS beamforming can be used in a simpler monostatic SAF-based system, making it possible to achieve adequate imaging performance. This technique, in fact, is generally worse than STA in terms of contrast resolution, but could be more appealing for a possible hardware implementation, as it involves only one single transducer element (and thus a simpler electronics with one single channel) both to transmit and receive the ultrasound wave.

In the following pages, the F-DMAS algorithm as well as the SAF and STA techniques are first described (Section 2). Henceforth, we will use the acronym SAF to refer to the classical monostatic implementation of this technique. We then compare F-DMAS and DAS performance by reconstructing images, either with fixed transmit focus and receive-only DF, so as to emulate a classical B-mode scan, or with STA and synthetic transmit focusing (i.e. emulating both transmit and receive dynamic focusing), and we evaluate the results achieved in simulations, phantom experiments and *in vivo* (Section 3). The performance of classical SAF together with F-DMAS is analyzed in phantom experiments too. Finally, in Section 4 we discuss the results and provide some conclusive remarks.

2. Materials and methods

2.1. SAF and STA techniques

The classical monostatic implementation of SAF consists in activating each time a single element of the array to transmit an unfocused spherical wave and to receive the echo signal. If we consider N transducers and we denote the active element with index i ($i = 1\ldots N$), then a set of raw radiofrequency (RF) signals $\boldsymbol{V}$ is collected after all elements have been used one by one to transmit and receive:

$$\boldsymbol{V}(t) = [\, v_1(t) \quad v_2(t) \quad \ldots \quad v_N(t)\,]. \tag{1}$$

Each column v_i of matrix $\boldsymbol{V}$ represents the RF signal received by element i after it has transmitted.

In order to realign the received signals v_i, the focusing delays τ_{ii} are computed by considering the two-way distance from element i to the focal point and vice-versa. For example, focusing delay τ_{ii} is computed as follows (Fig. 1a):

$$\tau_{ii} = \tau_{i,TX} + \tau_{i,RX} = \frac{2}{c}\sqrt{(x_F - x_i)^2 + z_F^2}, \tag{2}$$

where $\tau_{i,TX}$ and $\tau_{i,RX}$ are the transmit and receive delay of element i, respectively, the coordinates of the active element are (x_i, $z_i = 0$), and the focus is placed at (x_F, z_F); c is the sound speed in the medium. In this way, a new set $\boldsymbol{S}$ of focused signals is obtained:

$$\boldsymbol{S}(t) = [\, s_1(t) \quad s_2(t) \quad \ldots \quad s_N(t)\,] \tag{3}$$

where $s_i(t) = v_i(t - \tau_{ii})$.

In order to implement STA, instead, we use the following procedure. Each single transducer element in the active aperture is used in turn to transmit an un-focused spherical wave, and the backscattered echo signals are received by all elements; this process is repeated for each transducer in the aperture. If index i refers to the transmitting element and $j = 1\ldots N$ to the receiving elements, then a set of RF signals $\boldsymbol{V}_i$ is collected by the N receivers for each i-th transmission:

$$\boldsymbol{V}_i(t) = [\, v_{i1}(t) \quad v_{i2}(t) \quad \ldots \quad v_{iN}(t)\,], \tag{4}$$

where each column v_{ij} of the matrix represents the RF signal received by element j when element i transmits. In order to realign these signals, delays τ_{ij} are computed by considering the two-way distance from the transmitting element i to the focal point, and back to each receiving element j (Fig. 1b), as follows: