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Ultrasound Complementary Subset Transmit for Coherence-Based Multi-Angle Plane-Wave Power Doppler Detection

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1. Introduction

Delay-and-Sum (DAS) beamforming is routinely adopted to produce image output in medical ultrasound imaging but suffers from intrinsic limitations such as insufficient image resolution and noticeable off-axis clutter especially for plane-wave (PW) imaging. The image quality of PW imaging can be improved by coherent plane wave compounding (CPWC) in which low-resolution images are firstly acquired from several PW transmit angles and then coherently combined to achieve the final high-resolution CPWC image. CPWC imaging has been utilized to detect the motion of imaged objects in transient elastography [1-2] and Doppler flow imaging [3-4]. However, it should be noted that the image quality in CPWC imaging relies on the number of low-resolution images involved in the compounding and thus an inevitable trade-off between the image quality and the frame rate exists since CPWC imaging still relies on conventional DAS beamforming in both dimensions of the PW transmit angle and the receiving channel.

Recently, signal coherence of the two-dimensional CPWC data has been proposed to reject low-coherence clutters and thermal noises for improving the PW image quality. One particular example is Delay-Multiply-and-Sum (DMAS) beamforming [5] which extract the signal coherence by multiplying any pair of received echoes. Specifically, when a rational p value is used to represent the degree of signal coherence, DMAS beamforming involves the magnitude scaling of time-delayed channel signal by p-th root and the subsequent p-th power after channel sum. In this study, a novel coherence-based DMAS power Doppler detection together with complementary subset transmit (CST) is proposed for multi-angle PW imaging. The proposed method firstly adopts DMAS beamforming in the dimension of PW transmit angle to suppress the background noise and clutter. Then, the CST technique is used to further reduce the noise level in power Doppler detection by correlation of two complementary DMAS signals. It is compatible with current CPWC imaging and does not require huge memory allocation to retain the entire channel data.

2. Methods

DMAS beamforming in this study is implemented using baseband data to eliminate the need for oversampling of radio-frequency waveform [6]. Specifically, when the baseband data for low-resolution image pixel from the m-th PW transmit angle is represented as $x_m = a_m e^{j\phi_m}$, DMAS beamforming in the dimension of PW transmit angle is performed by

$$\mathrm{y}_{\mathrm{DMAS}} = \left(\sum_{m=1}^{M} \hat{x}_m \right)^p = \left(\mathbf{w}^H \hat{\mathbf{x}} \right)^p$$

where

$$\hat{x}_m = \sqrt[p]{a_m} e^{j\phi_m}$$

$$\mathbf{w} = [1 \quad 1 \quad 1 \quad \ldots \quad 1]^T = \mathbf{1}$$

$$\hat{\mathbf{x}} = [\hat{x}_1 \quad \hat{x}_2 \quad \hat{x}_3 \quad \ldots \quad \hat{x}_M]^T$$

Here, the real-valued weighting vector **w** is actually a unity vector **1** to equally emphasize the contribution from all the available PW transmit angles.

DMAS beamforming with CST technique (DMAS-CST) depends on DMAS signals from two subsets of PW transmit angles. The idea of complementary subset is similar to that in [7-8] but is defined in the dimension of PW transmit angle instead of receiving channel. The two DMAS signals are then correlated to reduce the noise level and a square root of the correlation is performed to restore the dimensionality of DMAS signal. In other words, the DMAS-CST beamformingcan be formulated as

$$\mathrm{y}_{\mathrm{DMAS\text{-}CST}} = \sqrt{\mathrm{y}_{\mathrm{DMAS1}} \, \mathrm{y}^{*}_{\mathrm{DMAS2}}} = \left(\mathbf{w}_1^H \ \mathbf{R} \ \mathbf{w}_2 \right)^{\frac{p}{2}}$$

where the weighting vector $\mathbf{w_1}$ for subset 1 is related to the weighting vector $\mathbf{w_2}$ for subset 2 by $\mathbf{w_1 = 1 - w_2}$ to ensure the complementary property. In other words, any PW transmit angle should belong to either one of the two complementary subsets. It should be noted that the DMAS beamforming in this study is calculated from low-resolution images after SVD clutter filtering [9] in order to remove both stationary tissue and noises for power Doppler estimation.

3. Results

Power Doppler images of the simulated flow phantom in DMAS beamforming and DMAS-CST beamforming are respectively provided in the left and right panels of Fig. 1. Seven PW transmit angles are used for coherent compounding (i.e., [−7.5° −5° −2.5° 0° +2.5° +5° +7.5°]). The flow velocity in the simulation is 15 mm/s and the ensemble number for averaging is 15. The Doppler SNR increases from 17.1 dB in DAS to 21.8 dB, 25.3dB and 28.4dB in DMAS, respectively with the p value of 1.5, 2.0 and 2.5. Take the p value of 2.0 in DMAS beamforming as an example, the improvement in Doppler SNR is 8.2 dB compared to the DAS counterpart. On the other hand, it is also apparent in Fig. 1 that the background noise can be further suppressed to a lower level in DMAS-CST beamforming where DMAS beamforming is performed together with the CST technique. The corresponding Doppler SNR improves by another 6.4 dB, 6.0 dB and 4.5 dB, respectively for the p value of 1.5, 2.0 and 2.5. Note that DAS beamforming with CST technique can also improve the Doppler SNR but only by 3.4 dB.

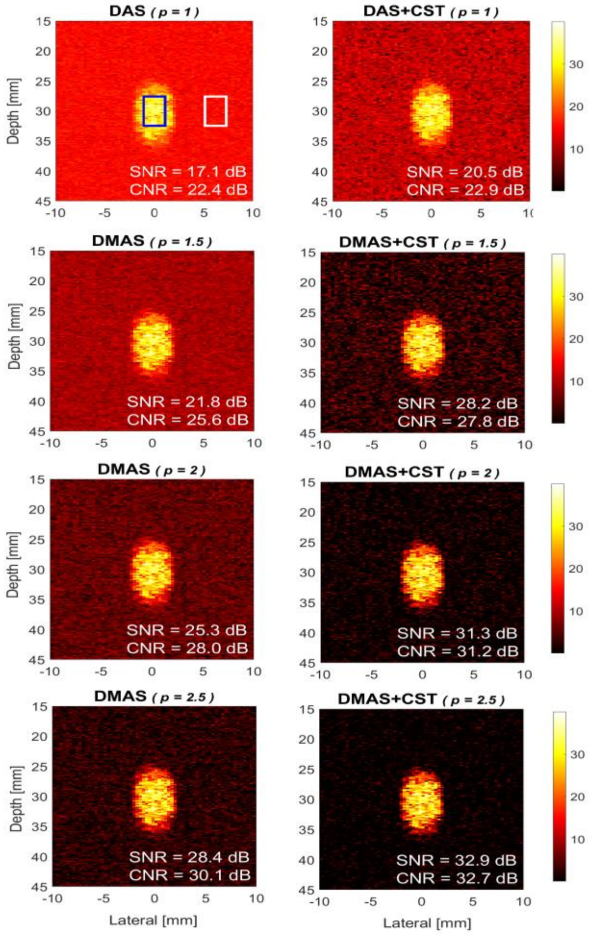

Fig. 1 Simulated power Doppler images of flow phantom for DAS beamforming, DMAS beamforming with and without CST technique.

4. Conclusions

In this study, DMAS beamforming of low-resolution images from distinct PW transmit angles is used to construct a novel coherence-based power Doppler detection in multi-angle PW imaging. Moreover, the CST technique is also developed to further reduce the noise level in power Doppler detection by correlation of two DMAS signals from complementary subset transmit. One major limitation of DMAS-based power Doppler imaging may be its computational efficiency. Since the proposed DMAS beamforming involves multiplicative operation of the low-resolution images from distinct PW transmit angles, the low-resolution images have to be firstly grouped according to its PW transmit angle and then each group is individually band-pass filtered in the direction of ensemble using SVD to remove the stationary tissue before DMAS beamforming. Consequently, the band-pass filtering has to be repetitively performed by M times where M is the total number of PW transmit angle for DMAS beamforming. For DAS beamforming (i.e., CPWC imaging), on the other hand, its linear operation allows the band-pass clutter filter to be implemented in the final high-resolution images to ease the computational burden.

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