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# Combined Sign Coherent Factor and Delay Multiply and Sum Beamformer for Plane Wave Imaging[1]

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**Abstract**—Plane wave imaging is a relatively new technique in ultrasound imaging. However, in traditional methods, the coherent information of different emissions and different elements are not considered. In fact, the sign coherent factor (SCF) can improve the lateral resolution of the imaging greatly. In addition, the delay multiply and sum (DMAS) beamformer is mainly based on the spatial correlation of background scattering signals, it has higher contrast and resolution, but suffers from energy loss at great depths. In this paper, combining the advantages of SCF and DMAS, the sign coherent factor delay multiply and sum (SCF-DMAS) beamformer for plane wave imaging is proposed. Unlike the traditional plane wave imaging, the proposed SCF-DMAS beamformer is based on the 2-D echo data set, which improves the imaging speed greatly. Finally, we simulated the point targets and the cyst phantom to evaluate the performance of proposed method. Compared with the traditional plane wave imaging, the lateral resolution of SCF-DMAS beamformer improves greatly for the point targets, and for the cyst phantom the contrast ratio (CR) and contrast-to-noise ratio (CNR) increased by 96.97 and by 79.98% respectively without reducing the frame rate.

*Keywords:* plane wave, delay multiply and sum, sign coherent factor, ultrasound medicine imaging

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## 1. INTRODUCTION

The plane wave coherent compounding imaging is a relatively new imaging technique with a high frame rate, dating from the 1980s [1]. Differently from the traditional line scan mode, the plane wave imaging needs to excite all the array elements at every pulse cycle, and the frame rate is improved greatly. However, the plane wave imaging has poor performance because of the absence of focusing in the process of pulse emission. In order to resolve this problem, Lu proposed the concept of spatial compounding which uses different excited plane waves or finite diffraction beams [2, 3]. Most related approaches focus on reducing speckle by incoherent summation of different frame images [4–6].

Recently, the coherent plane wave compounding imaging method was proposed by Montaldo et al. [7] to achieve a good balance between the imaging quality and the frame rate. This method combines the backscattered echo signals received by different excitation elements to obtain the final output and develops significantly other ultrasound imaging modes [8–11]. Austeng et al. [12] proposed a general coherent compounding plane wave imaging method. In this method, the final outputs are obtained by the compounding sum of plane wave from different directions by minimum variance (MV) beamformer. By doing this, the method could improve the image resolution and contrast. Unfortunately, this method suffers from a frame rate reduction due to high computational complexity of the MV beamformer. Based on the 2-D echo data set, a plane-wave compounding imaging with minimum variance of transmit–receive beamforming was proposed by Zhao et al. [13]. In this work, both the transmitting aperture weights and the receiving aperture weights are calculated by using the MV beamformer, and then combined them into a 2-D adaptive weighted function for compounding imaging. This method can achieve better performance with high cost of computational complexity, which is difficult to implement in real-time imaging. Alfonso et al. [14] revealed the relationship of apodization between focused imaging and coherent plane wave compounding imaging. This connection provides a research direction for the balance between the image quality and the frame rate. The method combining the coherent plane-wave compounding technique (CPWC) with Thomson's multi-taper was proposed by Toulemonde et al. [15]. This technique preserves the advantage of coherent and incoherent approaches. Zhao et al. [16] combined the eigen-space MV beam-

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former with a post filter based on sub-array coherence to improve the performance of imaging. Unfortunately, the complexity increases the difficulty of hardware implementation.

In a previous work, Matrone et al. [17] proposed the Delay Multiply and Sum (DMAS) non-linear beamformer algorithm to reconstruct ultrasound B-mode images. This beamformer algorithm shows significant improvements in terms of contrast and resolution compared with DAS beamformer. Park et al. [18] applied the DMAS algorithm to the synthetic aperture of photo-acoustic microscopy. Sign coherent factor (SCF) [19], as a nonlinear function of the beamformer for grating and the suppression of side lobes in ultrasound images, was used to weight the coherent sum output. In addition, the computation of the SCF is extremely simple and easily performed in real-time. However, there is a limit of higher suppression of side lobes and lower main lobe width just by using the SCF only.

Combined with the advantages of DMAS beamformer and SCF method, this paper presents the SCF-DMAS beamformer for plane wave imaging. There are two main advantages of SCF-DMAS method. One advantage is that DMAS has less computational complexity than MV beamformer, and improves the frame rate without reducing the image quality. Another one is that the SCF compensates the energy loss of the DMAS beamformer, which can improve the lateral resolution of plane wave imaging significantly.

The rest of the paper is organized as follows. Section 2 introduces the theoretical background. Section 3 explains the implementation of proposed SCF-DMAS method in details. Section 4 shows the simulation results of the point target and cyst phantom. Section 5 discusses the advantage of SCF-DMAS method. Section 6 draws the Conclusions and the prospects for the application.

## 2. BACKGROUND

The proposed method is based on the plane wave imaging, DMAS beamformer and SCF, so it would be necessary to explain the background of the medical ultrasound imaging.

### *A. Plane wave imaging*

In plane wave imaging, the entire imaging region is scanned by using a plane wave with a single pulse. The backscattered echo signals are added to obtain an RF image with low resolution. The specific process can be described as follows:

Suppose the plane wave is emitted by the $N$-element array with a linear array probe, and the echo signal $X(t)$ that we get at time $t$ can be expressed as

$$X(t) = [x_1(t), x_2(t), \dots, x_N(t)]^T,$$

where $x_i(t)$, $i = 1, 2, \dots, N$, represents the echo data after the time delay calculation received by the $i$-th array element, $N$ is the number of the array elements and $(\cdot)^T$ denotes the matrix transpose. The output of traditional plane wave imaging is obtained by simply averaging of all echo data:

$$y(t) = \frac{1}{N}\sum_{i=1}^{N} x_i(t), \tag{1}$$

where $y(t)$ denotes the final output of beamformer at time $t$.

Suppose the linear array with $N$ elements emits $M$ different steering angles of plane waves, the echo data are stored at every emission, then we can get a 2-D echo data matrix at time $t$ as follows [7]:

$$X(t) = \begin{bmatrix} x_{1,1}(t) & x_{1,2}(t) & \dots & x_{1,M}(t) \\ x_{2,1}(t) & x_{2,1}(t) & \dots & x_{2,M}(t) \\ \vdots & \vdots & \ddots & \vdots \\ x_{N,1}(t) & x_{N,2}(t) & \dots & x_{N,M}(t) \end{bmatrix}, \tag{2}$$

where $x_{i,j}(t)$, $i = 1, 2, \dots, N$, $j = 1, 2, \dots, M$, represents the echo data after the time delay calculation received by the $i$-th array element for the $j$-th emit at time $t$. The final output obtained by averaging the echo signals with different emission angles can be expressed as [7]

$$y(t) = \frac{1}{N}\sum_{j=1}^{M}\sum_{i=1}^{N} x_{i,j}(t). \tag{3}$$

### *B. DMAS beamformer*

The beamformer output $y(t)$ at time $t$ about the DMAS algorithm [14] can be described as

$$y^*(t) = \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \operatorname{sgn}\left(x_i(t)\,x_j(t)\right)\sqrt{\left|x_i(t)\,x_j(t)\right|}, \tag{4}$$

where $N$ is the size of array elements, $x_i(t)$ is the sampled delay signal obtained from the $i$-th array element, $\operatorname{sgn}(\cdot)$ is the sign function, $|\cdot|$ denotes the absolute value operation and $\sqrt{\cdot}$ represents the square root operation. $y^*(t)$ is the DMAS beamformer output, and then $y^*(t)$ is band-pass filtered to obtain the final output $y(t)$.

### *C. Sign coherent factor*

SCF is the extreme case of the phase coherent coefficient [19]. The main idea of SCF is to reconstruct the signal by using the positive and negative