044 PLURAL SPECTRAL FREQUENCY DIVISIONS FOR HIGH FRAME RATE ULTRASONIC TISSUE DISPLACEMENT VECTOR MEASUREMENT.

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Abstract

For achieving a real-time human tissue displacement vector and/or strain tensor measurement with a high frame rate, the plural spectral frequency division method (PSFDM) is presented. The effectiveness of processing is demonstrated by performing the measurements on an agar phantom interrogated by wideband ultrasonic (US) single beam scanning and compounding of steered plane wave or spherical wave transmissions.

Introduction

A high frame rate is required to achieve measurements of a high speed tissue motion or a shear wave propagation, which can be performed using a plane [1,2] or spherical [2] wave transmission, for instance. For a displacement vector measurement, a lateral modulation can be used together with the multidimensional autocorrelation method (MAM) [1]. Alternatively, the spectral frequency division method (SFDM) can also be performed with MAM (e.g., [3,4]). For increasing a lateral spatial resolution, the coherent compounding can be performed on steered plane or spherical wave transmissions, which can also achieve a high frame rate [2,4]. In this report, for achieving a high accuracy tissue displacement vector and/or strain tensor measurement with such a high frame rate, the plural spectral frequency division method (PSFDM) is presented.

Methods

The original spectral frequency division method (SFDM) is effective on large bandwidth spectra [4,5]. In this report, a laterally wideband single beam scanning is generated by performed a rectangular apodization on a single beam scanning [5] and a compounding of plural plane wave transmissions (Gaussian apodization) [4], of which reception beamforming can be performed once [2]. The plural steered beams or waves can also be transmitted simultaneously.

Specifically, (i) a vertical (axial) or beam direction and (ii) a horizontal (lateral) direction or a direction orthogonal to the vertical (axial) or beam (axial) direction; and (iii) disregarding low frequency spectra (High Pass Filtering) in the horizontal (lateral) direction or the direction orthogonal to the vertical (axial) or beam (axial) direction. The degree of the effects depends on the respective spectra. (iv) Moreover, the disregarding low frequency spectra in the vertical (axial) or beam direction can also be effective similarly and particularly effective in decreasing calculations of the Fourier's transform. The SFDMs of (i) to (iv) can be performed on such beamformings in two fashions, specifically AND or OR operations. We refer to such methods using plural (or multiple) spectral frequency divisions as the plural spectral frequency division method (PSFDM). Thus, with respect to a single beam scanning, original SFDM is (i), which is performed once for a single spectra to yield two quasi steered beams or waves (i.e., two simultaneous Doppler multidimensional equations), whereas PSFDM yields more quasi-steered beams or waves than the unknown displacement vector components (i.e., over-determined system). Here, the horizontal and vertical divisions are referred to as H and V, respectively. MOM means the use of non-divided spectra. AVE and no description of AVE respectively mean the averaging processing and least squares solution for solving the over-determined system.

Results

For instance, on the lateral strain measurement on an agar phantom compressed in a lateral direction (a nominal frequency, 7.5MHz [5]; and however, with larger steering angles, 0 to ±40 degrees, i.e., lateral frequencies, 0 to 7.5MHz), SDs (standard deviations) were obtained, i.e., original SFDM, 6.39; PSFDM, 6.18 (AVE V with low cutoff frequencies, 0, 0.23 and 0.47MHz for the single beam scanning) and 3.02 and 2.92 (V with 0 to 1.8MHz with 0.3MHz intervals + H and V with 0 to 2.1MHz with 0.3MHz intervals × H + MOM for plane wave transmissions, respectively) × 10^{-3}. In almost cases, the effects of PSFDM were obtained for the axial strain measurement simultaneously. Decreasing bandwidths of respective spectra also has an effective for stabilizing lateral and axial measurements. However, too many divisions on (i) and (ii) decreased the measurement accuracy in a contrary due to decreasing an independency of generated quasi-beams or waves. See Figures 1 and 2, which respectively show the representative results (measured lateral (y) and axial (x) strains) obtained for the single beam scanning and compounding plane wave transmissions. You can also confirm the results in the recently published paper [6], for instance. In this report, we introduce how to determine the cutoff frequency. By evaluating the statistics of measured lateral or axial strains (or displacements) with changing the lateral or axial cutoff frequency, we can achieve to find the best cutoff frequency of all. See Figure 3, for instance, when using a lateral cutoff frequency. For the compounding, a large steering angle interval (i.e., fewer plane waves) properly covering the large bandwidth with a high SNR [6] yields the most accurate results (see the 10 and 1 degree results). With changing both low and high cutoff frequencies, the best bandpass filter can also be determined (omitted here).

Other compoundings of plane wave transmissions, for instance, ±10 to ±40, ±20 to ±40, ±30 to ±40, can also be processed similarly. Moreover, bandpass Filtering can also be performed similarly. These can also be used for generating over-determined systems and will be published elsewhere.

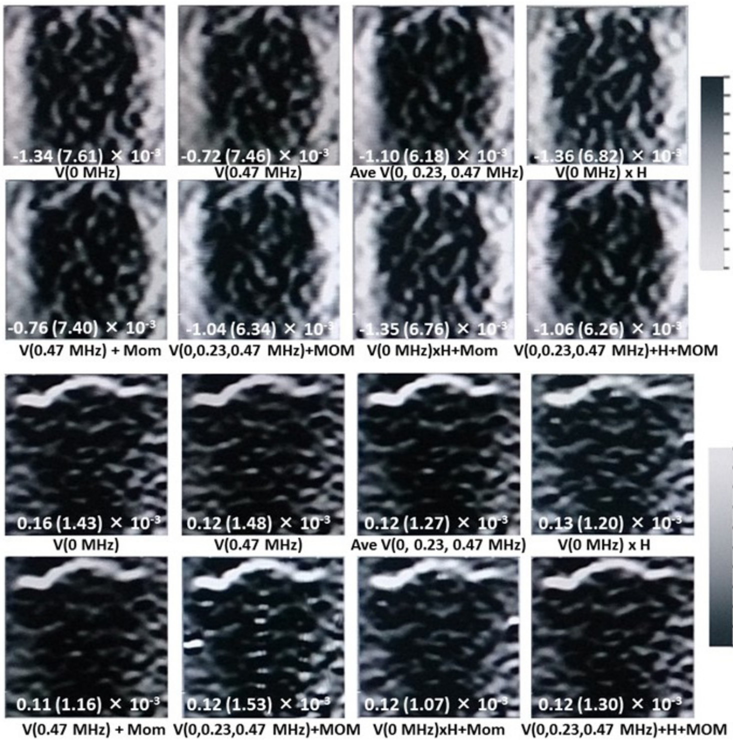

Figure 1. On single beam scanning, measured (a) lateral and (b) axial strains [6]. Means and SDs (in parentheses) are also shown.

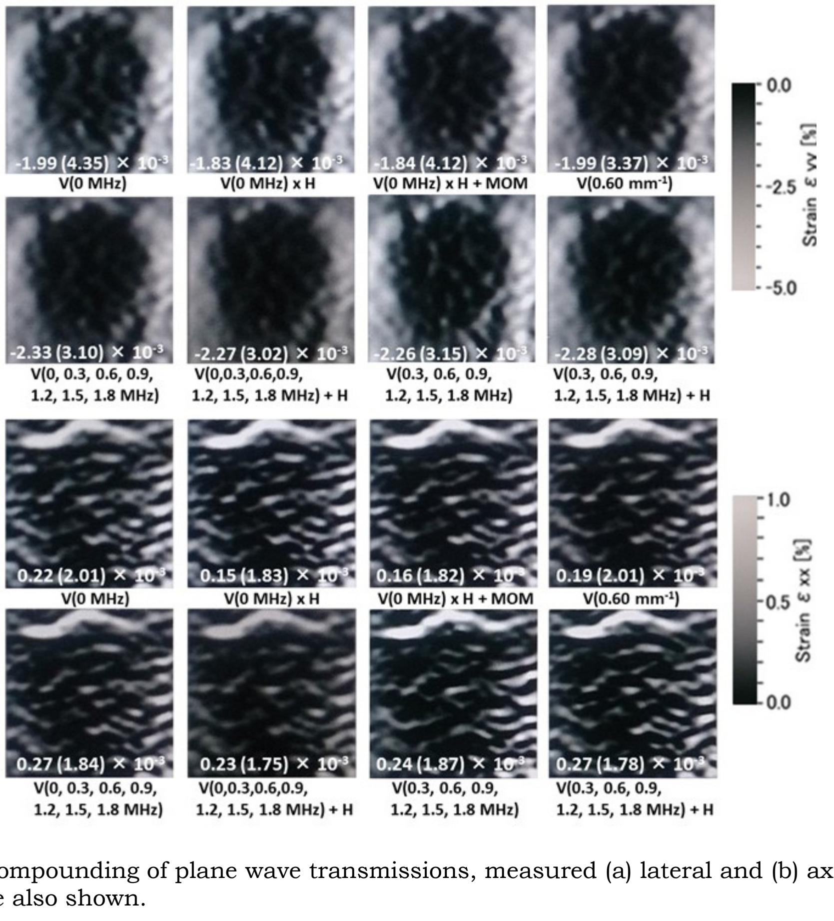

Figure 2. On coherent compounding of plane wave transmissions, measured (a) lateral and (b) axial strains [6]. Means and SDs (in parentheses) are also shown.

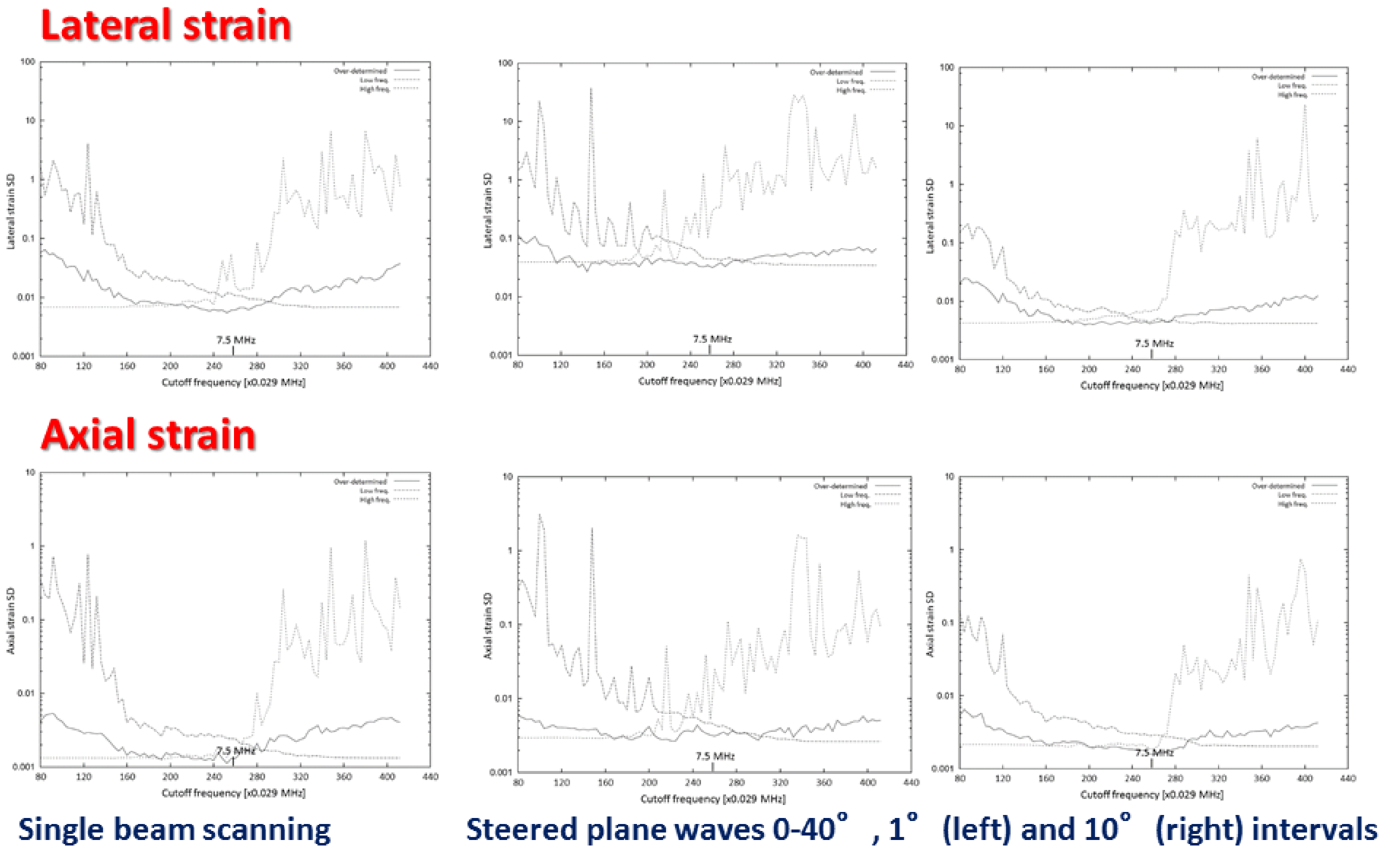

Figure 3. Changing a lateral cutoff frequency vs SDs of lateral and axial strain measurements using only low or high frequency spectra and both spectra (over-determined system).

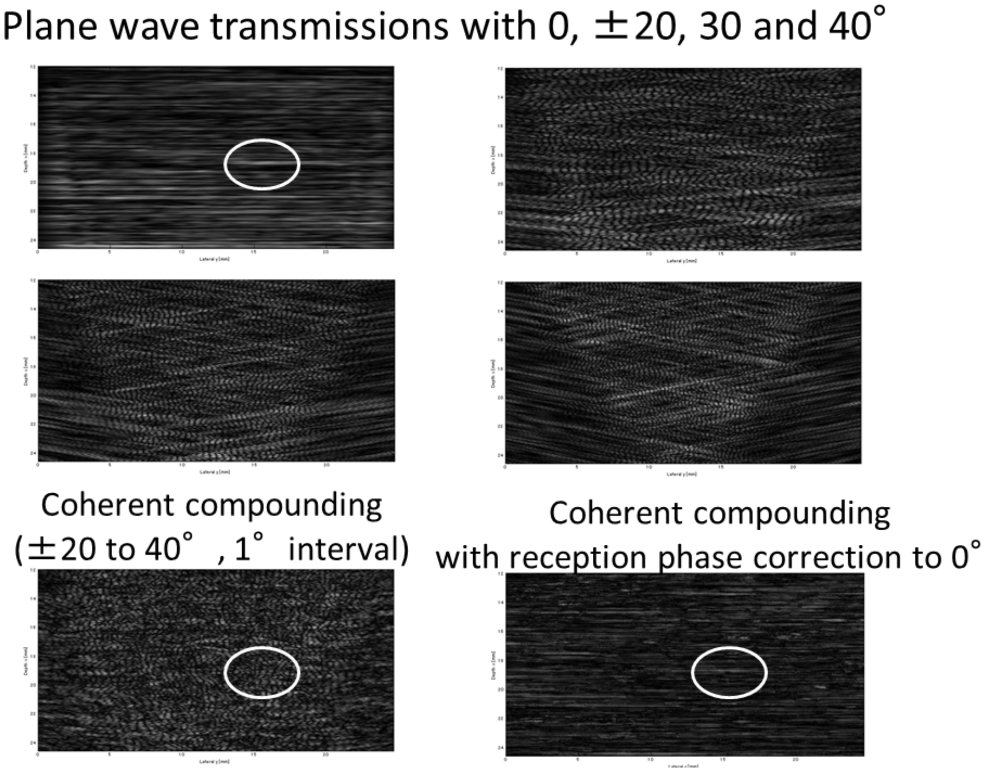

Figure 4. Reception phase aberration correction performed with respect to a non-steered plane wave transmission for compounding of steered plane wave transmissions (±20 to 40 degrees). For comparison to the compounding with the phase aberration corrections, that of no corrections (i.e., lateral modulation) is also shown. A strong scattering position is circled.

As we reported previously, compounding with a large steering angle yields a blurred echo image (also see [6]). An inhomogeneity of an ultrasound propagation speed as well as a directivity of the ultrasound propagation determined by the physical array aperture yields a degradation regarding a spatial resolution and a contrast. Recently, we performs a phase aberration correction on the basis of a cross-correlation or a cross-spectral phase gradient [7]. This will increase the accuracy of echo imaging, displacement measurement, superresolution etc. Figure 4 shows, for instance, the echo image obtained by implementing the reception phase aberration correction onto the steered plane wave transmissions (±20 to 40 degrees) with respect to a non-steered plane wave transmission (0 degree). For comparison, compounding of no phase aberration corrections is also shown (a widebanded, but blurred lateral modulation image). A strong scattering position is circled in the images. Actually, the effect was obtained for the target when dealing with plural reception signals as lateral modulation signals, i.e., by implementing the phase aberration correction onto the respective echo signals corresponding to left and right single quadrant spectra or laterally frequency divided spectra. Previous accurate and stable measurements using large steering angles [8] are spatially averaged data, which are still useful. The serious problem about the phase aberration correction is to require a computation time. However, if the case requires a precise measurement with a high spatial resolution, the phase aberration correction will be significantly useful. The target of this kind of phase aberration correction can also be physically performed, proper lateral modulation, steerings, or beamformings with transmission spherical focusings, for instance. The results will be reported elsewhere.

Conclusions

Using PSFDM, the single beam scanning allows the useful and high accuracy measurement/imaging of a displacement vector and/or a strain tensor by simple beamforming with a conventional effective aperture width and no apodization rather than the original SFDM, whereas the compounding of steered plane waves or spherical waves achieves a high frame rate and such much higher measurement accuracy, which will enable us to perform high accuracy observations of heart (sector or spherical wave scanning) and liver motions or various blood flows etc. In this report, a 2D displacement vector measurement case is explained and SFDM and PSFDM are significantly effective in a 3D displacement vector measurement case using a finite aperture size and channels of a 2D array transducer. The spectral divisions in the 3D case can be similarly performed and the divisions are explained in ref. 5, for instance.

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