015 NEW PHASE MATCHING METHOD THAT DIRECTLY WORKS ON PHASE.

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Abstract: To allow performing optimizations such as a regularized [1] or MAP (maximum *a posteriori*) estimation for ultrasonic human tissue Doppler equations directly expressed for a target displacement, the author's previously developed rf-echo phase matching method is modified. Instead of coarse and residual displacement estimates successively obtained with the multidimensional cross-correlation, and autocorrelation or cross-spectral phase gradient method etc., respectively, an addition is equivalently performed for the phase differences corresponding to the coarse and residual estimates. The method feasibility is verified through experiments for a displacement vector measurement (Vectoral Doppler) and a lateral Doppler on an agar phantom having a high shear modulus inclusion compressed laterally.

Background: For elasticity measurements, the phase matching method [2,3] using the multidimensional cross-correlation method (MCCM) is indispensable. The aim of phase-matching is to significantly increase the coherence as well as the correlation between a pair of rf-echo signals including speckle as well as specular echo signals, which considerably increases the detection accuracy of corresponding local rf-echo signals. The method proceeded the ultrasonic tissue elasticity measurement field in that the *in vivo* tissue strain measurement was enabled [4]. Figure 1 shows our firstly obtained *in vivo* breast absolute shear modulus reconstruction images (ratio and implicit-integration) [5,6] that well exhibits a soft fatty region and a stiff mammary gland etc, in which an agar phantom was attached onto a skin surface as a reference material (2.8×10^5 N/m^2). The corresponding strain image is presented in [3]. Recently, a displacement vector measurement [2-4,7] is focused on toward the using it as a practical diagnosis tool; and several years ago, a lateral Doppler measurement [8,9] became a practical tool. To increase the measurement accuracy, such an optimized estimation should be performed for a lateral modulation (LM), a single steering (ASTA) beamforming or over-determined (OD) system such as obtained by performing plural wave (PW) transmissions and/or performing spectral frequency divisions (SFDs) [7,10]. However, when a temporal target displacement component distribution has a large range due to a usual deformable motion, the remained phase difference between a pair of local rf-echo signals phase-matched tentatively by the coarse estimate becomes spatially discontinuous. Thus, the original phase matching method leads to erroneous estimates of the residual and target displacement distributions if trying to perform spatially stationary statistical processing for the raw discontinuous phase data in the optimization.

Aims: By performing a new phase matching method that directly works on a phase, performing the optimizations such as a regularization [1] and a MAP is enabled for a displacement vector measurement and a lateral Doppler. The method feasibility is verified through agar phantom experiments.

Methods: In the new phase matching, instead of coarse and residual displacement estimates successively obtained with the MCCM, autocorrelation method (AM) [7] and cross-spectral phase gradient method (CSPGM) [2,3], respectively, an addition is equivalently performed with respect to the phase differences corresponding to the coarse and residual estimates. The agar phantom having a high shear modulus inclusion with a high agar concentration [11] was compressed in a lateral direction (a relative shear modulus, 3.3). Practically, the compression direction was slightly slanted as shown in Fig. 2a, specifically, the direction of 7° with respect to a lateral direction. In this study, at fast, the new phase matching was performed for the 2-dimensional (2D) AM [7] and 2D CSPGM [2,3]. Displacement vector measurements including the MAP and ML (Maximum likelihood) estimations were performed for several lateral modulations (LMs) and OD systems generated with PW transmissions or spectral frequency dividings: (i) 4 beams were generated with steering angles, ±20° and ±30° (Fig. 2b), and (ii) intentionally, an ill-conditioned system was also generated for a single beam scanning by yielding 4 partial spectra (quasi-steered beams) with vertical and lateral spectral dividings (Fig. 2c). Next, a lateral Doppler measurement with a regularization was performed with respect to a single steering angle (ASTA), -10°, -20°, -30° and -40° (Fig. 2a). Focused beams and plane waves were generated, respectively.

Results: Here, as fundamental results, displacement vector measurement results obtained with 2D AM and 2D CSPGM for an LM system generated by ±20° steered beams are shown in Fig. 3. Results of a strain tensor measurement and a shear modulus reconstruction (2D stress assumption) are also shown. In figures, the means and standard deviations (SDs) estimated in the inclusion are shown. For both 2D AM and 2D CSPGM, almost the same results were obtained as those obtained by the original phase matching method [11]. The MAP estimation substantially increased the measurement accuracy and stability for the OD systems with ±20° and ±30° steering angles, and 4 spectral divisions. The results were recently published in [12], then omitted here. Next, the results of lateral Dopplers are shown in Fig. 4. That is, the results of displacements and strains in the dominant compression direction (7° with respect to a lateral direction shown in Fig. 2a) directly measured for the ASTAs are shown. In displacement figures, SNRs (signal-to-noise ratios) estimated by dividing means by

SDs in the inclusion are shown. The dominant strains were calculated from the displacement data using the directional, 2D differential filter. The regularized estimation respectively performed with respect to the proper steering angles -40° and -30° for a focused beamforming and a plane wave transmission increased the measurement accuracy and stability as shown in Fig. 4.

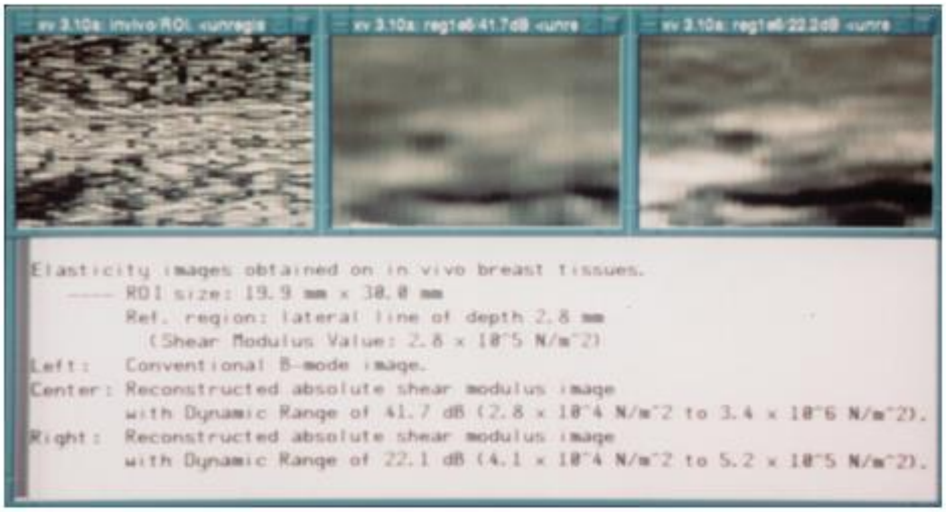

Figure 1. 1D shear modulus reconstrcution image obtained for human *in vivo* breast (healthy 37-years-old) [5,6].

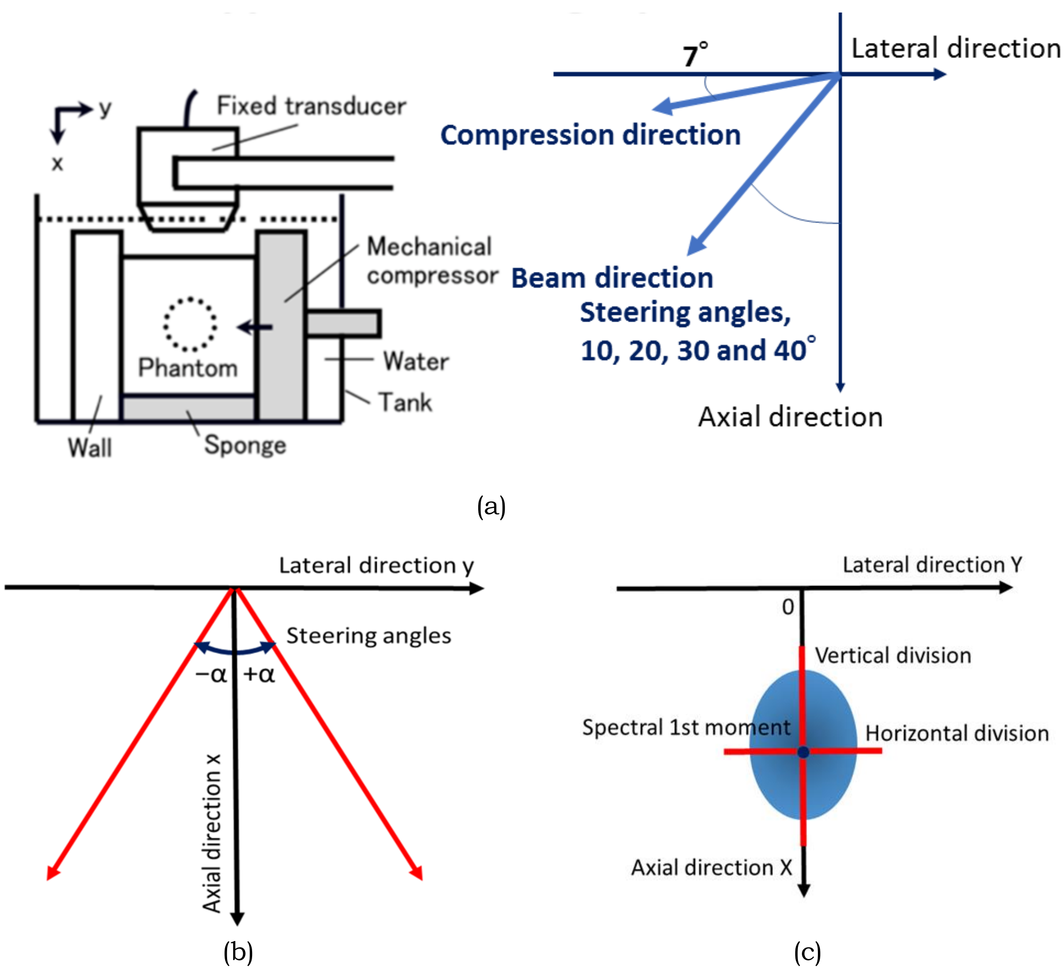

Figure 2. (a) Experimental schematic. (b) LM system generated with 2 steered waves. (c) Vertical and lateral spectral freuqency dividings.

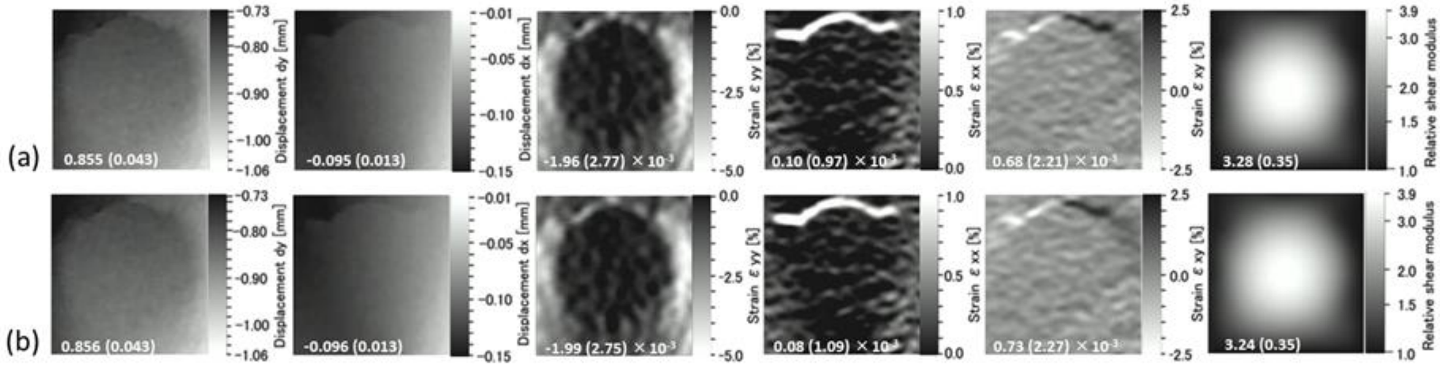

Figure 3. Measurement results of displacement vector obtained for an LM system using 2 crossed beams: (a) 2D AM and (b) 2D CSPGM. Optimized results are published in [12].

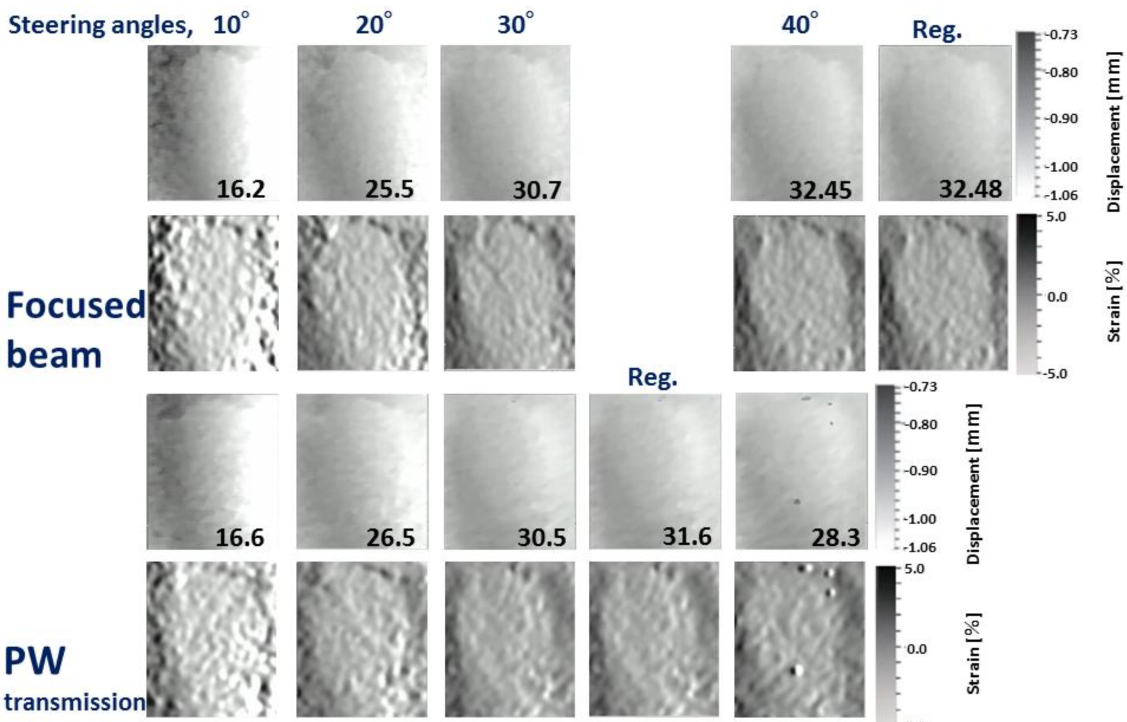

Figure 4. Measurement results of lateral Doppler obtained for ASTA: focused beamformings and plane wave transmissions.

Conclusions: The new phase matching method worked and allowed performing the MAP and the regularization estimations on the OD systems and the lateral Doppler systems (ASTAs), respectively. Several comparisons between the MAP and the regularization were delineated in [12], and experimental comparisons will be reported in detail elsewhere.

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