Accurate estimate of 2-dimensional motion vector via finite array synthetic aperture reconstruction processing of high-frame-rate speckle echo signal in living tissue

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(Received 30 June 2014, Accepted for publication 23 July 2014)

Keywords: Synthetic aperture, Array signal processing, Apodization, Motion vector, Point spread function

PACS number: 43.80.Vj [doi:10.1250/ast.36.158]

1. Introduction

Synthetic-aperture (SA) signal processing utilizing an array transducer is an ultrasonic imaging technology that plays an essential component in realizing a high-resolution image with a high frame rate (several thousand fr/s) as well as a breakthrough in transient elastography [1–3] which is being developed for medical diagnosis of living soft tissue in vivo. By introducing the above technology to measure small tissue movement of subwavelength order with a view to dynamical tissue characterization for clinical diagnosis, the authors of this paper have carried out system design in the spatial frequency domain for the purposes of lowering the calculation cost and expanding the visibility in the performance estimation of the entire measurement system [4–7].

The system herein adopted utilizes a pair of pulsed sound field irradiations originating from each virtual point sound source which is formed at a focal point of the array transducer in the estimation of the local displacement vector in the inhomogeneous tissue, because of the ease in the control of the sound field strength and in the choice of the measurement location. For these reasons, the SA range stacking algorithm enabling the measurement region to be expanded in the range direction is modified in accordance with the point sound source irradiation. Thus, SA reconstruction imaging with a resolution equivalent to that of a conventional ultrasonic image has been experimentally accomplished using the 2-dimensional RF echo data obtained from the array transducer with a high frame rate of four thousand fr/s [8].

However, even if the SA array signal processing is sufficient in the imaging of the amplitude information of the reconstructed result, it is necessary for the space invariance of the point spread function (PSF) given by the SA reconstruction system to be maintained with the phase order, so that tissue motion can be calculated from the local phase difference estimated by the local cross-correlation between two reconstructed successive echo frames. In this paper, we propose a method for expanding the region in which high-accuracy motion vector estimation from two successive echo signal frames is possible, by adopting apodization [9] at each range interval in the spatial frequency domain for SA array signal processing to comply with the azimuth asymmetry of the 2-dimensional echo signal truncated with a finite aperture.

2. Statistical property of motion vector estimation errors and its spatial distribution

The PSF of a finite-array SA reconstruction system gradually loses its space invariance because of the azimuth asymmetry of the acquired 2-dimensional echo signal, owing to azimuthal target deviation from the range axis passing through the center of an aperture. Confronting such a situation, evaluation was carried out using of the reconstruction data in accordance with the simulation described below in order to quantify the motion estimation errors and to recognize the application range of the quantification. The range stacking SA array signal-processing algorithm involving point sound source irradiation [6] for reconstruction is depicted in Fig. 1, where p(t), s₀(t, u), and s(t, u) are the transmitted pulsed signal, 2-dimensional reference echo signal from a point target located at a distance of x₀ from the aperture center, and a 2-dimensional received echo, respectively.

An array transducer, in which 256 elements with a central frequency of 3 MHz and a bandwidth of 2 MHz are arranged at an element pitch of 0.25 mm, was put in place, and thereafter, a virtual point source of pulsed sound was formed at a focal point of the array transducer in transmission phase. For sound source irradiation at the position of (8 mm, 16 mm), given as an x₁,y₁-coordinate with the origin at the array center, Figs. 2(a) and 2(b) respectively show the reconstruction images corresponding to specular echo from the point reflectors at even intervals and speckle echo from statistical random point reflectors as which is a simulation model of inhomogeneous tissue. The random tissue medium is simulated by point scatterers randomly distributed throughout a target area at 25 points/mm² mean density with each random reflectivity given by a zero-mean Gaussian distribution function to take account of incoherent scattering from the medium [6], where each target reflects a pulsed circular wave caused by transient irradiation from a virtual point source. Throughout the image, the desired resolution and its spatial uniformity can both be maintained and they coincide with the experimental data [8].

In the condition above, the two local phase differences caused by a given movement in the simulated tissue are
estimated by preparing each set of reconstruction data in accordance with the different sound source locations of (8 mm, ±/16 mm) by the 2-dimensional cross-correlation method. As a result, the actual motion vector can be calculated from both phase differences on the same position, and the statistical performance of the errors is ensured [4]. The result has made it possible to conclude that in order for the estimation error in the azimuthal direction being dominant here in comparison with the range direction to be confined less than 10%, the measurement area must be restricted within ±10 mm in range direction and ±8 mm in the azimuthal direction around the center of the target area (50 mm, 0 mm) as shown in Fig. 3(a) [10]. The estimated interframe displacement of 0.01 mm is in an appropriate range of living tissue motion under the acquisition rate of a few thousand fr/s. For local cross-correlation estimation, a moving average window has the size of 3 mm × 3 mm in practice. Thus a method to expanding the accurate measurement region is investigated.

3. Apodization in the spatial frequency domain in SA signal processing

The reconstructed value of the target echo deviating in the azimuthal direction from the range axis passing through the center of the arrayed finite aperture, which tends to be accompanied by complicated alteration at the phase level, is expected to generate serious errors in the local phase difference between speckle echo frames. To suppress such error, it is necessary to restrict the unnecessary spatial frequency component in the azimuthal direction in the spatial frequency domain to carry out the reconstruction of the individual range stacking segments. In this paper, the Kaiser window, which can eliminate unnecessary band without exerting a serious influence on the resolution and can control adequate weighting of the effective band using a single parameter (α), is introduced. Thus, dynamic windowing has been successfully carried out in accordance with the spatial frequency spectrum in the azimuth direction in the individual range stacking segments. As a result, it is confirmed that the measurement region maintained less than 10% estimation error, complying with the expansion of the azimuthal movement of 0.01 mm ensured in the previous section to within ±20 mm in both range and azimuthal direction, as shown in Fig. 3(b).

4. Conclusions

Utilizing the proposed synthetic aperture algorithm for a finite array, precise dynamic information in living tissue could be detected at a high frame rate. The experimental results obtained using a tissue phantom and further optimization of the system design will be referred to separately.
References


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Fig. 3 Estimated displacement of 0.01 mm in cross-range direction for data reconstructed by (a) original range stacking and (b) range stacking with apodization.