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Target Area Extension in Synthetic Aperture Array Signal Processing for High Frame-Rate Estimate of 2D Motion Vector In-Vivo

生体の２次元変位ベクトル高速推定のための配列型開口合成処理領域の拡張

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1. Introduction

The Synthetic Aperture (SA) array signal processing is an atractive tool to realized ultra-high framerate ultrasonic imaging and tissue dynamic property detection for quatitative analusis of various tissue oriented characteristics in-vivo. For fully utilizing the flexibility of the ultrsonic arrayed transducer Range Stacking (RS) algorithm is still an active tool of Synthetic Aperture Radar (SAR) signal processing [1,2] in spatial frequency domain toward extension of target area to be measured. This algorithm can be straightforwardly applied to SA array signal processing of successive ultrasonic echo frames which could be obtained by pulsed irradiations of plane wave transmitted from an array transducer. However we have been studying to estimate overall system performances of SA array processing controlled by localization and power of a point irradiation source generation for accurate and ultra-high framerate measurement [3-6]. Herein the passive (one-way receiving) SA algorithm in spatial frequency domain is modified for spherical transmission and its overall sysytem performance is quantitativly evaluated as a practical method to extend the targer area to be measured.

2. Passive Range Stacking Algorithm

The Range Stacking algorithm for successive calibration of range dependent point spread function in ordinary SA signal processing is described by spectrum $S(\omega, k_u)$ of 2D echo signal $s(t, u)$, where ω and k_u are angle frequency on delayed time t from a pulsed transmission p(t) and spatial frequency on lateral range u along an arrayed aperture, respectively [1,2]. As a simplified case the passive array Range Stacking is performed by superposing each successive reconstruction at the range bins x_n's over the total measurement range with a fixed resolution, as shown in **Fig. 1**.

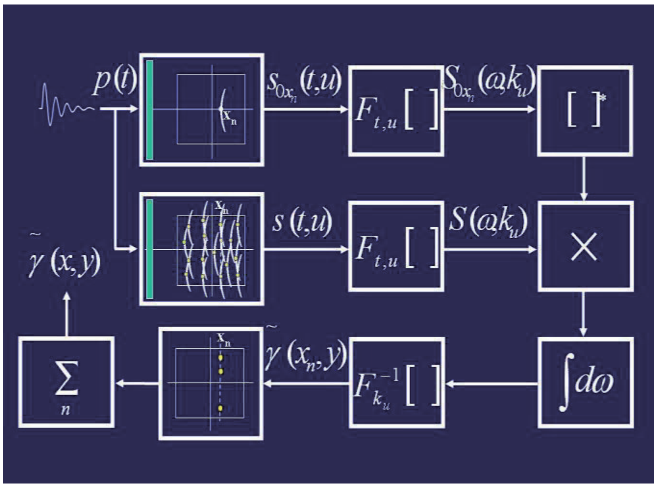

Fig. 1 Synthetic Aperture digital reconstruction processing via passive array Range Stacking.

Substituting the spatial frequency spectrum in terms of plane waves into the Fourier-transform with respect to u, of the spherical wave having a wavenumber k (= ω/c) the spectrum $S(\omega, k_u)$ of 2D signal $s(t, u)$ recieved by a pulsed irradiation from target's function $\gamma(x, y)$ is formulated as follows

$$S(\omega,k_u) = P(\omega)\, e^{-j\sqrt{k^2-k_u{}^2}X_c - jk_nY_c}\,\Gamma(\sqrt{k^2-k_u{}^2}, k_u),$$

where $P(\omega)$ and $\Gamma(k_x, k_y)$ are the spectrum of a transmitting pulse p(t) and the 2D Fourier-transform of $\gamma(x, y)$ which is located with the offset from the target center (X_C, Y_C), respectively. Consecutively the spectrum is matched-filtered with the following spectrum $S_{0xn}(\omega, k_u)$ of the reference signal $s_{0xn}(t, u)$ at the range bin x_n.

$$S_{0x_n}(\omega,k_u) = P(\omega)\, e^{-j\sqrt{k^2-k_u{}^2}(X_c+x_n) - jk_nY_c}$$

The result is integrated over the available frequency band with the assignment of $k_y = k_u$ and inversely Fourier-transformed with respect to k_y. Thus the target function $\gamma(x_n, y)$ at the range x_n is formulated as follows,

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$$\gamma(x_n, y) = \int_{k_u} \int_{\omega} S(\omega, k_u) S^*_{0x_n}(\omega, k_u) d\omega \, e^{jk_u y} dk_u$$

The total target function is obtained by superposing the local reconstruction at the range x_n successively.

3. Extended Range Stacking Algorithm

When utilizing the active spherical source generated by each arrayed element in transmitting phase the Range Stacking algorithm has to be extended to account for the time delay that the pulsed irradiation takes to arrive at each target with the different cross range in the same range bin from that of the spherical source, as shown in **Fig. 2.**

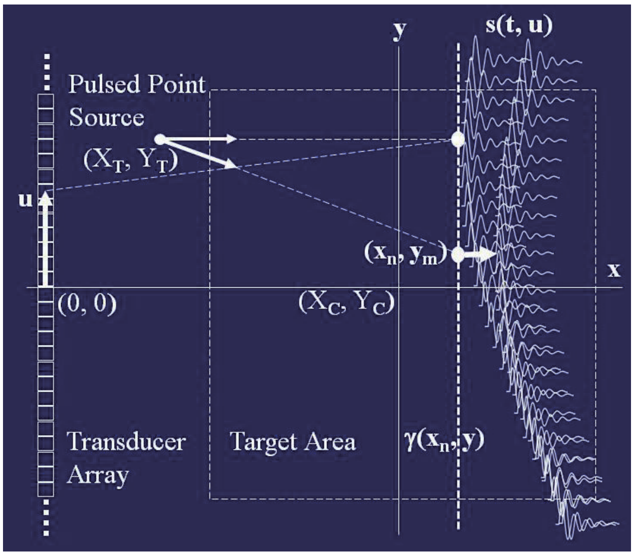

Fig. 2 The 2D echo signal s(t, u) from the target function γ(x_n, y) by a pulsed irradiation of a spherical source .

Thus, we propose the extended Range Stacking algorithm which includes the modified 2D matched filter $S^*_{0xn}(\omega, k_{\mathbf{u}})$ with the additional phase spectrum by the incremental time delay mΔt to detect the entire target function at the range x_n as follows

$$\gamma(x_n, y) = \sum_m \gamma(x_n, y_m)$$

$$= \sum_m \int_{k_u} \int_{\omega} S(\omega, k_u) S^*_{0x_n}(\omega, k_u) e^{jm\omega\Delta t} d\omega \, e^{jk_u y} dk_u ,$$

in which the re-sampled cross range y_m is obtained from the following parabolic curb of the time delay vs. y_m under the point source location (X_T, Y_T).

$$m\Delta t = (\sqrt{(X_C + x_n - X_T)^2 + (Y_C + y_m - Y_T)^2}$$
$$- (X_C + x_n - X_T))/c$$

where c is sound velocity.

4. Simulation Results

The modified Range Stacking algorithm was numerically evaluated for the same parameters as the experimental SA array signal processing system. The linear array transducer is having 256 elements with 0.25 mm pitch, 3 MHz center frequency and 2 MHz bandwidth. The fine reconstructions throughout the extended target area of 40mm by 32mm are depicted for the different point source irradiations, as shown in **Fig. 3**

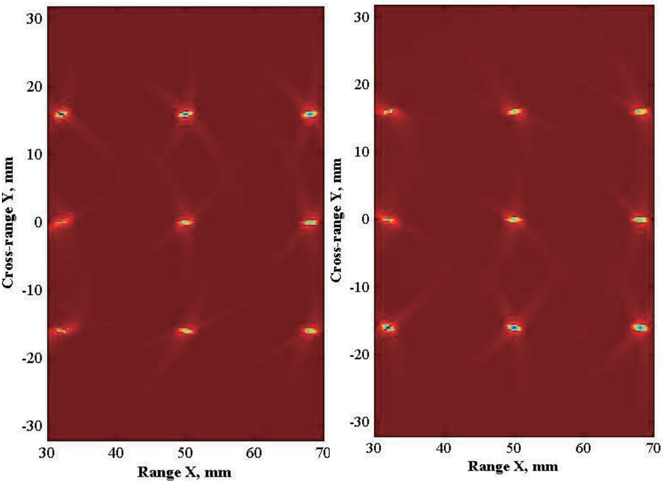

Fig. 3 The SA reconstructed target functions by utilizing the extended Range Stacking array processing for each symmetric point source location at (8mm, 16mm) and (8mm, -16mm) as in the left and the right image, respectively.

4. Discussion

The proposed Range Stacking algorithm in SA array signal processing by point source generation contributes to the stable extension of target area with controllable resolution, in which the overall optimal system design can be quantitatively pursued in measurement accuracy and statistical variance for the evaluation of 2D motion vectors in-vivo.

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