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Maximum likelihood estimation of scattering strength applied to beamformed ultrasonic signals
散乱強度の最尤推定法のビームフォーミング後超音波信号への適用

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1. Introduction

A finite size of the point spread function (PSF) of an ultrasound imaging system limits the analysis of fine structure of biological tissue, e.g., a thin layer would be visualized clearly with a small PSF in the axial direction. A deconvolution method is often used for improvement of the spatial resolution of an ultrasound image [1]. We developed a method for improvement of the axial spatial resolution by deconvolution with the concept of the Wiener filter [2]. Furthermore, we developed a method of maximum likelihood estimation of the scattering strength distribution for improvement of the axial resolution [3]. However, the method described in [3] was applied to ultrasonic echo signals received by individual transducer elements in an ultrasonic probe and, therefore, its implementation is limited to a system in which element echo signals are available. In the present study, we investigated the feasibility of our maximum likelihood estimator in application to beamformed ultrasonic signals.

2. Methods

2.1. Maximum likelihood estimation of scattering strength

In the present study, we used the method described in [3]. Let us define vector $\mathbf{s}$ of sampled radio-frequency (RF) echo signals s_i $(i = 0, 1, 2, \cdots, N-1)$ in a scan line in a B-mode image as

$$\mathbf{s} = (s_0 \ s_1 \ s_2 \ \cdots \ s_{N-1})^{\mathrm{T}}, \tag{1}$$

where N and the superscript T denote the number of sampled points and the transpose, respectively. Also, the PSF of an ultrasound imaging system is defined as

$$\mathbf{h} = (h_0 \ h_1 \ h_2 \ \cdots \ h_{K-1})^{\mathrm{T}}, \tag{2}$$

where K is the number of samples for the PSF.

In the present study, it was assumed that there is one point scatterer at each sampled point and that M scatterers contribute to produce echo $\mathbf{s}_n = (s_n \ s_{n+1} \ s_{n+2} \ \cdots \ s_{n+K-1})^{\mathrm{T}}$ beginning from the n-th sampled point. Such a discrete signal model $\hat{\mathbf{s}}_n$ can be described as

$$\hat{\mathbf{s}}_n = \mathbf{Hz} + \mathbf{n}, \tag{3}$$

where $\mathbf{n}$ is the noise vector and $\mathbf{z}$ represents the scattering strength of the scatterer at each sampled point defined as

$$\mathbf{z} = (z_0 \ z_1 \ z_2 \ \cdots \ z_{M-1})^{\mathrm{T}}. \tag{4}$$

Also, $\mathbf{H}$ is a matrix expressing the convolution of scattering strength distribution $\mathbf{z}$ and PSF $\mathbf{h}$.

By assuming that noise $\mathbf{n}$ included in echo signal $\mathbf{s}_n$ as Gaussian white noise, likelihood p_n of echo signal $\mathbf{s}_n$ is expressed as

$$p_n = \frac{1}{\det(\pi\mathbf{K})} \exp[-(\mathbf{s}_n - \mathbf{Hz})^{\mathrm{H}} \mathbf{K}^{-1} (\mathbf{s}_n - \mathbf{Hz})], \tag{5}$$

where the superscripts H and -1 represent the Hermitian operator and inverse matrix, respectively, and $\mathbf{K} = \mathrm{E}[\mathbf{s}_n \mathbf{s}_n^{\mathrm{H}}]$ ($\mathrm{E}[\cdot]$: expectation). The scattering strength $\hat{\mathbf{z}}$, which maximizes the likelihood p_n, is estimated as

$$\hat{\mathbf{z}} = \frac{\mathbf{K}^{-1}\mathbf{H}}{\mathbf{H}^{\mathrm{H}}\mathbf{H}^{-1}\mathbf{H}} \cdot \mathbf{s}_n.$$

Finally, $\hat{z}_0$ is used as the estimated scattering strength at sampled point s_n. By changing the value of the subscript n, the scattering strength distribution along each scan line is estimated.

2.2. Estimation of PSF of imaging system

To estimate scattering strength distribution $\mathbf{z}$ by the proposed method, PSF $\mathbf{h}$ of an imaging system is required. In the present study, PSF $\mathbf{h}$ was estimated by the method described in [2,4]. PSF $\mathbf{h}$ can be estimated if its spectrum is obtained. In the present study, by neglecting the phase of the spectrum, the amplitude spectrum was estimated from measured echo signals. For this purpose, amplitude spectra of measured echo signals were obtained using Fourier transform with a 1D axial kernel. As illustrated in **Fig. 1**, the 1D axial kernel was slid within the B-mode image, and the amplitude spectrum was obtained at every position by applying Fourier transform to the received RF signal. There are a lot of dips in the single amplitude spectrum obtained at each kernel position because of interferences of

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echoes. The frequencies at which such dips are present depend on the positions of the scatterers. Therefore, such dips can be suppressed by averaging amplitude spectra obtained at different positions in the B-mode image owing to the randomness of the scatterer distribution. The PSF of the imaging system used in the present study was obtained by applying Fourier transform to the averaged amplitude spectrum under the assumption that the phases of the spectrum are zero at all frequencies.

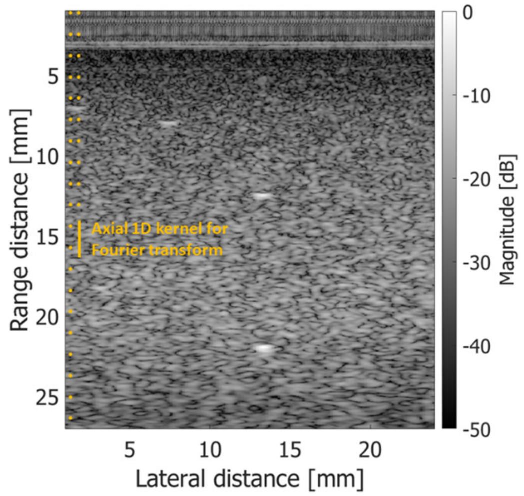

Fig. 1: Standard B-mode image of phantom and illustration of 1D axial kernel for Fourier transform.

3. Results

Figure 1 shows a B-mode image of a phantom (model 040GSE, CIRS, USA). The B-mode image was obtained with a 7.5-MHz linear array (UST-5412, Hitachi, Japan) based on line-by-line acquisition with 121 transmit beams focused at 30 mm emitted from transmit apertures with 32 elements. Ultrasonic echo signals received by individual transducer elements were acquired by a custom-made scanner (RSYS0016, Microsonic, Japan), and the standard delay-and-sum beamforming was applied to the acquired signals using a custom-made software based on MATLAB (MathWorks, USA).

Figure 2 shows a B-mode image obtained by applying the proposed method to the beamformed RF signals which were used to generate the B-mode image shown in Fig. 1. The PSF of the imaging system was also estimated using the same RF signals in Fig. 1. **Figure 3** shows the axial (vertical) amplitude profiles at a lateral position of 12.75 mm obtained from the standard B-mode image and B-mode image processed by the proposed method. As can be seen in Figs. 2 and 3, the peak of each ultrasonic pulse is enhanced by the proposed method and, as a result, the width at half maximum of the PSF is reduced particularly in the axial direction.

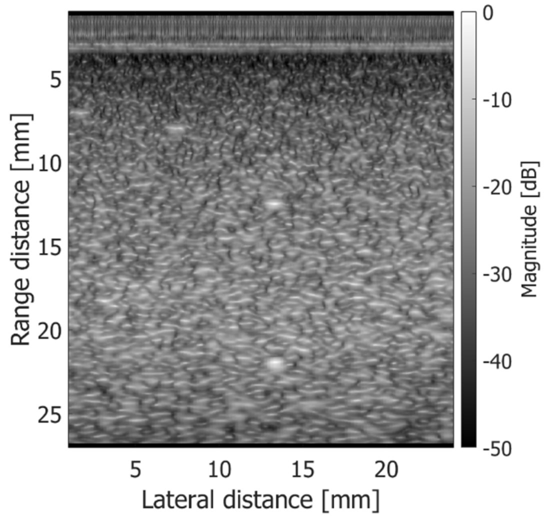

Fig. 2: B-mode image of phantom processed by the proposed method.

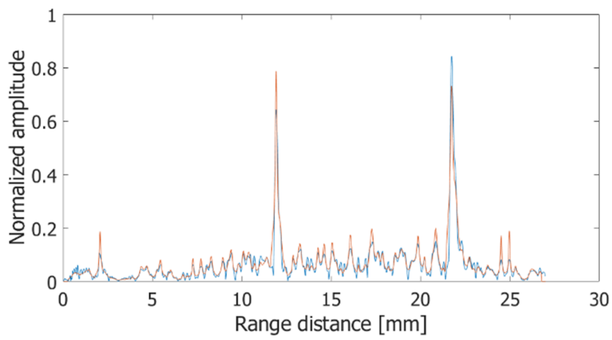

Fig. 3: Axial amplitude profiles obtained at lateral position of 12.75 mm without (blue) and with (orange) the proposed method.

4. Conclusion

In the present study, a method for maximum likelihood estimation of the scattering strength distribution was applied to beamformed ultrasonic RF signals. The phantom experimental results showed that the proposed method could enhance the peak of each ultrasonic pulse and, as a result, the range spatial resolution of the B-mode image was improved.

References

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