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Accurate Intensity Estimation in High-Resolution Ultrasound Imaging Based on Adaptive Beamforming Technique

適応型信号処理を用いた高分解能超音波イメージングにおける高精度推定

Hirofumi Taki[1,2†], Hiroshi Kanai[2,1] ([1] Grad. School of Biomedical Eng.; [2]Graduate School of Eng., Tohoku University)
瀧 宏文 [1,2†]，金井 浩 [2,1] ([1] 東北大院・医工, [2] 東北大院・工)

1. Introduction

Cardiovascular disease is one of the major causes of mortality, and it is mainly caused by atherossclerosis . Because carotid intima-media thickness estimated by ultrasonography is widely used as an indicator for atherosclerosis, the improvement of spatial resolution in ultrasound imaging is highly desirable to detect atherosclerosis at the early stage.

In ultrasound imaging, adaptive beamforming techniques have employed to improve spatial resolution[1)]. We have employed an adaptive beamforming technique with frequency domain interferometry (FDI), and succeed to improve the range resolution in ultrasound imaging[2,3)]. The proposed method uses the Capon method, and it does not work when echoes from different targets are correlated. Therefore, the method employs frequency averaging to suppress the correlation between echoes. However, the suppression level of the correlation using frequency averaging is unstable, and the accuracy in estimating echo intensity decreases when the suppression is insufficient.

In this study, we propose a technique to suppress the correlation between echoes with no deeterioration in range resolution.

2. Materials and Methods

The proposed technique is applied to the high-resolution imaging method using FDI with adaptive beamforming technique. First, we explane the methodology of the high resolution imaging method. We then describe the technique to improve the accuracy in estimating echo intensity.

2.1 High resolution imaging method using FDI with adaptive beamforming technique

The imaging method is applied to the received signal of a scan line separately. The phase of a frequency component of the received signal depends on the product of the frequency and the target depth. Therefore, the summation of the frequency components after phase compensation can emphasize the contribution of the echo returned from the measurement depth. The imaging method calculates the optimum phase compensation weights, where the weights minimize the output power subject to a constant response at the measurement depth. This strategy enables to selectively suppress echoes returned from undesired depths. The output power of the imaging method at the measurement depth of $r/2$ is expressed by:

$$P(r) = \left|\mathbf{x}^{\mathrm{T}}\mathbf{w}^{*}\right|^{2} = \mathbf{w}^{\mathrm{T}*}\mathbf{R}\mathbf{w}, \qquad (1)$$

$$\mathbf{R} = \mathbf{x}\mathbf{x}^{\mathrm{T}*}, \qquad (2)$$

where $\mathbf{w}$ is a weighting vector for the phase compensation, $\mathbf{x}$ is a set of frequency components of the received signal, $[]^{\mathrm{T}}$ and $[]^{*}$ denote the transpose and the conjugate,respectively. $\mathbf{R}$ is the covariance matrix of the received signal in the frequency domain.

Figure. 1 shows frequency averaging used by the imaging method. The technigue is applied to the covariance matrix:

$$\mathbf{R}_{\mathrm{A}} = \frac{1}{M}\sum_{m=1}^{M}\mathbf{R}_{m}, \qquad (3)$$

$$R_{m,i,j} = x_{i+m-1}x_{j+m-1}^{*}, \qquad (4)$$

where $\mathbf{R}_{\mathrm{A}}$ is a covariance matrix after frequency averaging and $R_{m,i,j}$ is the (i, j) element of a m-th sub-matrix $\mathbf{R}_{m}$. The minimization of the output power is expressed by:

$$\min_{\mathbf{w}_{\mathrm{A}}} \quad P_{\mathrm{A}}(r) = \mathbf{w}_{\mathrm{A}}^{\mathrm{T}*}\mathbf{R}_{\mathrm{A}}\mathbf{w}_{\mathrm{A}}$$

$$\text{subject to} \quad \mathbf{c}^{\mathrm{T}*}\mathbf{w}_{\mathrm{A}} = 1, \qquad (5)$$

$$\mathbf{c} = \left[\exp(\mathrm{j}k_{1}r) \quad \cdots \quad \exp(\mathrm{j}k_{N-M+1}r)\right]^{\mathrm{T}}, \qquad (6)$$

where k_l is the wavenumber of the l-th frequency component of the received signal, N is the number of the employed frequency components. The solution to (5) is given by:

$$P_{\mathrm{Cap}}(r) = \frac{1}{\mathbf{c}^{\mathrm{T}*}(\mathbf{R}_{\mathrm{A}} + \eta\mathbf{E})^{-1}\mathbf{c}}, \qquad (7)$$

where $\eta\mathbf{E}$ is a diagonal loading matrix to acquire the inverse matrix stably.

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taki@ecei.tohoku.ac.jp

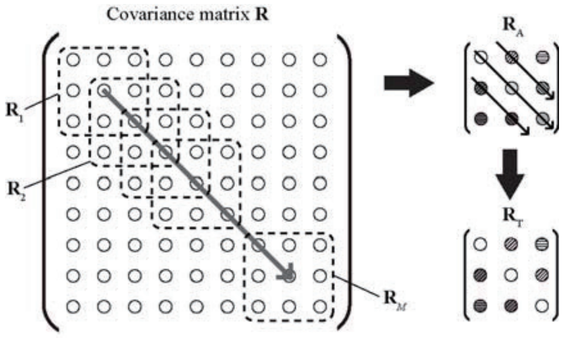

Fig. 1 Covariance matrix after frequency averaging $\mathbf{R}_A$ and that after Torplitz frequency averaging $\mathbf{R}_T$.

2.2 Toeplitz frequency averaging

When frequency averaging suppresses the correlation between echoes perfectly, the covariance matrix after frequency averaging $\mathbf{R}_A$ becomes a Toeplitz matrix[4]. Therefore, we average the covariance matrix $\mathbf{R}_A$ in the diagonal direction to enforce a Torplitz form on the covariance matrix, as shown in Fig. 1. The estimated intensity of the imaging method using Toeplitz frequency averaging is expressed by:

$$P_T(r) = \frac{1}{\mathbf{c}^{T*}(\mathbf{R}_T + \eta \mathbf{E})^{-1}\mathbf{c}}, \quad (8)$$

where $\mathbf{R}_T$ is the covariance matrix after Toeplitz frequency averaging. We use the estimated intensity using Toeplitz frequency averaging to compensate the echo intensity at the target position.

3. Results

We investigated the performance of the high-resolution imaging method using Toeplitz frequency averaging in the severe condition that the received signal consists of two echoes of identical waveform, that is, the two echoes perfectly correlate with each other. Figure 2 shows the waveform of a single echo and that of the received signal with two identical echos, where we set the target distance as 0.077 mm. As the single echo, we used the echo returned from a gelatin-agar interfac acquired by a commercial ultrasonographic device (ProSound F75, HItach-Aloka Medical). The transmit center frequency is 7.5 MHz, and the sampling frequency is 40 MHz.

Figure 3 shows the echo intensity profile estimated using the high-resolution imaging with frequency averaging and that with Toeplitz frequency averaging. The high-resolution imaging method with frequency averaging succeeded in depict two targets clearly; however, it underestimated the echo intensity at the two target positions by 7.0 and 8.0 dB compared to the true intensity. In contrast, the underestimation of the proposed method was suppressed to 2.9 dB. This result shows the efficiency of the compensation process using Toeplitz frequency averaging.

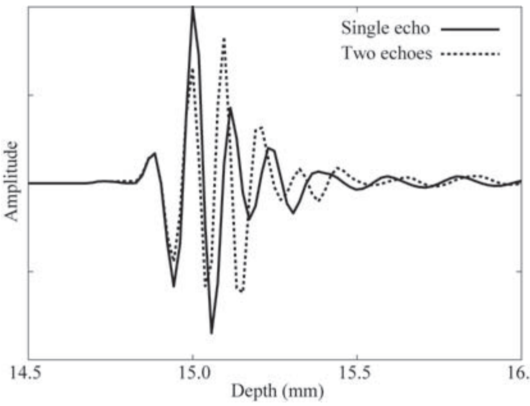

Fig. 2 Echo waveforms returned from a single target and two targets, where the target distance is 0.077 mm.

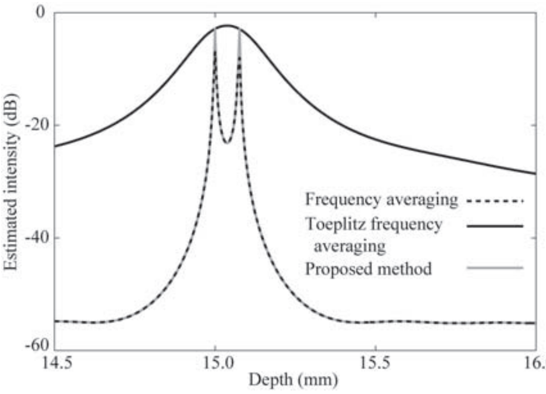

Fig. 3 Echo intensity profiles estimated by the proposed high-resolution imaging method. The target depths are 15.0 and 15.77 mm, and the true echo intensity is 0 dB.

4. Conclusion

We propose a compensation method that improves the accuracy in estimating echo intensity acquired by the high-resolution imaging method using FDI with an adaptive beamforming technique. The proposed method succeeded to clearly depict two targets that were 0.077 mm apart, where the estimation error in echo intensity at the target position is 2.9 dB. This study shows the potential of the adaptive beamforming technique in high-resolution ultrasound imaging.

References

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