

ADAPTIVE-BEAMFORMER WITH ACCURATE INTENSITY-ESTIMATION TECHNIQUE FOR HIGH-RANGE-RESOLUTION VASCULAR ULTRASOUND IMAGING

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Abstract—For the early detection and for the treatment assessment of cardiovascular disease, improvement in range resolution of vascular ultrasound imaging is highly desirable. The employment of frequency domain interferometry with the Capon method largely improves the range resolution of ultrasound imaging; however, this methodology often underestimates the echo intensity. In this paper, we propose a compensation method to improve the estimation accuracy in echo intensity acquired by the high-range-resolution ultrasound imaging method based on frequency domain interferometry. The method requires 0.18 s/frame using a single CPU PC. The proposed method has the spatial resolution of 0.05 mm with the average estimation intensity error of 0.15 dB on the log scale, where we employ an ultrasound pulse of 7.5 MHz center frequency. We have applied the proposed method to a swine femoral artery *in vitro* and a human carotid artery *in vivo*, and verified its efficiency to improve the accuracy in echo intensity estimation.

Keywords—Ultrasound imaging; vascular ultrasound; frequency domain interferometry; adaptive beamforming; high resolution

I. INTRODUCTION

Cardiovascular disease is the major cause of mortality. Since Ultrasonography (US) is one of the primary imaging modalities to investigate small abnormality of artery [1], [2], its improvement in range resolution is highly desirable.

Since the 1960s, adaptive beamforming techniques have reported to acquire high spatial resolution images. A common technique is the Capon beamformer that minimizes the output power subject to a constant response at the desired direction [3], [4]. In US, several groups have applied adaptive beamforming techniques to improve the lateral resolution [5], [6]. For the improvement of the range resolution of US, we have employed frequency domain interferometry (FDI) with the Capon method [7]. The method has the high range-resolution of 0.05 mm when an ultrasound pulse of 7.5 MHz center frequency is used, while the image acquired by the method has lower continuity in the lateral direction than a conventional B-mode image.

The FDI imager with the Capon method employs frequency averaging to suppress the correlation between echoes from different targets; however, the suppression level of the correlation by frequency averaging is unstable. Since the estimated intensity largely depends on the suppression level of

the correlation between echoes, the instability of the suppression level causes the low continuity of the FDI image in the lateral direction [7], [8]. In this study, we propose a technique to suppress the correlation between echoes from different targets to improve the accuracy of echo intensity estimation with no deterioration in range resolution.

II. MATERIALS AND METHODS

The proposed imager employs FDI with the Capon method. In this section, we briefly explain the methodology of FDI imager with the Capon method, and subsequently describe the technique to suppress the correlation between echoes from different targets. We explain the strategy to compensate the echo intensity estimated by the FDI imager. Finally, we report the experimental setup used in this study.

A. FDI Imaging with the Capon Method

The phase of each frequency component of the echo from a depth depends on the product of the frequency of the component and the depth. Therefore, the summation of the frequency components after phase compensation emphasizes the echo from a desired depth. FDI imager with the Capon method selects the optimum phase-compensation weight that minimizes the output intensity subject to a constant response at a desired depth. This strategy suppresses the contribution of interferences under the condition to maintain the contribution of the desired signal [7]. The output power of a FDI imager is given by

$$P(r) = |\mathbf{X}^T \mathbf{W}^*|^2 = \mathbf{W}^T \mathbf{R} \mathbf{W}, \quad (1)$$

$$\mathbf{R} = \mathbf{X} \mathbf{X}^T, \quad (2)$$

where \mathbf{W} is a weighting vector for the phase compensation at the desired depth $r/2$, \mathbf{X} is a set of frequency components of the signal, $[\]^T$ and $[\]^*$ denotes the transposed and the conjugate, respectively, and \mathbf{R} is the covariance matrix of \mathbf{X} . The conventional FDI imager with the Capon method uses uniform frequency averaging to suppress the correlation between echoes, as shown in Figure 1.

$$\mathbf{R}_A = \frac{1}{M} \sum_{m=1}^M \mathbf{R}_m, \quad (3)$$

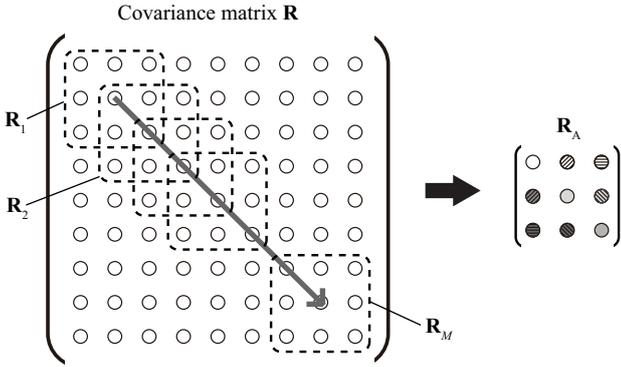


Figure 1. Covariance matrix after uniform frequency averaging \mathbf{R}_A .

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

where \mathbf{R}_A is a covariance matrix after uniform 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 based on the Capon method is expressed as follows:

$$\min P_A(r) = \mathbf{W}_A^T \mathbf{R}_A \mathbf{W}_A \quad \text{subject to} \quad \mathbf{C}^T \mathbf{W}_A = 1, \quad (5)$$

$$\mathbf{C} = [\exp(jk_l r) \quad \cdots \quad \exp(jk_{N-M+1} r)]^T, \quad (6)$$

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

$$P_{\text{Cap}}(r) = \frac{1}{\mathbf{C}^T (\mathbf{R}_A + \eta \mathbf{E})^{-1} \mathbf{C}}, \quad (7)$$

where $\eta \mathbf{E}$ is a diagonal loading matrix to acquire the inverse matrix stably [7].

B. Toeplitz Frequency Averaging for Accurate Echo-Intensity Estimation

Uniform frequency averaging cannot suppress the correlation between echoes perfectly, and the conventional FDI imager with the Capon method often underestimates the echo intensity [8]. In atmospheric radar imaging, adaptive frequency averaging is employed to suppress the correlation strongly [9]; however, it is unsuitable for medical ultrasound imaging that utilizes a broad-band pulse wave [8].

When the correlation between echoes is suppressed perfectly, the covariance matrix after frequency averaging becomes a Toeplitz matrix [9]. We thus enforce a Toeplitz form on the covariance matrix after frequency averaging, as shown in Figure 2. We call this technique Toeplitz frequency averaging.

$$R_{T,i,j} = \begin{cases} \frac{1}{N+i-j} \sum_{m=1}^{N+i-j} R_{m,(m-i+j)} & (i \leq j) \\ R_{T,j,i}^* & (i > j) \end{cases}, \quad (8)$$

where $R_{T,i,j}$ is the (i, j) element of the covariance matrix after Toeplitz frequency averaging.

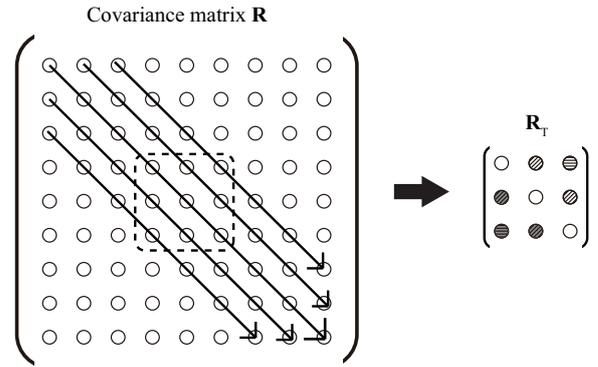


Figure 2. Covariance matrix after Toeplitz frequency averaging \mathbf{R}_T .

The estimated intensity acquired by the FDI imager with the Capon method using Toeplitz frequency averaging is given by

$$P_T(r) = \frac{1}{\mathbf{C}^T (\mathbf{R}_T + \eta \mathbf{E})^{-1} \mathbf{C}}. \quad (9)$$

C. Echo-Intensity Compensation from the Estimated Intensity Using Toeplitz Frequency Averaging

Covariance matrix after Toeplitz frequency averaging is enforced to become a Toeplitz matrix. Since a covariance matrix of a Toeplitz form contains no coherent interference, Toeplitz frequency averaging is supposed to convert coherent interferences to incoherent interferences. Therefore, the FDI imager with the Capon method using Toeplitz frequency averaging has high performance in echo-intensity estimation at the target position at the cost of range resolution and image quality. Since the conventional FDI imager with the Capon method has high range resolution, we compensate the echo intensity at the target positions acquired by the conventional FDI imager with the Capon method from the intensity acquired by the FDI imager with the Capon method using Toeplitz frequency averaging.

We compensate the estimated intensity of the conventional FDI imager with the Capon method using three steps. First, we choose the region of echo intensity higher than average echo intensity in the FDI image using Toeplitz frequency averaging, Ω . We select peak positions of the conventional FDI image in the region Ω . We then calculate the compensated echo intensity given by

$$I_{\text{cmp}}(r) = \max_l \left[\frac{I_C(r) I_T(r_{pl})}{I_C(r_{pl})} 2^{-\left(\frac{r_{pl}-r}{r_0}\right)^2} \right] \quad (10)$$

where $I_C(r)$ and $I_T(r)$ are the echo intensity estimated by the conventional FDI imager with the Capon method and that using Toeplitz frequency averaging, respectively, $r_{pl}/2$ is the depth of l -th peak position of the conventional FDI image in Ω , r_0 is a positive number. When $I_{\text{cmp}}(r) < I_C(r)$, we use $I_C(r)$ as the final estimated intensity at the depth of $r/2$. In this study, we set r_0 at 0.05 mm.

D. Simulation and Experimental Setup

In the simulation study, we investigate the performance of the proposed method in the ideal condition that two flat interfaces exist in a ROI. The echo returned from two interfaces is given by

$$s(d_1, t) = s_R(t) + s_R(t - 2d_1/c) \quad (11)$$

where d_1 is the interface distance, $s_R(t)$ is the echo returned from a horizontal interface between 20% gelatin and 4% ager at the depth of 15 mm. In the experimental study, we used a swine femoral artery in vitro and a normal living human carotid artery in vivo. We utilized a commercial US device (Hitachi EUB-8500, Hitachi, Japan) with a 7.5 MHz linear array to acquire the echo.

III. RESULTS

Another strategy to suppress the underestimation of the FDI imager with the Capon method is the employment of large diagonal loading η in Eq. (7). Since the Capon beamformer with large diagonal loading approaches a simple beamformer using a fixed compensation weight, the employment of large η soothes the effect of correlation between echoes on the underestimation of echo intensity at the cost of range resolution. We compare the performance of the FDI imager with the Capon method using large diagonal loading and that using Toeplitz frequency averaging in the estimation accuracy of the echo intensity. We used -10 dB of the average value of the diagonal terms of \mathbf{R}_A and \mathbf{R}_T as η for uniform frequency averaging with large diagonal loading and that with Toeplitz frequency averaging, respectively. The conventional FDI method used -40 dB of the average value of that.

Figure 3 shows echo waveforms used in the simulation study. Figures 4 and 5 show the echo intensity profile and maximum intensity acquired by the compensated FDI imager using Toeplitz frequency averaging. The wavelength of the transmit pulse is 0.2 mm, the maximum intensity estimated using the conventional B-mode imager varies considerably, as shown in Figure 5. Both the FDI imager with the Capon method using large diagonal loading and that using Toeplitz frequency averaging are effective in compensating echo intensity of the conventional FDI imager with the Capon method. The average estimation intensity error on the log scale using a conventional B-mode imager, the conventional FDI imager with the Capon method, that using large diagonal loading, and that using Toeplitz frequency averaging are 0.42, -8.0 , -1.0 and 0.15 dB of the true intensity, respectively, where their standard deviations are 2.7, 3.7, 2.5 and 1.8 dB. This result indicates the efficiency of the proposed method in the echo intensity estimation.

Figure 6 shows the ultrasound images of a fixed swine femoral artery in vitro. The employment of the compensation based on Toeplitz frequency averaging improves the continuity in the lateral direction with no deterioration in the range resolution. The proposed method also succeeded to acquire a normal human carotid artery in vivo with high range-resolution, as shown in Figure 7. These results indicate that the proposed method will be suitable to acquire a high-range-resolution image of human carotid artery. The proposed method requires

0.18 s/frame on a Desktop PC with a single CPU for a ROI of 1×2 cm.

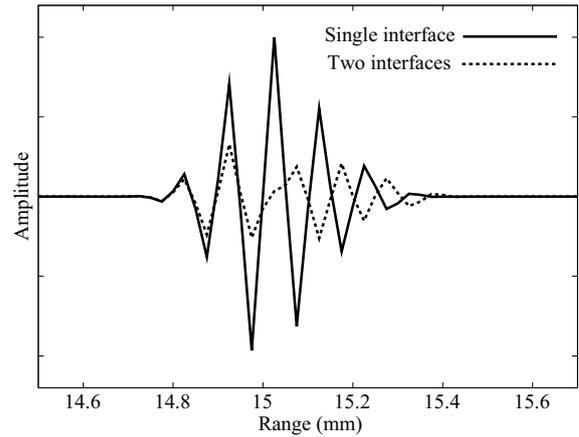


Figure 3. Echo waveforms returned from a single interface and from two interfaces. The echo from two interfaces is constructed from the echo from a single interface, where the interface distance is 0.05 mm.

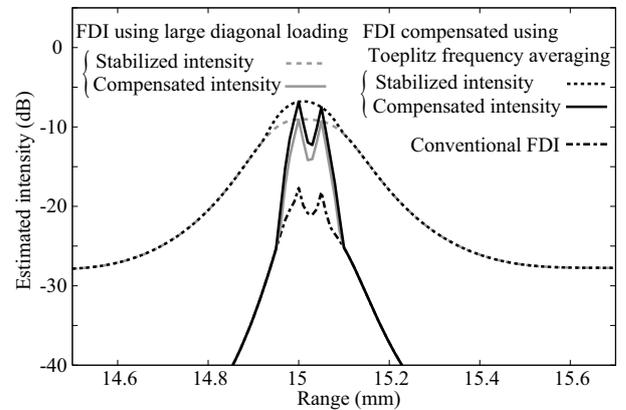


Figure 4. Echo intensity profiles estimated by a conventional FDI imager with the Capon method, that compensated using large diagonal loading, and that compensated using Toeplitz frequency averaging. Two horizontal interfaces exist in a ROI, where the interface distance is 0.05 mm.

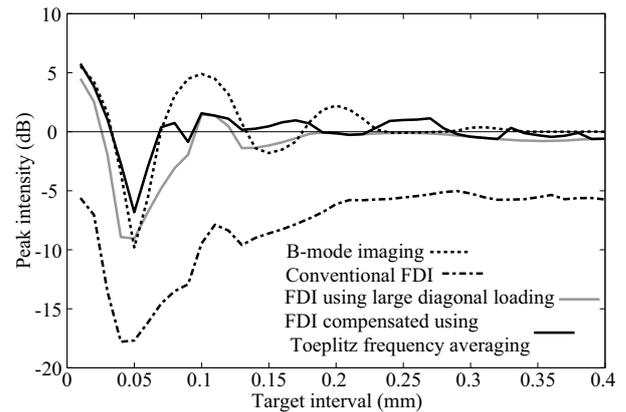


Figure 5. Maximum estimated intensity of a conventional FDI imager with the Capon method, that compensated using large diagonal loading, and that compensated using Toeplitz frequency averaging. Two horizontal interfaces exist in a ROI, where the interface distance is from 0.01 to 0.40 mm.

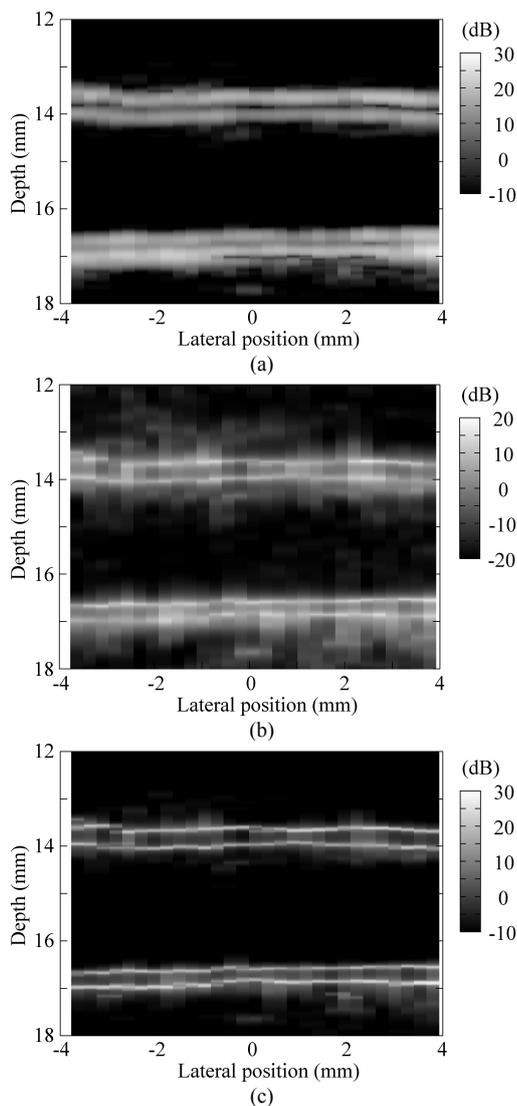


Figure 6. Ultrasound images of a fixed swine femoral artery embedded in gelatin acquired (a) by a conventional B-mode imager, (b) by the conventional FDI imager with the Capon method, and (c) by the FDI imager with the Capon method using Toeplitz frequency averaging.

IV. CONCLUSION

We propose a compensation method to improve the estimation accuracy in echo intensity acquired by the high-range-resolution ultrasound imaging method based on FDI. The proposed method has the spatial resolution of 0.05 mm with the average estimation intensity error of 0.15 dB on the log scale, where we use an ultrasound pulse of 7.5 MHz center frequency. The proposed method succeeded to acquire high-range-resolution images of a swine femoral artery in vitro and a human carotid artery in vivo with good continuity in the lateral direction, requiring 0.18 s/frame for a ROI of 1×2 cm using a Desktop PC with a single CPU. These results indicate the high potential of the proposed method to improve the performance of vascular ultrasound.

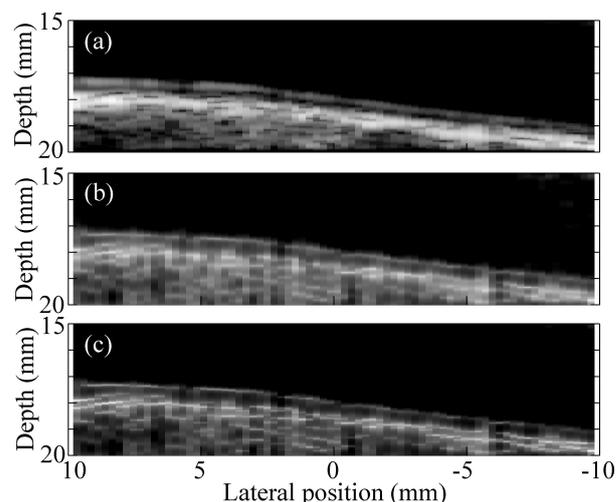


Figure 7. Ultrasound images of a normal living human-carotid-artery in vivo at the posterior wall acquired (a) by a conventional B-mode imager, (b) by the conventional FDI imager with the Capon method, and (c) by the FDI imager with the Capon method using Toeplitz frequency averaging.

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