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Plane Wave Beamforming Using Each Frequency with Adaptive Weight

適応的な重みづけによって周波数成分を合成する平面波ビームフォーミング

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1. Introduction

We have proposed a simultaneous optimization method for frequency and spatial compounds using plane waves [1], which is an expansion of DCR-MVDR (Data Compounded on Receive-Minimum Variance Distortionless Response) proposed in [2] as an optimization of plane-wave compounding. We call this method FPWC-MVDR (Frequency and Plane Wave Compounding-MVDR). In this method, the plane wave transmission direction is set to multiple angles, and transmission with different frequencies is performed a plurality of times in each direction. Then, for each of the frequency and the angle, an appropriate weight is determined by the minimum variance criterion, and the beam forming is performed. This method enables high resolution imaging in both the range direction and the lateral direction. However, multiple transmissions with different frequencies using a single probe only end up using the effective band of that probe separately.

Therefore, in this study, we improve the method that the transmission is performed once by using the effective band of the probe, and the obtained received echo is divided into multiple frequency bands. To confirm that changing multi-frequency transmission to wideband simultaneous transmission and frequency division processing does not degrade the performance of FPWC-MVDR, transmission is limited to the front direction. That is, no spatial compound is performed. We evaluate the proposed method by simulation under ideal conditions.

2. Method

Similar to FPWC-MVDR, it is easy to control the used band and the FM chirp pulse that is effective from the viewpoint of SNR is used as the transmission signal. An FM chirp pulse is sent using the entire effective band of the probe, and L randomly selected narrowband components are extracted from the received signal. The value corresponding to the pixel to be imaged is extracted from the j-th band component (IQ signal) of the echo received by the i-th element of the array probe and set as x_{ij}. It is assumed that the phase shift due to the delay process has been compensated.

First, the variance-covariance matrix $\mathbf{R}_F$ for the frequencies required for the frequency weight calculation is estimated. The snapshot vector $\mathbf{s}_i$ is calculated as follows:

$$(s_i)_j = \frac{1}{N-1}\sum_{k=1,k\neq i}^{N} x_{ij}\,, i=1,\cdots,N, j=1,\cdots,L. \quad (1)$$

$\mathbf{R}_F$ is estimated using the snapshot as follows:

$$\hat{\mathbf{R}}_F = \frac{1}{N}\sum_{i=1}^{N}\mathbf{s}_i\mathbf{s}_i^{\mathrm{H}}, \quad (2)$$

where $^{\mathrm{H}}$ is Hermitian transposition. By the minimum variance criterion, the optimal weight vector is obtained as follows:

$$\mathbf{w}_F = \frac{\mathbf{R}_F^{-1}\mathbf{1}_L}{\mathbf{1}_L^{\mathrm{T}}\mathbf{R}_F^{-1}\mathbf{1}_L}, \mathbf{1}_L = [1,\cdots,1]^{\mathrm{T}}. \quad (3)$$

Then, the output of FPWC-MVDR with one wideband transmission y_F is defined as the following equation.

$$y_F = \mathbf{w}_F^{\mathrm{H}}\mathbf{u}, u_j = \sum_{i=1}^{N} x_{ij}. \quad (4)$$

The pixel value can be calculated as $(y_F{}^* y_F)^{1/2}$.

2. Simulation

To verify the effectiveness of the proposed method, we used MATLAB software to build an ideal experimental environment. The beamforming procedure was performed offline on the ultrasound

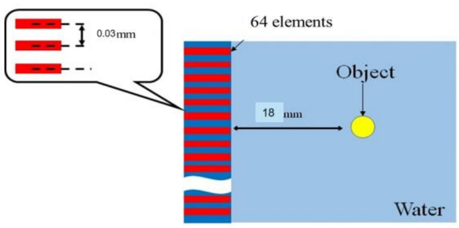

Fig. 1 Experimental setup.

echoes received by the individual transducer elements. In our simulation, the sampling frequency is 800 MHz and the number of sampling points is 30,000.

Figure 1 shows that in this simulation a plane wave was transmitted and the entire array composed of 64 elements received the echo. The element width is 0.04 mm and the pitch is 0.03 mm. Place the target 18 mm from the transducer in the water-filled area. A chirp with a minimum frequency of 5 MHz and a maximum frequency of 11 MHz (center frequency is 8 MHz) was used as the transmission pulse.

Our previous method made multiple transmissions using different band chirps. This method increases the measurement time and reduces the frame rate. Therefore, in this study, a wideband chirp is transmitted only once, the received echo is compressed, and then divided into six bands with a 2 MHz bandwidth whose center frequency is randomly determined. These narrow band components were extracted by a band pass filter using the Hanning window function. Then, we use the six chirp signals for beamforming. In this paper, all observations are treated as analytic signals obtained by quadrature detection of RF signals, that is, IQ (In-phase and Quadrature-phase) signals. Equation 4 is used as a beamformer output with $N = 64$ and $L = 6$.

3. Result and Discussion

Figure 2 illustrates the B-mode images of various methods in dB. Figure 2(d) shows the result of using the optimum frequency weighting based on the single transmission proposed this time. On the other hand, the result of FPWC-MVDR which transmitted and received each of the same 6 narrow bands is shown in Fig. 2(c). By comparing the two, even if the narrowband transmission/reception of 6 times was replaced with the wideband transmission/reception of 1 time, no significant difference was seen in the B-mode image.

Figure 3 shows the amplitude distribution profiles along the range direction and the lateral direction. The profiles of the naïve DAS using an entire frequencies (red line), the profiles of the integration of 6 narrow bands with constant weight (blue line), the profiles of FPWC-MVDR with 6 transmissions (black line) and the profiles of the proposed method (green line) are individually shown in Fig. 3. What is interesting is that FPWC-MVDR, which transmits and receives 6 times, has a lower sidelobe level in the range direction than the proposed method, that is, the method of 1 time wideband transmission.

4. Conclusion and Future Work

We have proposed a method to optimize the frequency compound in one wideband transmission. By comparing the performance with the already proposed FPWC-MVDR based on multiple transmissions, it was confirmed that there is a difference in the side lobe level in the distance direction. In the future, the reason will be clarified and the sidelobe level reduction of this method will be examined.

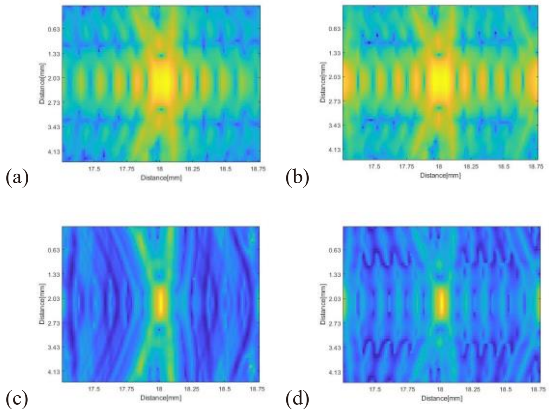

Fig. 2 B-mode images: (a) naive DAS using entire frequencies; (b) integration of 6 narrow bands with constant weight; (c) FPWC-MVDR with 6 transmissions; (d) integration of six narrow bands with optimal weight (proposed method).

5. References

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2. N.Q. Nguyen and R.W. Prager, "A spatial coherence approach to minimum variance beamforming for plane-wave compounding," IEEE Trans. UFFC, vol. 65, no. 4, pp. 522-534, 2018.

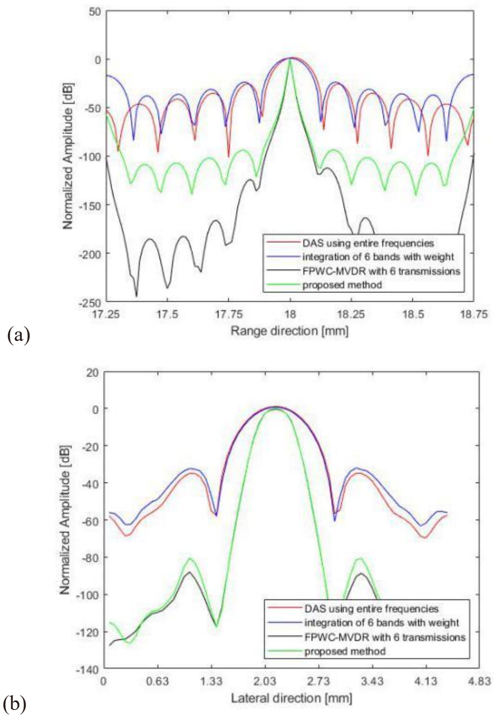

Fig. 3 Amplitude distribution profiles along (a) range direction and (b) lateral direction.