2Pb5-2

Investigation on effects from sub-aperture overlapping ratio for adaptive beamforming

Ryo Nagaoka[1†], Masaaki Omura[1], and Hideyuki Hasegawa[1] ([1]Faculty of Engineering, Univ. of Toyama)

1. Introduction

Minimum variance (MV) adaptive beamforming improves the lateral spatial resolution in a B-mode image compared with a conventional delay and sum (DAS) beamforming[1-3]. However, the computational load of the MV adaptive beamforming is more significant than that of the DAS beamforming because the MV adaptive beamforming needs to calculate the spatial covariance matrix of element signals and its inverse matrix.

We proposed a method for reduction of the computational cost in MV beamforming by dividing a receiving aperture into several sub-apertures. The MV beamformer was applied to the outputs of DAS beamforming applied to the sub-apertures[4]. By doing so, the dimension of the covariance matrix could be reduced from the number of elements in the receiving aperture to the number of sub-apertures. In this reduction method, the sub-apertures were not overlapped. In this study, the effects from the sub-aperture overlapping ratio on the MV adaptive beamforming were investigated by performing a wire phantom experiment.

2. Material and Methods

2. 1 MV adaptive beamforming[1-4]

Let us define the delay-compensated complex signal received at the ith ultrasonic element as $s_d(z,i)$. The delay time is calculated from the geometric relationship between the positions of the ultrasonic element and focal position (x,z). Also, the vector $\boldsymbol{s}(z)$ consisting of the complex signals $s_d(z,i)$ is expressed as

$$\boldsymbol{s}(z) = [s_d(z,0) \quad \cdots \quad s_d(z,i) \quad \cdots \quad s_d(z,L-1)], \qquad (1)$$

where L denotes the total number of the ultrasonic elements. The output $r_{ds}(x,z)$ of the DAS beamformer is expressed as follows:

$$r_{ds}(x,z) = \boldsymbol{w}_{ds}^H(x,z)\boldsymbol{s}(z), \qquad (2)$$

where H is the Hermitian operator. Also, the vector $\boldsymbol{w}_{ds}$ is weight values for the element signals in the DAS beamforming. The MV beamformer determines the weight vector $\boldsymbol{w}_{mv}$ by minimizing the variance of the output $r_{mv}(x,z)$ which is expressed as the following equation under a condition of $\boldsymbol{w}_{mv}^H\boldsymbol{a} = 1$.

$$r_{mv}(x,z) = \boldsymbol{w}_{mv}^H(x,z)\boldsymbol{s}(z). \qquad (3)$$

The vector $\boldsymbol{a}$ is a steering vector. This problem can be expressed as the following minimization problem:

$$\min_{\boldsymbol{w}_{mv}} \boldsymbol{w}_{mv}^H\boldsymbol{R}\boldsymbol{w}_{mv}\text{, subject to } \boldsymbol{w}_{mv}^H\boldsymbol{a} = 1, \qquad (4)$$

where $\boldsymbol{R}$ is the spatial covariance matrix and is calculated using the the vector $\boldsymbol{s}(z)$ as

$$\boldsymbol{R} = \mathrm{E}[\boldsymbol{s}(z)\boldsymbol{s}^{\boldsymbol{H}}(z)]. \qquad (5)$$

The solution of Eq. (4) can be obtained as

$$\boldsymbol{w}_{mv}(x,z) = \frac{\boldsymbol{R}^{-1}\boldsymbol{a}}{\boldsymbol{a}^H\boldsymbol{R}^{-1}\boldsymbol{a}}. \qquad (6)$$

Meanwhile, in the DAS beamforming without apodization in reception, i.e., a rectangular apodization, the weight vector $\boldsymbol{w}_{ds}$ is expressed as

$$\boldsymbol{w}_{mv}(x,z) = \frac{\boldsymbol{I}^{-1}\boldsymbol{a}}{\boldsymbol{a}^H\boldsymbol{I}^{-1}\boldsymbol{a}}, \qquad (7)$$

where the matrix $\boldsymbol{I}$ is the identity matrix. By comparing Eq. (6) with Eq. (7), as the spatial covariance matrix $\boldsymbol{R}$ is needed to be calculated, the computational load of the MV adaptive beamforming is much heavier than that of the conventional DAS beamforming. In the previous paper[4], the reduction of the computational load was achieved by dividing the receiving apertures into several sub-apertures and employing the output of the DAS beamformer at each sub-aperture for the calculation of the spatial covariance matrix $\boldsymbol{R}'$ instead of the vector $\boldsymbol{s}(z)$. The vector $\boldsymbol{s}_{j,k}(z)$ at the jth sub-aperture is defined as

$$\boldsymbol{s}_{j,k}(z) = [s_d(z,j) \quad s_d(z,j+1) \quad \cdots \quad s_d(z,j+K-1)], \qquad (8)$$

where K denotes the total number of the sub-apertures. Also, the variable j can be expressed as follows:

$$j = 1 + k \times m, m = 0,1,2,\cdots \qquad (9)$$

where k denotes the difference in the lateral positions of the adjacent sub-apertures in elements. Then, the output of the DAS beamformer without apodization in reception is calculated as

$$r_{j,k}(z) = \boldsymbol{w'}_{ds}^H\boldsymbol{s}_{j,k}(z), \qquad (10)$$

where a vector $\boldsymbol{w'}_{ds}$ is weight values for the sub-aperture in the DAS beamforming. These outputs are arranged as a vector $\boldsymbol{s}'_k(z)$ as

$$\boldsymbol{s}'_k(z) = [r_{0,k}(z) \quad r_{1,k}(z) \quad \cdots \quad r_{L-K,k}(z)], \qquad (11)$$

and the spatial covariance matrix $\boldsymbol{R}'_k$ is calculated using the the vector $\boldsymbol{s}'_k(z)$ as

$$\boldsymbol{R}'_k = \mathrm{E}\left[\boldsymbol{s}'_k(z)\boldsymbol{s}'^H_k(z)\right]. \qquad (12)$$

Using the modified covariance matrix $\boldsymbol{R}'_k$ instead

nryo@eng.u-toyama.ac.jp

of $\boldsymbol{R}$, the computational load of the MV beamforming can be reduced. As described above, the computational load can be more reduced by increasing the sub-aperture step k.

2. 2 Phantom experiments

In this study, full widths at half maximum (FWHM), which was defined as lateral resolution, were compared among four beamforming methods: DAS and MV beamforming methods and proposed MV beamforming methods with sub-aperture steps of 1 and 30. A wire phantom (model 040GSE, CIRS Inc.) was used and echo signals from the wire phantom were measured using a programmable ultrasonic data acquisition system (RSYS-0011, Microsonic Co., Ltd.). A linear array probe with a center frequency of 7 MHz was used, and the sampling frequency was set at 31.25 MHz for the acquisition. The phantom measurement was performed using a conventional line-by-line sequence with a transmit focal depth of 20 mm. A F-number was fixed at 1 for the beamforming in the reception.

3. Results and Discussions

Fig. 1 shows the B-mode images of the wire phantom reconstructed by the DAS (a) and MV (b) beamforming methods and proposed MV beamforming methods with sub-aperture steps of 1 (c) and 30 (d), respectively. The red arrows indicate the wire targets. **Fig. 2** shows the comparison of the lateral resolutions obtained from the wire targets of the B-mode images shown in Fig. 1. As shown in Fig. 2, the lateral resolutions of the wire targets in a shallow area (depths: 7.5 mm and 12 mm) were improved using the proposed method with a line shift of 1 in comparison with the conventional MV adaptive beamforming.

4. Conclusion

In this paper, the effects from the sub-aperture overlapping ratio on the MV adaptive beamforming were investigated by performing the wire phantom experiment. The lateral resolutions were compared among four beamforming methods: the DAS and MV beamforming methods and proposed MV beamforming methods with sub-aperture steps of 1 and 30. Consequently, the lateral resolutions of the wire targets in the shallow area were improved using the proposed method with a sub-aperture step of 1 in comparison with the conventional MV adaptive beamforming.

We will investigate the relationship between the improvement of the lateral resolutions and the sub-aperture overlapping ratio in more detail.

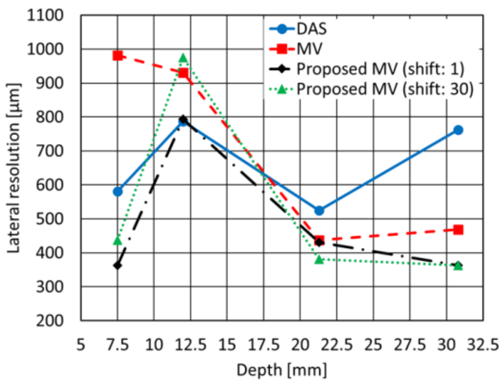

Fig. 2 Comparison of the lateral resolutions obtained from the wire targets.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 22K18205.

References

1. J.-F. Synnevåg, A. Austeng and S. Holm: IEEE Trans. Ultrason. Ferrorelect. Freq. Contr. **54** (2007) 1606.
2. J.-F. Synnevåg, A. Austeng and S. Holm: IEEE Trans. Ultrason. Ferrorelect. Freq. Contr. **56** (2009) 1868.
3. B. M. Asl and A. Mahloojifar: IEEE Trans. Ultrason. Ferrorelect. Freq. Contr. **56** (2009) 1923.
4. H. Hasegawa and H. Kanai: IEEE Trans. Ultrason. Ferrorelect. Freq. Contr. **62** (2015) 511.

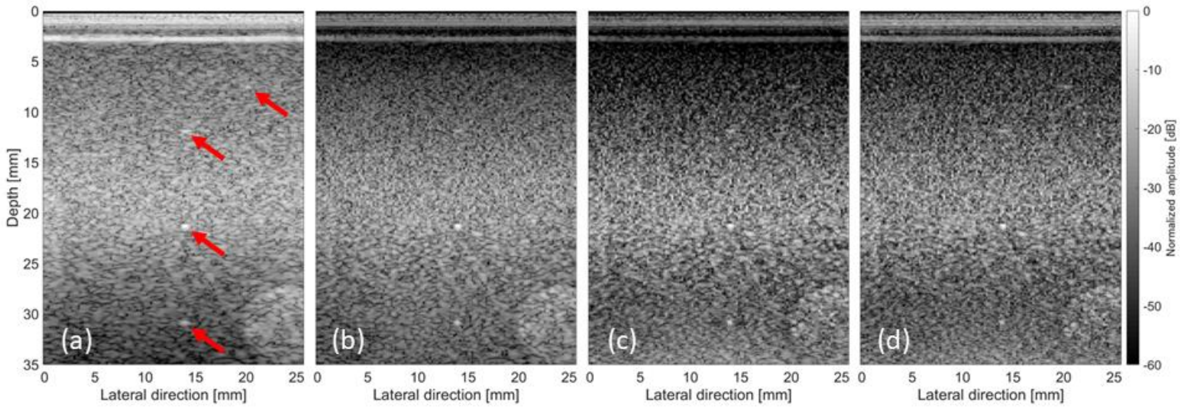

Fig. 1 B-mode images of the wire phantom reconstructed by the DAS (a) and MV (b) beamforming methods and proposed MV beamforming methods with sub-aperture steps of 1 (c) and 30 (d).