STABILIZATION TECHNIQUES FOR HIGH RESOLUTION ULTRASOUND IMAGING USING BEAMSPACE CAPON METHOD

Shigeaki Okumura, Hirofumi Taki, Toru Sato

Graduate School of Informatics, Kyoto University, Kyoto, Japan
sokumura@sato-lab.0t0.jp

ABSTRACT

Several adaptive beamforming imagers have been proposed to improve the spatial resolution of medical ultrasound imaging. These imagers employ spatial averaging technique and diagonal loading technique to suppress correlated interferences and to acquire robustness, respectively. In this study, we propose the technique that selects the optimum size for spatial averaging with respect to the measurement depth. We employ a small diagonal loading factor of –40 dB to avoid the deterioration in image quality. In a simulation study, the proposed method succeeded to improve the image quality compared to a conventional beamspace Capon method. The sidelobe level and the –6 dB beam width in the proposed method were –26 dB and 0.27 mm, respectively, where those in the conventional method were –16 dB and 0.40 mm, respectively. The proposed method succeeded to depict the higher resolution image than that of the conventional method.

Index Terms— Ultrasound imaging, Ultrasonography, Adaptive beamforming, beamspace, Capon method.

1. INTRODUCTION

Delay-and-sum (DAS) beamformer have been employed for the standard technique in medical ultrasound imaging. Because the improvement of spatial resolution in medical ultrasound imaging may achieve the progress in medical diagnoses, the improvement of the spatial resolution in medical ultrasound imaging is highly desirable. Adaptive beamforming techniques have been proposed for the high resolution imaging, and the Capon beamformer is one of the most common adaptive beamforming techniques [1, 2]. The strategy of this method is minimizing the output power under the constraint that the response of a desired signal is constant. Beamspace (BS) method has been reported to decrease the computational complexity in the Capon beamformer [3].

In medical ultrasound imaging, a desired signal and interferences are correlated significantly. Because the Capon beamformer assumes that the desired signal has no correlations to interferences, the spatial averaging technique or the frequency averaging technique has been employed to suppress the cross-correlation between the desired signal and interferences [4, 5]. The spatial averaging technique averages sub-arrays of the covariance matrix along the diagonal direction. The employment of a large size for spatial averaging or frequency averaging suppresses the cross-correlation between the desired signal and interferences effectively at the cost of the spatial resolution of the imager. A previous study has reported the proper size for frequency averaging [6]; however, no study reports a sufficient investigation into the proper size for spatial averaging.

The diagonal loading technique also has been employed to acquire robustness in ultrasound imaging using an adaptive beamforming technique [4, 7, 8]. The technique adds a constant value to the diagonal of the covariance matrix. When a large constant value is employed in diagonal loading, the covariance matrix approaches to the product of the constant value and the identity matrix. Therefore, the employment of a large constant value for diagonal loading is equivalent to the employment of a weight that is close to the DAS beamformer. Consequently, the employment of the diagonal loading acquires robustness at the cost of the spatial resolution.

Both spatial averaging and diagonal loading directly affect the imaging quality. However, the size for spatial averaging has not been optimized and most studies have employed relatively large constant value for diagonal loading. In this study, we investigate the residue of the correlation after spatial averaging technique theoretically and propose the technique to optimize the size for spatial averaging with respect to the measurement depth, where the conventional method employs constant size for spatial averaging. We apply the proposed technique to BS Capon method with small diagonal loading, and evaluate the performance of the proposed method in a simulation study.

2. MATERIALS AND METHODS

2.1. BS Capon method

BS method is one of the common strategies to decrease the computational complexity of the adaptive beamforming technique [3, 9]. In this study, we suppose the employment of a linear array composed of M element whose pitch is half of the wavelength at center frequency λ_c. First, the time-delay process is applied to received signals. This process enables one of the beams used by the BS method to focus at the measurement point.

The BS method forms the orthogonal beams by multiplying signal vector after time-delay process $\mathbf{y}(t)$ with selected Butler matrix $\mathbf{B}_s$, as shown in Fig. 1.

$$\mathbf{y}_{BS}(t) = \mathbf{B}_S \mathbf{y}(t), \quad (1)$$

$$\mathbf{B}_S = [\mathbf{b}_{-(L-1)/2} \cdots \ \mathbf{b}_0 \ \ \cdots \ \ \mathbf{b}_{(L-1)/2}]^T, \quad (2)$$

$$[\mathbf{b}_q]_p = \exp(j2\pi pq/M)/\sqrt{M}, \quad (3)$$

where $\mathbf{y}_{BS}(t)$ is an output of selected Butler matrix, $[]^T$ is the transpose, and L is the number of the selected beams. We assume M is an even number. Because ultrasound imaging is one of the active systems, the spatial distribution of the transmit energy is a priori information determined by the transmit beam. Therefore, we can select a few useful beams that are close to the transmit beam. In this study, we set L = 3 [3]. The beam using $\mathbf{b}_0$ focuses at the measurement point.

The Capon method works when there are no correlations between the desired signal and interferences. The spatial averaging is employed to suppress the correlation. The covariance matrix of $\mathbf{y}(t)$ after spatial averaging is given by the following formula:

$$[\mathbf{R}_A]_{p,q} = \sum_{n=1}^{N} y_{n+p-1}(t) y^*_{n+q-1}(t)/N, \quad (4)$$

where $y_m(t)$ is the received signal at the m-th element, N is the size for spatial averaging, and the size of $\mathbf{R}_A$ is $N_{ave} = M - N + 1$. In this study, we call N_{ave} as the sub-array size.

The BS Capon method then computes the optimum weighting by solving the follows:

$$\min_{\mathbf{W}_{BS}} \left(P_{out} = \mathbf{W}_{BS}^H \mathbf{R}_{ABS} \mathbf{W}_{BS}/2 \right) \text{subject to } \mathbf{W}_{BS}\mathbf{e}_1 = 1, (6)$$

$$\mathbf{R}_{ABS} = \mathbf{B}_S \mathbf{R}_A \mathbf{B}_S^H, \quad (7)$$

$$\mathbf{e}_1 = \mathbf{B}_S [1 \ \cdots \ 1]^T, \quad (8)$$

where P_{out} is output power of the BS Capon, $\mathbf{W}_{BS}$ is the optimum weight vector, $\mathbf{R}_{ABS}$ is the beam selected covariance matrix. Here, $\mathbf{W}_{BS}$ is expressed as follows:

$$\mathbf{W}_{BS} = \frac{(\mathbf{R}_{ABS} + \eta \,\text{trace}\{\mathbf{R}_{ABS}\}\mathbf{I}/N_{ave})^{-1}\mathbf{e}_1}{\mathbf{e}_1^T(\mathbf{R}_{ABS} + \eta \,\text{trace}\{\mathbf{R}_{ABS}\}\mathbf{I}/N_{ave})^{-1}\mathbf{e}_1}, \quad (9)$$

where η is a diagonal loading factor to acquire a numerical stability and $\mathbf{I}$ is an identity matrix.

2.2. Optimization of the size for spatial averaging

Spatial averaging technique expressed by Eq.(4) is effective to suppress the cross-correlation between the desired signal and the interferences. The large averaging size for the spatial averaging can decrease the correlations better than the small size, however, substantially available elements for imaging and the spatial resolution of image are decreased. Because the optimum size for spatial averaging should depend on the target depth, the employment of the proper size for spatial averaging at each measurement depth may be important to acquire the high-quality images. Therefore, we select the optimum size for spatial averaging with respect to the measurement depth.

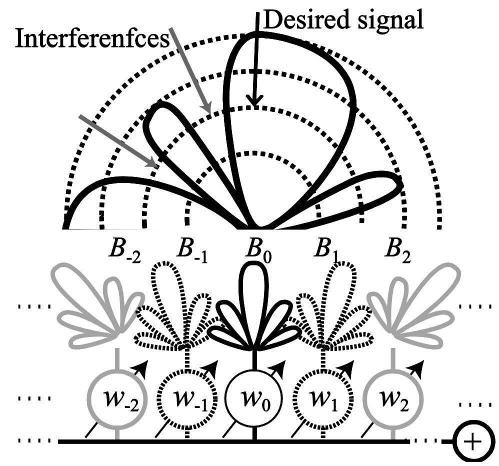

Fig 1. Schematic of a BS Capon beamformer.

When the lateral resolution of d_{min} is required, the proposed method should depict two targets separately under the condition that the difference of their arrival directions is larger than θ_i:

$$\theta_i(z) = \tan^{-1}(d_{min}/z), \quad (10)$$

where z is the axial depth. For simplicity, we suppose that there are a desired signal $s(t)$ and an interference $c(t)$. When the arrival-direction difference is equal to θ_i, the received signal at m-th element is approximated to the following formulae:

$$y_m(t) \simeq s(t) + c(t)\exp(j\phi_m(z)), \quad (11)$$

$$\phi_m(z) = k_c d_e \{m - (M+1)/2\} \sin\theta_i(z), \quad (12)$$

where d_e is an element pitch and k_c is a wave number at the center frequency. Then, Eq.(4) is rewritten as follows[10]:

$$[\mathbf{R}_A]_{p,q} = P_S + P_I \exp\{jk_c d_e (p-q)\sin\theta_i(z)\} + \xi(\lambda_c, N, z)\{\mu\rho(p,z) + \mu^*\rho^*(q,z)\}, \quad (13)$$

where $$\mu = E[c(t)s^*(t)], \quad (14)$$

$$\rho(p,z) = \exp\{jk_c d_e (p - (N_{ave}+1)/2)\sin\theta_i(z)\}, \quad (15)$$

$$\xi(\lambda_c, N, z) = \text{sinc}\{Nk_c d_e \sin\theta_i(z)/2\}/N, \quad (16)$$

where P_S is the power of the desired signal and P_I is the power of interferences. As shown in Eq.(13), the correlation suppression performance of the spatial averaging is expressed by $\xi(\lambda_c, N, z)$.

Typically, the medical ultrasound system employs a wideband signal. Because the investigation shown in Eq.(16) takes account of only the center-frequency component, we modified Eq.(16) to apply the investigation to the medical ultrasound imager using a wideband signal.

$$\xi'(N,z) = \underset{\lambda}{E}[P(\lambda)\xi(\lambda,N,z)], \qquad (17)$$

where λ is a wave length, $P(\lambda)$ is the power spectrum used in the ultrasound imager. We select the minimum size of spatial averaging N that satisfies the constrain $\xi' < \xi'_{th}$, where ξ'_{th} is a constant.

When the correlation between the desired signal and the interferences remains after the spatial averaging, the Capon method may require a large diagonal loading to acquire robustness. In contrast, the employment of the optimum size for spatial averaging may effectively suppress the correlation between the desired signal and interferences. Thus, we employ small diagonal loading factor to maintain the spatial resolution of the Capon method.

2.3. Simulation setting

In the simulation study, we used Field II simulation package [11, 12]. We used a 128-element linear array with the 96-element active array. The transmit focus depth was 50 mm, the center frequency was 4.0 MHz, the bandwidth of the signal was 2.0 MHz, the pitch of probe was $\lambda_c/2$, the required lateral resolution d_{min} was 1.5 mm and ξ'_{th} was 0.1. The point targets were placed with the lateral and depth intervals of 1.5 mm and 4.0 mm, respectively. The imaging depth was from 40 mm to 62 mm. We ignored the effect of the noise and the images were acquired by a trial.

To evaluate our proposed method, we compared three imaging techniques; a conventional DAS beamformer, a conventional BS Capon method, and the BS Capon with the proposed method. The sub-array size N_{ave} and diagonal factor η of the conventional BS Capon method were 32 and –20 dB, respectively [3]. In the BS Capon method with the proposed method, N_{ave} ranged from 24 to 50 for the measurement depth from 40 mm to 62 mm, and η was –40 dB.

We evaluate the proposed method using three indicators; the sidelobe level, the –6 dB beam width, and the estimation error in intensity. The sidelobe level was calculated by the intensity at the lateral distance of 0 mm normalized by the peak intensity at the same depth. The estimation error in intensity was calculated by the difference between the estimated intensity and the estimated intensity using a DAS method. In the evaluation, we averaged these indicators at the depth the targets exited.

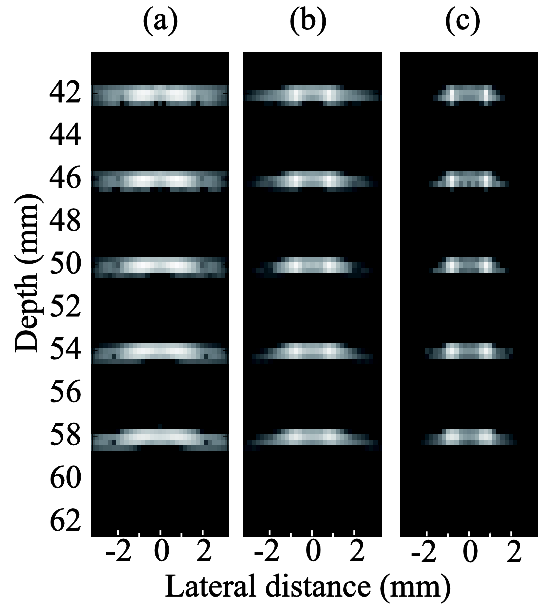

Fig. 2. B-mode images of point targets using (a) a DAS method, (b) a conventional BS Capon with the sub-array size of 32 elements and a diagonal loading factor of –20 dB, and (c) a BS Capon method with the proposed technique and diagonal loading factor of –40 dB.The dinamic range is 60 dB. Target depths were 42 mm, 46 mm, 50 mm, 54 mm, and 58 mm.

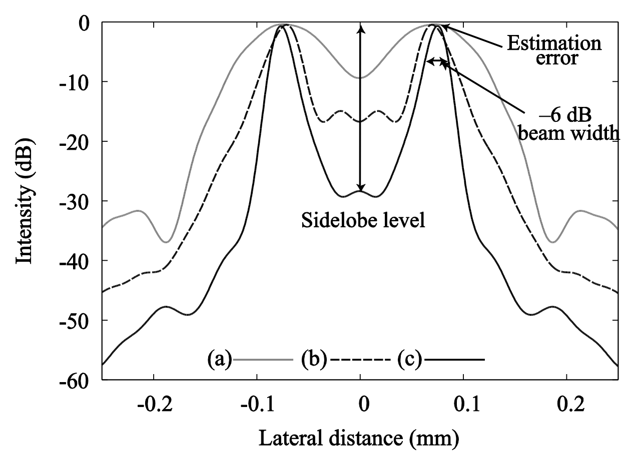

Fig. 3. Cross-sectional images at a 50 mm depth using (a) a DAS method, (b) a conventional BS Capon with sub-array size of 32 element and diagonal loading factor of –20 dB, and (c) the BS Capon method with proposed method.

3. RESULTS

Fig. 2 shows the images acquired by three methods. The dynamic range of the figure is 60 dB. Fig. 3 is a cross-section view of Fig. 2 at the depth of 50 mm. The proposed method succeeded to depict the targets clearly compared with a DAS method and a conventional BS Capon method.

The performances of the three methods are shown in Table 1. Each value is calculated by averaging the results at five depths, 42, 46, 50, 54, and 58 mm. The two BS Capon methods had lower sidelobe level and narrower beam width compared with a DAS method. The sidelobe level of the BS Capon with the proposed method was 10 dB lower than that of a conventional BS Capon method. The –6 dB beam width of the proposed method was 0.013 mm narrower than that of the conventional BS Capon method.

Table 1. Performance of (a) a DAS method, (b) a conventional BS Capon with sub-array size of 32 element and diagonal loading factor of –20 dB, and (c) the BS Capon method with proposed method. Each value is calculated by averaging the results at five depths, 42, 46, 50, 53 and 58 mm.

	Sidelobe level (dB)	–6 dB beam width (mm)	Estimation error (dB)
(a)	–9.0	0.95	0
(b)	–16	0.40	0.32
(c)	–26	0.27	0.75

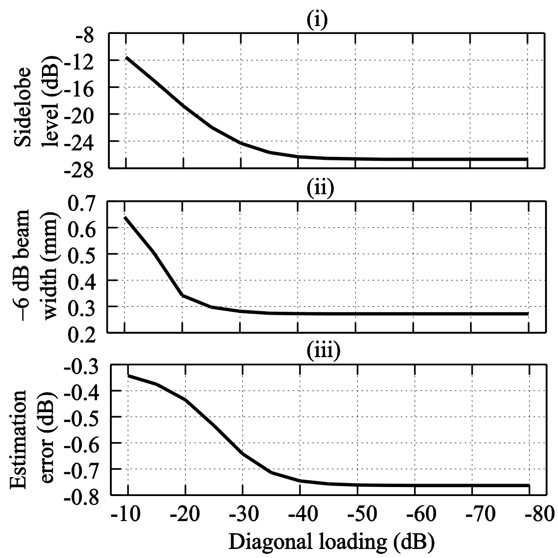

Fig. 4. (i) Sidelobe level, (ii) –6 dB beam width, and (iii) estimation error in intensity using proposed method, where the diagonal loading factor was ranges from –10 dB to –80 dB.

Fig. 4 shows the performance of the proposed method using η from –10 to –80 dB. When η ranged from –10 dB to –40 dB, the sidelobe level and –6 dB beam width improved to –26 dB and 0.27 mm, respectively. Contrary, there was a slight increase in the intensity estimation error. This result indicates that the proposed optimization of the size for spatial averaging was reasonable, and that the employment of a small diagonal loading is suitable when the proper size for spatial averaging is employed.

4. CONCLUSIONS

To improve the image quality of medical ultrasound imaging using the adaptive beamforming technique, we proposed the method to select the optimum size for spatial averaging with respect to the measurement depth. In addition, we employed a small diagonal loading factor of –40 dB to maintain the spatial resolution of the Capon method. In a simulation study, the conventional DAS method had the sidelobe level of –9.0 dB and –6dB beam width of 0.95 mm with accurate estimation in intensity. Compared to the DAS method, the proposed method had the sidelobe level of –26 dB, the –6 dB beam width of 0.27 mm, and the estimation error in intensity of 0.75 dB, where those of conventional BS Capon method were –16 dB, 0.40 mm, and 0.32 dB, respectively. The proposed method had the lowest sidelobe level and narrowest beam width at the cost of a slight deterioration of the estimation error in intensity. According to these results, the proposed method succeeded to depict the higher resolution image. Future work should include the experimental studies and the additional computational reduction technique for clinical use.

5. ACKNOWLEDGEMENT

This work was partly supported by the Innovative Techno-Hub for Integrated Medical Bio-imaging Project of the Special Coordination Funds for Promoting Science and Technology, from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan, and by MEXT/JSPS KAKENHI Grant Number 25249057.

6. REFERENCES

[1] J. Capon, “High-resolution frequency-wavenumber spectrum analysis,” *Proc. IEEE*, vol. 58, no. 8, pp. 1408–1418, Aug. 1969.

[2] O. L. Frost, “An algorithm for linearly constrained adaptive array processing,” *Proc. IEEE*, vol. 60, no. 8, pp. 926–935, Aug. 1972.

[3] C. C. Nilsen and I. Hafizovic, “Beamspace adaptive beamforming for ultrasound imaging,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 56, no. 10, pp. 2187-2197, Oct. 2009.

[4] H. Taki, K. Taki, T. Sakamoto, M. Yamakawa, T. Shiina, M. Kudo, and T. Sato, “High range resolution ultrasonographic vascular imaging using frequency domain interferometry with the Capon method,” *IEEE Trans. Med. Imaging*, vol. 31, no. 2, pp. 417-429, Feb. 2012.

[5] J.-F. Synnevåg, A. Austeng, and S. Holm, “Adaptive Beamforming applied to medical ultrasound imaging,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 54, no. 8, pp. 1606-1613, Aug. 2007.

[6] H. Taki, T. Sakamoto, M. Yamakawa, T. Shiina, and T. Sato, “High resolution ultrasound imaging using frequency domain interferometry -suppression of interference using adaptive frequency averaging-,” *IEEJ Trans. Electron. Inf. Syst*., vol. 132, no. 10, pp. 1552-1557, Oct. 2012.

[7] B. M. Asl and A. Mahloojifar, “A low-complexity adaptive beamformer for ultrasound imaging using structured covariance matrix,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 59, no. 4, pp. 660-667, Apr. 2012.

[8] A. C. Jensen and A. Austeng, “An approach to multibeam covariance matrices for adaptive beamforming in ultrasonography,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 59, no. 6, pp. 1139-1148, June 2012.

[9] H. Moody, “The systematic design of the Butler matrix,” *IEEE Trans. Antennas Propag*., vol.12, no. 6, pp. 786-788, Nov. 1964.

[10] K. Takao and N. Kikuma, “An adaptive array utilizing an Adaptive spatial averaging technique for multipath environments,” *IEEE Trans. Antennas Propag*., vol. 35, no. 12, pp. 1389-1396, Dec. 1987

[11] J. A. Jensen, “Field: A program for simulating ultrasound systems,” *Med. Biol. Eng. Comput.*, vol. 34, suppl. 1, pt. 1, pp. 351-353, 1996.

[12] J. A. Jensen and N. B. Svendsen, “Calculation of pressure fields from arbitrarily shaped, apodized, and excited ultrasound transducers,” *IEEE Trans. Ultrason., Ferroelec., Freq. Contr.*, vol. 39, no. 2, pp. 262–267, Mar. 1992.