2P5-9

Super-Resolution Ultrasound Imaging Based on Change of Carrier Frequency and Synthetic Aperture System

搬送波周波数の変更と合成開口システムに基づく超解像超音波イメージング

Norio Tagawa†, Jing Zhu, Nguyen Chi Hai, Yihsin Ho and Kan Okubo (Tokyo Metropolitan Univ.)
田川 憲男†, 祝婧, ハイ　グエンチ, 何 宜欣 , 大久保 寛　(首都大学東京)

1. Introduction

In recent years there has been an increase in cardiovascular diseases such as myocardial infarction and it is important to diagnose atherosclerosis at an early stage. To accurately evaluate this disease with ultrasound, high frame rate and high resolution imaging is required.

Synthetic Aperture (SA) imaging method has been applied widely in diagnosis of a cardiovascular disease for its various modifications of high-frame performance. Additionally, in a SA system, a high-resolution image can be reconstructed from multiple low-resolution images obtained from multiple sub-apertures.

Furthermore, we proposed the Super resolution FM-Chirp correlation Method (SCM) based on the MUSIC (Multiple SIgnal Classification) algorithm introduced by Schmidt [1], which was used for electro-magnetic wave processing at the begining. Nowadays, it plays an important role in acoustic applications has advantages over other methods in resolution improvement.

In order to perform further high-resolution ultrasonic imaging, we proposed an extension scheme of the SCM to the SA system called the SA-SCM [2]. In this study, first of all, by reversing the processing of the SCM and the SA in the SA-SCM, another method called SCM-SA can be constructed. Next, in order to further improve the resolution, a method is constructed to execute the SA process with the SCM result obtained for each echo received by each transducer as a weight. This method is called SCM–weighted-SA. Those methods based on the MUSIC and the SA are expected to have better resolution performance than the naive SA, which is evaluated by experiments.

2. Outline of SCM

The SCM can execute a super-resolution imaging by utilizing the phase information of the carrier waves after transmitting the pulse having different carrier frequencies. We obtain an analytic signal z consisting of an in-phase (I) component and a quadrature (Q) component from a received echo to calculate the covariance matrix R=E$\{zz^H\}$. From the eigenvalue equation

$$Re_i = \lambda_i e_i \quad : i = 1,2,\ldots,M, \tag{1}$$

the eigenvalues λ_i and the corresponding eigenvectors e_i (i=1,2,…, M) can be estimated, where M indicates the number of temporal sampling of the echo. To estimate R by which different scatterers are distinguished, we define the following estimate using the analytic echo set $\{z(j)\}$, in which each $z(j)$ is measured by transmitting the pulse having different carrier frequencies.

$$\hat{R} = \frac{1}{N}\sum_{j=1}^{N} z(j)z(j)^H. \tag{2}$$

Then, we arrange the M eigenvalues in a descending order, and the first D eigenvalues are much bigger than σ^2 indicating the noise variance and those eigenvectors corresponding to the signal subspace. While the M-D remaining small eigenvalues equal to σ^2 and the corresponding eigenvectors span the noise subspace.

In order to estimate the delay of the reflections of targets, we use a measure of the orthogonality of the steering vectors to $\{e_i\}_{i=D+1}^{M}$. Finally, a super-resolution delay profile $S(\tau)$ based on the MUSIC algorithm can be expressed as

$$S(\tau) = \frac{u(\tau)^H u(\tau)}{\sum_{i=D+1}^{M} \left| u(\tau)^H e_i \right|^2} \tag{3}$$

where $u(\tau)$ denotes the delay profile vector for each delay τ. In actual applications, D should be determined using, for example, AIC or MDL.

3. Experiments

We confirmed the effectiveness of the proposed methods through experiments using RSY0003, Microsonic Co., Ltd., Japan, that is a custom-made ultrasonic scanner at a sampling frequency of 31.25 MHz. A linear array ultrasonic probe at a nominal center frequency of 7.5 MHz, T0-1599, Nihon Dempa Kogyo Co., Ltd., Japan, was also used. The beamforming procedure was performed offline on the ultrasound echoes received by the individual transducer elements using MATLAB software.

Figure.1 shows the experimental setup. In this study, a rectangular wave pulse was transmitted as a diffuse wave by the sub-array consisting of 8 elements placed at the center of the probe, while an echo is received by the whole array consisting of 64 elements. The element pitch of this array is 0.315 mm. A target was located 15 mm away from the transducer in the area filled with water. In the scanning process, 15 pulses with randomly varying the center frequency from 4MHz to 10MHz were transmitted and received.

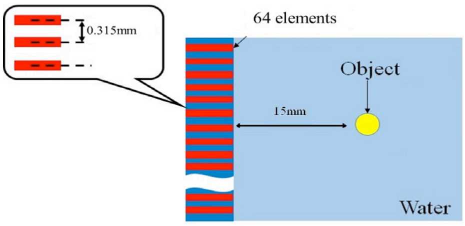

Fig. 1 Experimental setup.

4. Results and Discussion

Figure 2(a)-(d) illustrate the B-mode images of the naive SA, the SA-SCM, the SCM-SA and the SCM-weighted-SA, respectively. By comparing those with the naive SA image, it is considered that the range resolution has been clearly improved.

Figure 2(e) shows the amplitude profiles along the range direction. The SA profiles (black dotted line), the SA-SCM profiles (blue dash-dot line), the SCM-SA profiles (red dashed line) and the SCM-weighted-SA (green line) are also shown individually. All results are normalized and indicate that the range resolution enhancement of the SA-SCM is slightly better than the SCM-SA and the SCM-weighted-SA. In addition, all the associations between the SA and the SCM provide a better range resolution than that of the naive SA.

However, as shown in **Fig. 2**(f), significant discrepancy between the three proposed methods occurs in the azimuth direction. It is easy to see that the SA-SCM has a discontinuity curve while the SCM-SA has a smooth one. It is confirmed that the azimuth resolution of the SCM-SA is good, because the target cannot be clearly detected by the SA-SCM. Furthermore, the SCM-weighted-SA is a more useful method than the others in the azimuth direction. The reason is that, in the SCM-SA, the positive signal obtained by the SCM applied to the echo of each element is used for delayed sum beamforming, so that cancellation by positive and negative signals is less likely to occur. On the other hand, in the SCM-weighted-SA, since delayed sum processing weighted by the SCM signal is applied to the RF echo signal, a sharp signal can be obtained.

As shown in **Table I**, as the SCM processing is required for each line of the image, the SA-SCM imaging takes 4349 seconds. On the other hand, since the SCM processing is applied to each echo

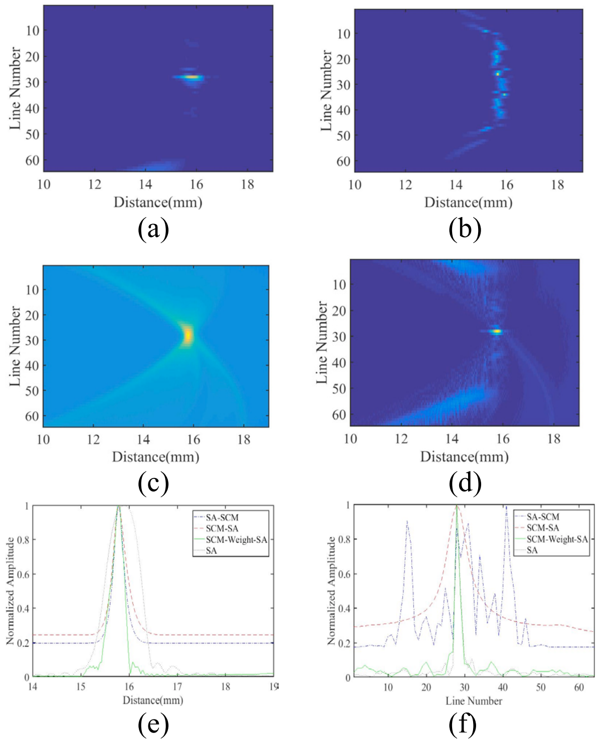

Fig. 2 B-mode images of experiment results: (a) SA; (b) SA-SCM; (c) SCM-SA; (d) SCM-weighted-SA; (e) amplitude profiles along range direction; (f) amplitude profiles along azimuth direction.

Table I Processing time for experimental imaging

Method	SA	SA-SCM	SCM-SA	SCM-weighted-SA
Time (sec.)	32	4349	319	320

received by each element, the number of which is usually smaller than then the number of the lines constituting the image, the processing time of the SCM-SA and the SCM-weighted-SA is very short.

5. Conclusion and Future Work

Through experiments, it is confirmed that the range resolution is improved by adopting the SCM method. In fact, the azimuth resolution of the SCM-weighted-SA is highly improved compared to the SCM-SA. Considering further processing time, SCM-weighted-SA seems to be the most excellent method. In the future study, we investigate the influence of adaptive beamforming on performance instead of delay-and-sum method.

References

1. R.O. Schmidt: IEEE Trans. Antennas and Propagation. **34** (1986) 276.

2. T. Wada, Y. Ho, K.Okubo, N. Tagawa, and Y. Hirose: Physics Procedia, **70** (2015) 1216.