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High-resolution Ultrasound Imaging in Both Range and Lateral Directions Using Subspace Methods

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1. Introduction

Time reversal algorithms are often used in antenna arrays to detect the position of strongly reflecting objects due to the high resolution of the beam focus at the targets. To obtain higher resolution, time reversal algorithms have been used in conjunction with other methods. Devaney[1)] combined time reversal with MUSIC, so that the MUSIC algorithm, which was originally used to detect the direction of arrival of the signal, could form a two-dimensional pseudo-spectrum with peaks at the target location. This method is called TR-MUSIC.

Because TR-MUSIC can detect point-like scattering in homogeneous medium and has a high resolution. The method is also used for ultrasound imaging. Although TR-MUSIC is well known for its super-resolution capability in point scatterer localization, this super-resolution property can be easily corrupted in the presence of noise. In particular, the axial resolution can be greatly affected.

On the other hand, we propose Range-MUSIC (R-MUSIC)[2)], R-MUSIC is based on the MUSIC algorithm and uses the noise subspace obtained by subtracting the signal subspace from the total function space spanned by the echo. This is a method for detecting the position of a scatterer with super-resolution based on the received signal of each element of an array transducer. This method can effectively improve the axial resolution.

Therefore, in this study, to improve the axial resolution while maintaining the lateral resolution of TR-MUSIC, we propose a method that combines R-MUSIC and TR-MUSIC, which improves TR-MUSIC image through the high axial resolution of R-MUSIC. The method takes the profile obtained from R-MUSIC of each element and utilizes the Delay-and-Sum(DAS) method to obtain the luminance value of each pixel , and multiplies it with the luminance value of TR-MUSIC then squares it. We experimentally demonstrate the effectiveness of the method.

2. Method

2.1 Range-MUSIC

R-MUSIC utilizes the principle that the rotation of the echo phase is linearly related to the position of the scatterer, which is faster at higher frequencies. In this paper, R-MUSIC will be calculated in the frequency domain. First, the received signal is extracted in the frequency domain through a band-pass filter into M subbands of the same bandwidth with different frequencies as $\mathbf{s}_1$, $\mathbf{s}_2$, ..., $\mathbf{s}_m$, ..., $\mathbf{s}_M$. $\mathbf{s}_m = [\omega_1, \omega_2, ..., \omega_j, ..., \omega_J]$, ω_j is the frequency component of each frequency component in the sub-band.

Then, the variance covariance matrix $\mathbf{R}$ is calculated by the following equation:

$$\hat{\mathbf{R}} = \frac{1}{M}\sum_{m=1}^{M} \mathbf{s}_m \mathbf{s}_m^{\mathrm{H}} , \qquad (1)$$

The eigenvalues and eigenvectors of $\mathbf{R}$ are computed, and after arranging the eigenvalues from largest to smallest, each eigenvalue λ_i corresponds to an eigenvector $\mathbf{e}_i$. eigenvectors $\{\mathbf{e}\}_{i=1}^{D}$ corresponding to portions of the eigenvalues with larger eigenvalues are signal subspace, and eigenvectors $\{\mathbf{e}\}_{i=D+1}^{J}$ corresponding to eigenvalues close to zero are noise subspace.

Finally, the R-MUSIC is computed from the steering vector $\mathbf{r}_i$ expressed in the frequency domain at each moment t_i as follows:

$$S(t_i) = \frac{\mathbf{r}_i^H \mathbf{R}_0^{-1} \mathbf{r}_i}{\sum_{j=D+1}^{J} \left|\mathbf{r}_i^H \mathbf{e}_j\right|^2} . \qquad (2)$$

After calculating the profile of R-MUSIC for each element, the profiles from all the elements are summed up by DAS method after delay correction.

2.2 Time reversal MUSIC

TR focusing requires an array of N transducers. Each element in the array transmits a signal in turn and all elements receive the signal in parallel[3)]. The corresponding matrix $K(\omega)$ consisting of the angular frequencies ω is obtained. TR matrix can be computed as $T(\omega) = K^{\mathrm{H}}(\omega) * K(\omega)$[4)]. The eigenvalues and eigenvectors $\mathbf{u}$ of $\mathbf{T}$ are then computed. The signal and noise subspaces are defined in the same way as for R-MUSIC. Finally, the TR-MUSIC is computed by the following equation:

$$Y(r) = \frac{1}{\sum_{m=D+1}^{N} \left|\mathbf{u}_i^H \mathbf{G}_r\right|^2} , \qquad (3)$$

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where **Gr** is the Green's function from pixel point r to each element.

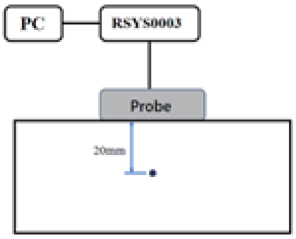

Fig. 1 Experiment setup.

Finally, we combine the individual pixel values of the two methods by multiplying them together and then squaring them.

3. Experiments

To verify the effectiveness of the proposed method, we use an experimental platform for medical ultrasound applications (Microsonic RSYS0003) with a sampling rate of 31.25 MHz. A linear array probe (Nihon Dempa Kogyo T0-1599) was also used. The number of transducer elements used is 64, while the element pitch is 0.315 mm. The signal processing step was performed using MATLAB software.

Figure 1 shows experimental setting. to realize TR-MUSIC, the entire array of 64 elements transmits the signal sequentially and all elements receive the echo in parallel. We present the experimental results obtained using a soft tissue-mimicking phantom (Kyoto Kagaku US-2 multi-purpose phantom N-365), the phantom contains a 0.1 mm diameter string line located 20 mm in front of the transducer. A pulse with a frequency of 5.21 MHz and a period of 3.5 was used as the transmitting signal.

For each element the received echo is extracted through a band-pass filter with 13 subbands of different frequencies for R-MUSIC calculation randomly.

4. Result and Discussion

Figure 2 illustrates the images of 3 methods. Fig. 2(a) shows the result of TR-MUSIC. Fig. 2(b) shows the result of DAS using R-MUSIC profiles. Fig. 2(c) shows the result of the combination of R-MUSIC and TR-MUSIC (Proposed method). By comparing Fig. 2(a) and Fig. 2(c), it can be clearly seen that the proposed method effectively improves the axial resolution.

Figure 3 shows the amplitude distribution profiles along the range direction and the lateral direction. The profiles of the TR-MUSIC, the profiles of DAS using R-MUSIC profiles and the proposed method in Fig. 3. It is known that the proposed method has almost the same resolution as R-MUSIC in the distance direction and almost the same

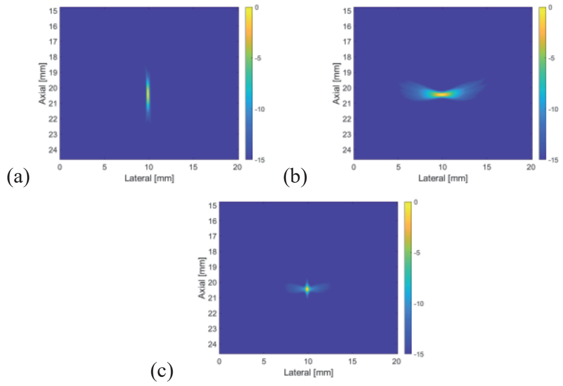

Fig. 2 B-mode images: (a) Time-reversal imaging with multiple signal classification (TR-MUSIC); (b) DAS using profiles of R-MUSIC; (c) Combination of R-MUSIC and TR-MUSIC (Proposed method).

resolution as TR-MUSIC in the lateral direction, but the sidelobe level is slightly higher in both distance and lateral direction.

5. Conclusion and Future Work

We propose to improve the problem of TR-MUSIC degradation due to noise in distance resolution by combining R-MUSIC and TR-MUSIC. In the future, we intend to improve the resolution of TR-MUSIC more rationally by adding the information of R-MUSIC to the computational equation of TR-MUSIC.

References

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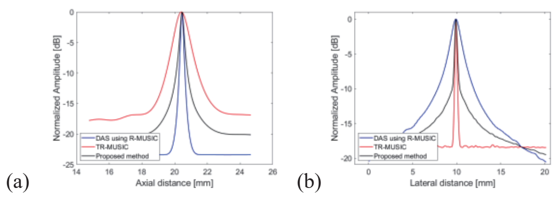

Fig. 3 Amplitude distribution profiles along (a) range direction and (b) lateral direction.