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Adaptive Compound of Angle and Frequency with Simultaneous Transmission for Multiple Direction using M-sequence

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1. Introduction

Ultrasound imaging systems are useful in that allow non-destructive and non-exposure internal inspection [1]. Especially in the medical field, this system has the advantage of real-time imaging, which is difficult with other systems [2]. This leads to the diagnosis of dynamic functional deterioration of the circulatory system. However, the image quality of ultrasound images is inferior to other modalities, and research is actively being conducted to improve the image quality of ultrasound images by using harmonics and nonlinear processing based on deep learning [3]-[4]. In our previous study [5], we proposed filtered FPWC-MVDR (frequency and plane-wave compounding-minimum variance distortion less response) that transmits wideband plane waves in many directions and achieves high resolution by the adaptive compound of the subband that is divided after reception and the of the transmission directions. However, this method transmits plane waves individually in each direction. Therefore, increasing the transmission direction to improve image quality reduces the temporal resolution.

To improve the temporal resolution, we propose a method of simultaneous transmitting plane waves in all directions [6]. In our previous work, we used a method in which different subband was assigned to each angle so that one echo received by simultaneous transmission can be separated into echoes corresponding to each angle. However, the frequency bandwidth used for each direction was reduced, resulting in a loss of resolution. This study proposes a method to transmit and receive a wideband signal to all directions simultaneously by using phase modulation.

2. Method

In order to improve the frame rate, that is the temporal resolution, while maintaining the spatial resolution, we propose a method of simultaneously transmitting a pulse consisting of the entire effective band of the transducer in multiple directions. We introduce phase modulation so that echoes in each direction can be separated after the reception. Here, phase modulation is performed by multiplying the carrier with the M-sequence.

We aim to improve spatio-temporal resolution by adaptively compounding the third-order tensor data, which consists of frequency, direction, and element, pixel by pixel. In order to suppress unwanted signals generated by phase modulation and artifacts caused by echo interference between transmission directions, we introduce a minimum variance distortionless response (MVDR) when performing direction and frequency compounds, which is an improved method of the filtered FPWC-MVDR. Furthermore, we also introduce coherent factor (CF) to improve the image quality by utilizing contrast improvement when compounding the element.

Simultaneous transmission is realized by applying all the signal voltages with appropriate delay time in each direction to the element.

Ultrasound images are archived by following steps. First, the phase modulated echo signal is separated into echoes in each direction by the decoding procedure after being received by the elements. After that, the echoes are divided into subbands by digital filtering. Each pixel value is calculated by adding up all the third-order tensor data, which consists of frequency, direction, and element (Delay-and-Sum: DAS), or by compounding with the adaptive weight (weighted DAS).

3. Simulation

In this study, the echo signals were calculated using Onscale which is a standard FEM simulator for ultrasound analysis. The echo signals were received individually by 96 transducer elements. In these simulations, the sampling frequency is 812.87 MHz. A model shown in **Fig. 1** is used for the simulation. The transmission direction was set to -12, -6, 0, 6, and 12 degrees.

The transmitted signal in each direction is a phase modulated signal that can be separated from the other direction after the reception. Phase modulation was performed by M-sequence with values 1 and -1. The phase modulation signals used in the simulation were created by multiplying a carrier wave with a

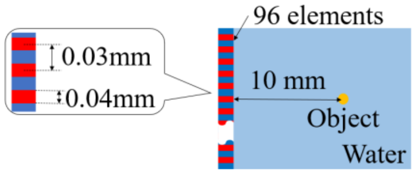

Fig 1. Simulation Model

frequency of 5.5 MHz with the M-sequence generated by a 7-stage shift register. For comparison, a wideband FM chirp signal with a center frequency of 5.5 MHz and a bandwidth of 6 MHz, which is a conventional method was also transmitted. We divided a wideband into 9 subbands which have a bandwidth of 2 MHz.

4. Results and Discussion

Figures 2 (a) and (b) show the B-mode images using an FM chirp signal. Figure 2 (a) is a DAS and Fig. 2 (b) is a weighted DAS by individual transmission in each direction. A comparison of the two images shows that the weighted one has fewer artifacts and improved resolution. Figures 2 (c) and (d) are the B-mode images when individual transmission of phase modulated signal (Method A), and Figs. (e) and (f) are the B-mode images when transmitted simultaneously (Method B: proposed method). Additionally, the profiles of the B-mode images in Figs. 2 (b), (d), and (f) for the range and the lateral direction are shown in **Fig 3**.

As can be seen from Fig. 3, Method A causes many artifacts that are not present in the FM chirp. This is due to noise generated by the introduction of phase modulation. We consider that this noise was caused by the inability to transmit and receive an ideal phase modulation signal due to the limitation of the effective bandwidth of the element. In addition, artifacts are even more prevalent when Method B is used. We think this is due to interference with signals from other directions. On the other hand, in the vicinity of the target, the resolution with Method B was similar to that obtained with the FM chirp. **Figure 4** shows the compression waveforms of the received echo at 0 degrees during FM chirp, the individual transmission of phase-modulated signals, and simultaneous transmission. In individual transmission, the pulse width is narrower than the FM chirp, but noise, the cause of the artifact, has been generated. Furthermore, it can be seen that the noise is even larger during simultaneous transmission.

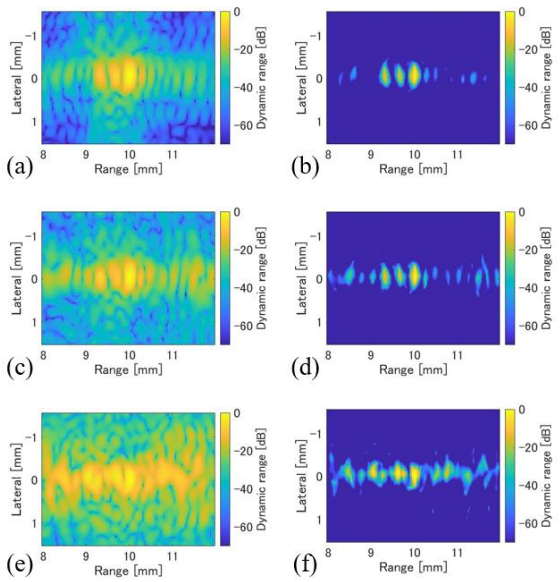

Fig 2. B-mode images. (a) and (b) are FM chirp, (c) and (d) are Method A, and (e) and (f) are Method B. The left column is DAS and the right column is weighted DAS.

5. Conclusions and Further Works

In this paper, we evaluate the performance of direction and frequency compounds by simultaneous transmission. While the simultaneous transmission of phase modulated signals produced many artifacts, the resolution in the vicinity of the target was maintained at the same level as the conventional method. It was also confirmed that the improved filtered FPWC-MVDR could suppress artifacts to some extent.

For further work, we will try to introduce a better compounding method to suppress artifacts that have not yet been suppressed by the proposed method.

References

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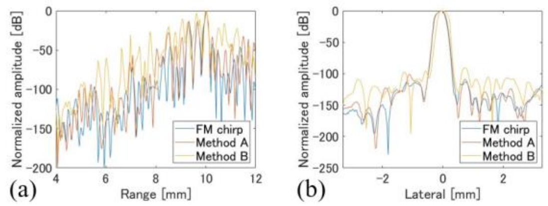

Fig 3. Profiles of B-mode images in Figs. 2 (b), (d), and (f) for (a) the range and (b) the lateral direction.

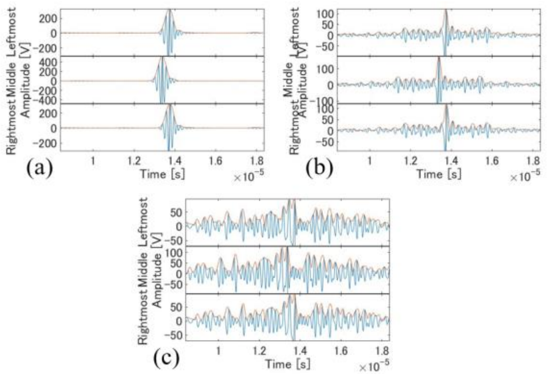

Fig 4. Compressed signals of (a) FM Chirp, (b) phased modulated signal separately, and (c) phase modulated signal simultaneously for 0 degree.