3P5-3

Ultrasonic Doppler Imaging Based on Steered Beam-forming Using Dual-Chirp Plane Wave

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1. Introduction

Doppler measurement is a very important technique in the medical field, and various methods have been proposed to measure the velocity and position of the measured object. Common methods include the pulsed Doppler method [1], the color Doppler method [2], and the single FM chirped-pulse compression method [3]. However, each of these methods has its limitations. The pulsed Doppler method can only detect the average velocity from about 10 transmissions/receptions. The color Doppler method is a spatially averaged velocity detection due to correlation operations. The single FM chirped-pulse compression method is not applicable in situations where multiple scatterers have different velocities.

To address these issues, we consider the application of the dual-chirp method [4][5] to plane-wave imaging. In reference [6], we have provided a principled confirmation of the method. In this paper, we consider a measurement method based on steered beamforming. According to this method, the velocity vector of a target can be estimated by a single plane wave transmission/reception. The velocity component for each angle can be calculated by generating up-chirp and down-chirp images while changing the angle of steered beamforming, and measuring the displacement of the target between the two images. By combining several of these, the velocity, including the orientation, can be obtained. The method is evaluated by simulation.

2. Method

2.1 Principle of dual chirp method

When a chirp echo signal undergoes a Doppler shift, its compressed waveform is almost undistorted, but is shifted in position according to the Doppler frequency. This occurs in the opposite direction for up-chirp and down-chirp. Therefore, if a dual chirp pulse consisting of FM up-chirp and FM down-chirp pulses is transmitted and the echoes are compressed at each, the time shift that occurs between them can be expressed as follows.

$$t_d = \frac{f_d T}{B}. \quad (1)$$

In this equation, f_d represents the Doppler frequency, which is caused by the relative motion of the target, T represents the duration of the transmitted dual FM-chirp pulse, and B is the frequency bandwidth of the dual FM-chirp signal.

By measuring t_d, the Doppler frequency is obtained. However, to determine even the direction of velocity with this method, t_d must be measured in multiple directions.

2.2 Dual chirp method for plane wave imaging

By applying the dual chirp method to plane-wave imaging, the velocity can be determined up to the direction in a single transmission and reception. If the angle between the velocity vector $\boldsymbol{v}$ of the target and the direction of plane wave transmission is θ_T and the angle between $\boldsymbol{v}$ and the direction of steered beamforming is θ_R, the Doppler shift f_R is given by the following equation.

$$f_R = \left(\frac{f_0 \left(1 + \frac{v \cos \theta_T}{c}\right)}{1 - \left(\frac{v}{c}\right) \cos(\theta_R)} \right) \quad (2)$$

The geometric relationship is shown in Fig. 1. Calculate multiple f_ds using Eq. 1 while changing the direction of steered beamforming. Let this be equal to f_R in Eq. 2, and solve for them by the least-squares method, taking the magnitude and direction of v as unknowns.

3. Simulation

In this study, the echo signals were calculated using steered beamforming. Steered beamforming involves receiving echo signals with a linear array transducer that is angled relative to the horizontal direction.

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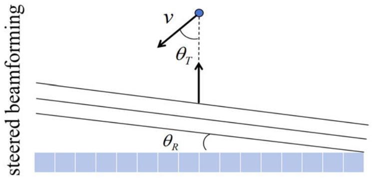

Fig. 1 Geometric relationship of dual chirp method in plane wave imaging

A simulation model is shown in **Fig. 1**. In this system, one scatterer is placed in the field, moving at a velocity of 50 m/s and positioned at a 45-degree angle to the linear array transducer. To simulate our method, we used a 128-element linear array transducer, with the up-chirp frequency set from 1~7 MHz and the down-chirp frequency set from 7~1 MHz. The pulse width was 10 μs and 20 μs, and the sampling frequency was set to 200 MHz.

4. Result and discussion

Figure 2 (a) and **(b)** are DAS images of up and down chirp with a steering angle of 0° and a pulse width of 10 μs, **(c)** and **(d)** are DAS images of up and down chirp with a steering angle of -10° and a pulse width of 10 μs, and **(e)** shows the time shift of the target. From the B-mode images, it is possible to estimate which target corresponds to which echo, and then calculate the Doppler frequency using Eq. (1). In this simulation, as seen in **Table 1** and **Table 2**, the error is approximately 25%.

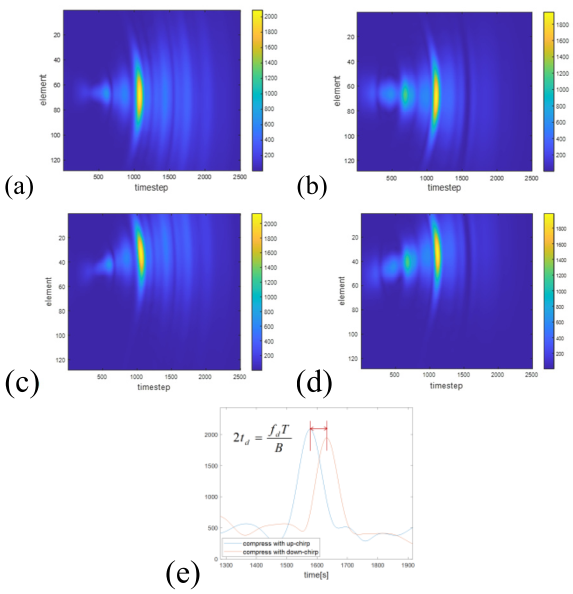

Fig. 2 Simulation results. (a) and (b) are DAS images of up and down chirp with a steering angle of 0° and a pulse width of 10μs, (c) and (d) are DAS images of up and down chirp with a steering angle of -10° and a pulse width of 10μs, (e) time shift of target.

5. Conclusion and future works

In this study, we focused on verifying the accuracy with which Doppler frequency or time shift could be determined. Our findings provided insights into the precision of these measurements, which are crucial for understanding the behavior of scatterers. However, the challenge of accurately estimating both the magnitude and direction of velocity for multiple targets remains unresolved. Addressing this issue will be a key focus of our future work, as it is essential for improving the reliability and applicability of this technique in more complex scenarios.

References

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Table 1 Comparison of results when the pulse width is 20μs.

steering angle in beamforming [degree]	0	-10	-20	-30
Theoretical Value of t_d [ns]	573	567	552	526
Measured Value of t_d [ns]	429	425	417	363
Relative Error Rate	25.1%	25.0%	24.5%	31.0%

Table 2 Comparison of results when the pulse width is 10μs.

steering angle in beamforming [degree]	0	-10	-20	-30
Theoretical Value of t_d [ns]	285	285	275	265
Measured Value of t_d [ns]	215	215	215	371
Relative Error Rate	24.6%	24.6%	21.8%	28.5%