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Development of a Simulator of Backscattered Signals from Inhomogeneous Medium for Speed of Sound Measurement and Imaging

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***Abstract* — Speed of sound (SOS), which is the propagation speed of a longitudinal wave, is a promising index for diagnosis. Several methods for SOS measurement and imaging have been proposed. Among them, some methods using the backscattered signals are expected to be useful for the clinical use, but since generally these are ill-posed problem, it is difficult to verify the logical validity. In order to verify the validity of the developed algorithm logically, conducting numerical simulations will be effective prior to the validation using real data. Therefore, in this study, the backscattered wave simulation for SOS measurement and imaging was investigated.**

Keywords — speed of sound distribution, backscattered wave, simulation, time of flight, inhomogeneous medium

I. Introduction

Speed of sound (SOS), which is the propagation speed of a longitudinal wave of ultrasound, is a promising evaluation index for disease detection, diagnosis and monitoring response. Therefore, methods for SOS measurement and imaging have been proposed [1-9]. Among them, methods using the backscattered signals [5-9] are expected to be useful for the clinical use because the handheld probe is available. However, since generally these are ill-posed problem, it is difficult to logically verify the validity.

In order to verify the validity of the developed algorithm for SOS measurement and imaging using backscattered signals logically, conducting numerical simulations will be effective prior to the validation using real data. Therefore, in this study, a simulator of backscattered wave suited to the validation of SOS measurement and imaging methods was developed.

II. Development of Simulator

The simulator in this study was designed to enable any beamforming and channel data collection under consideration of SOS distribution in the inhomogeneous medium, and was developed by using the Microsoft® Visual C++®.

Figure 1 shows the configurations of beamforming and channel data collection in the developed simulator. By adjusting the delay time given to each channel aligned on the linear array probe surface, plane wave or focused wave can be transmitted in any direction. Moreover, in order to simulate the focusing in the slice direction by the acoustic lens, several virtual elements were arranged in the slice direction of the linear array probe surface as shown in Fig. 1 (b). That is, the backscattered wave signal to be obtained in each channel was generated by the delay-and-sum (DAS) processing in consideration of the curvature of the acoustic lens to the signals received by the virtual elements. Table I shows an example of transmission parameters in the simulator. The frequency and the fractional bandwidth of the transmitting pulse are set at each channel, and the spherical waves are transmitted from each channel.

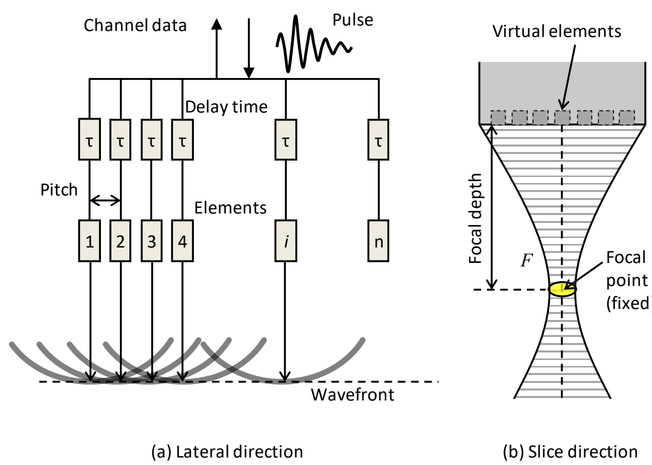

Fig. 1. Configurations of beamforming and channel data collection in the simulator. (a) and (b) show the configurations in the lateral and slice directions, respectively.

TABLE I. An Example of Transmission Parameters in the Simulator

Elements	161
Pitch	0.25 mm
Frequency	3.75 MHz
Sampling frequency	20 MHz
Fractional bandwidth	0.8

The novelty of this simulator is that the time of flight (TOF) is calculated as the propagation time on two-point raypath between one transducer element and one scatterer placed in the medium having the SOS distribution. In this simulator, as shown in Fig. 2, the distance between two points, (i or j) and (k), is divided into a finite number of elements, and then by accumulating the local propagation time t_n in each element, the TOF between (i or j) and (k) is calculated. The local propagation time t_n is calculated as the product of the slowness v_n and the distance d_n at each element, where the slowness v_n is the reciprocal of SOS c_n. That is, $v_n = 1/c_n$. This processing means that the SOS distribution had been considered in calculating the TOF. In principle, it is possible to calculate the TOF between two points in consideration of the influence of refraction, but in this study, the TOF is calculated by approximating the raypath as a straight line.

Figure 3 shows a calculation method of radio frequency (RF) signal at each channel incorporating the TOF calculation. The backscattered wave signal at each channel is obtained by superimposing the backscattered waves from all scatterers distributed in the medium in consideration of the TOF described above. Here, on the basis of the concept of Fig. 2, t_{ik} and t_{kj} in Fig. 3 (that is, TOFs of going and return) are calculated as follows.

$$t_{ik} = \sum_{n=1}^{N} v_n d_n \quad (1)$$

$$t_{kj} = \sum_{m=1}^{M} v_m d_m \quad (2)$$

Therefore, it is possible to simulate the backscattered wave signals from not only the homogeneous media but also the medium with inhomogeneous SOS distribution.

III. VALIDATION OF SIMULATOR

A. Homogeneous Medium

First, the performance of this simulator was evaluated by using a medium model with uniform distribution of SOS. 2500 scatterers were randomly arranged three-dimensionally in a medium with a height of 40 mm, a width of 40 mm, and a depth of 1 mm, as shown in Fig. 4, and then the scattering coefficient distribution was given as a Gaussian distribution as shown in Fig. 5. In this model, a spherical inclusion was included at an any position inside, and the SOS of a spherical inclusion different from that of the surrounding medium can be set. However, in order to evaluate the performance for the homogeneous medium, the SOSs of the inclusion and the surrounding medium was set equal. Table II shows parameter values applied to the simulation model.

In order to evaluate whether the backscattered wave signals generated on the basis of the TOF correctly reflects the SOS distribution, the backscattered wave signals were calculated for the homogeneous medium with the SOS of 1480, 1500, 1530, 1550, 1570 m/s, respectively. In addition, in order to estimate the SOS of the medium, a point scatterer with a scattering

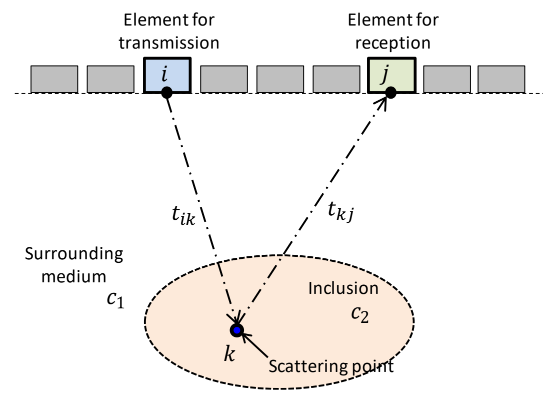

Fig. 3. A calculation method of RF signal at each channel incorporating the TOF calculation.

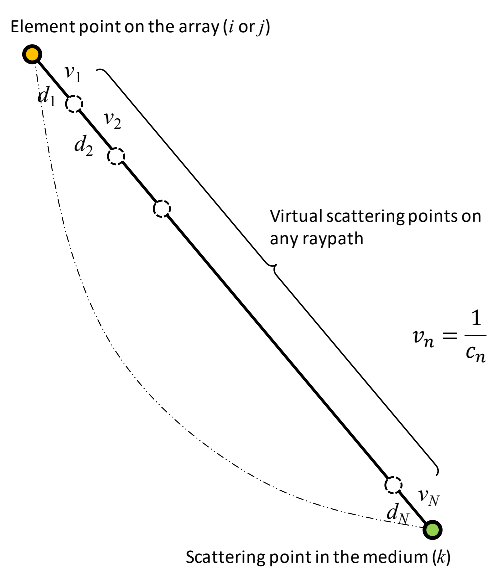

Fig. 2. A concept of TOF calculation between two points.

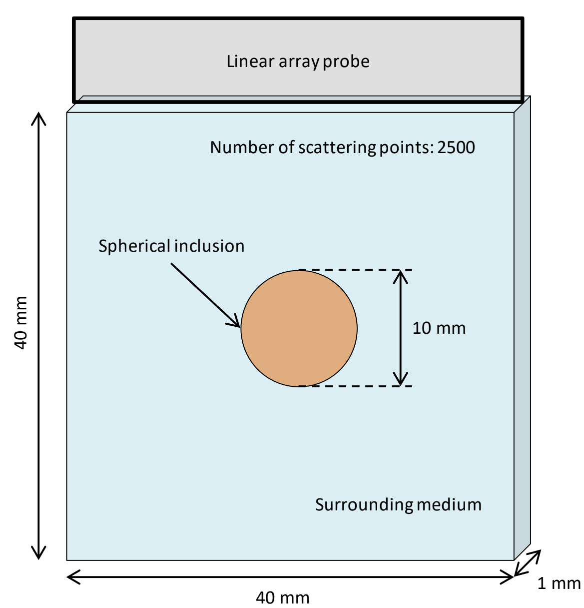

Fig. 4. A simulation model with an inclusion.

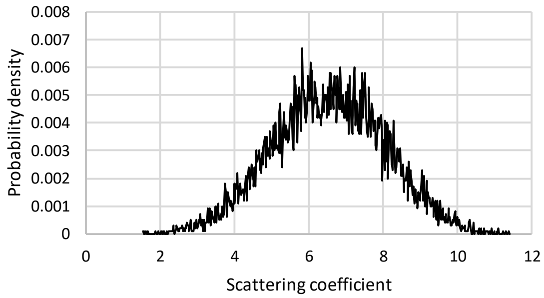

Fig. 5. A scattering coefficient distribution used in the simulation.

TABLE II. PARAMETER VALUES APPLIED TO THE SIMULATION MODEL

Density	1000 kg/m^3
Number of scattering points	2500
Scattering coefficient (mean)	6.5
Scattering coefficient (SD)	1.5
Scatter coefficient distribution	Gaussian
SOS in the surrounding tissue	1480 to 1570 m/s
SOS in the inclusion	1530 to 1570 m/s
Diameter of an inclusion	10 mm
Size of whole medium	40 x 40 x 1 mm

coefficient 10 times larger than that of the surroundings was placed at a depth of 20 mm as shown in Fig. 6(a), and a focused beam as shown in Fig. 6(b) was irradiated to the position of the point scatterer. As the result, the backscattered wave signals at all channels could be generated as shown in Fig. 6(c). In order to verify that the TOF involved in the backscattered signals reflect the true SOS distribution, the 'focusing method' [4] was used as the SOS estimation. That is, by arranging the delay time of each channel so that the focusing point was set to the depth of 20 mm, the test SOS in the range of 1400 to 1700 m/s which was maximized the amplitude of the aperture synthetic wave, was determined as a true SOS. Fig. 6(d) shows the result that the positions of the strong echoes were aligned when the test SOS and the true SOS coincided with each other. The maximum amplitude of the aperture synthetic wave was searched during the time period [T_1, T_2] as shown in Fig. 6(d).

Figure 7 shows the result of the SOS estimation in the homogeneous medium, where the horizontal axis represents the true SOS of the medium and the vertical axis represents the SOS estimated by the focusing method. The estimated SOS coincided well with the true SOS, and the coefficient of variation of the estimation was 0.2%. From this result, it was confirmed that the backscattered wave signals were calculated correctly by this simulator.

B. Inhomogeneous Medium

Next, as an investigation using an inhomogeneous medium, a medium including an inclusion at the position shown in Fig. 8(a) was assumed. The SOS of the surrounding medium is

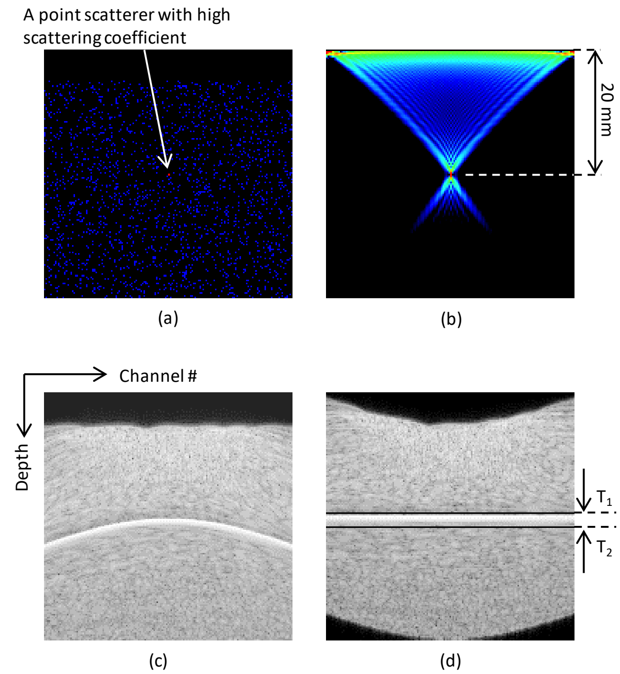

Fig. 6. A procedure for the SOS estimation using the 'focusing method'.

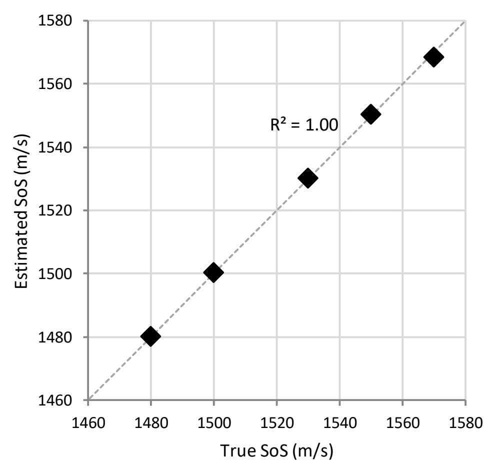

Fig. 7. A result of the SOS estimation in the homogeneous medium.

constant at 1530 m/s, and the SOS of the inclusion was set to 1530, 1540, 1550, 1560, 1570 m/s, respectively. As in the previous section, a point scatterer was placed at a depth of 20 mm and a focused beam was irradiated on that position, and the backscattered wave signals in each channel were calculated.

Figure 8(b) shows the result of SOS estimated by the focusing method. The horizontal axis represents the true SOS of the inclusion, and the vertical axis represents the SOS estimated by the focusing method. The focusing method was expected to obtain an average value of the SOS distribution on the propagation path, but the result was different from the prediction. This is because the delay time was calculated by using the test SOS assuming the homogeneous medium. Since

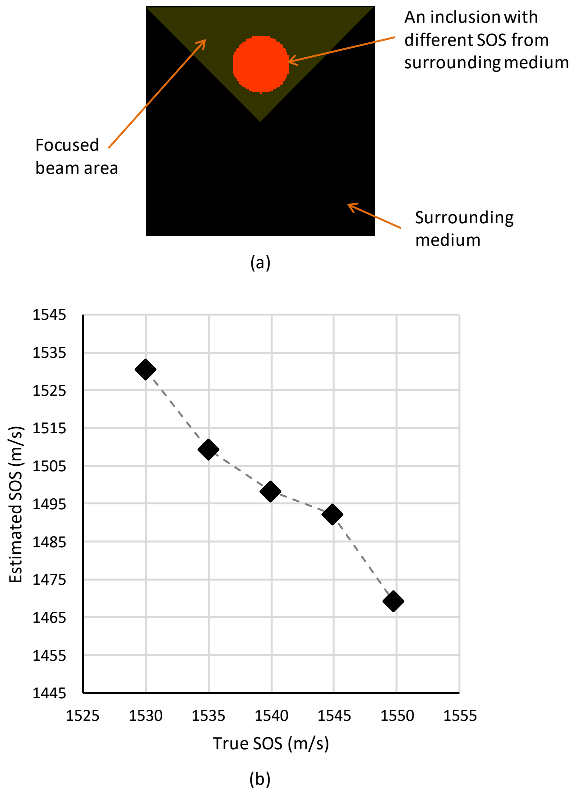

Fig. 8. A result of the SOS estimation in the inhomogeneous medium.

the wavefront distortion was not corrected correctly, the maximum amplitude of the aperture synthesis wave was obtained in the wrong test SOS.

However, on the other hand, this result paradoxically suggest that the calculation of the backscattered wave signals reflecting the difference in the SOS of the inclusion was conducted appropriately.

IV. CONCLUSIONS

In this study, a simulator of the backscattered wave signals considering the inhomogeneous SOS distribution was investigated. As the results, it was suggested that the developed simulator appropriately could calculate the backscatter wave signals arrived at each channel on the basis of the TOF reflecting the SOS distribution in the inhomogeneous medium. In conclusion, the simulator has a potential to evaluate the logical correctness of any methods for SOS measurement and imaging using the backscattered wave signals.

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