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Estimation of Sound Velocity Distribution Using Global Heuristic Search

大局的なヒューリスティック探索手法を用いる音速分布推定

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1. Introduction

Sound velocity is an important parameter for getting environmental information like temperature, wind velocity, and so on. Currently, a pair of ultrasonic probes is a major instrument for measuring the sound velocity. However, average of sound velocity between the two transducers is only acquired using the ultrasonic probe.

If a sound velocity distribution is needed, computerized tomography (CT) method[1)] is adapted. This method, however, has a problem. It is necessary that a sound wave goes straight or an ideal sound source, a plane sound wave is propagated from the sound source, is needed. To solve the problem, we propose a method for estimating a sound velocity distribution using optimization and near-field acoustical holography (NAH) [2)], which is applied of the past work [3)]: a uniform sound velocity vector is determined by inverse analysis of NAH. An advantage of using NAH is that any sound source can be used.

In this paper, we propose a system to estimate a one-dimensional sound velocity distribution by measuring three sound fields of two-dimension using common sound source. The sound velocity distribution is estimated by combination method of NAH and global heuristic search, simulated annealing (SA) [4)], and genetic algorithm (GA) [5)].

2. Principles of Sound Velocity Estimation

We consider a coordinate system as shown in **Fig. 1**. Estimation of a sound velocity distribution follows the steps below.

i. **Measurement** of Sound fields in three planes.
ii. **Calculation** of sound fields as Fig. 1 using **NAH** with an initial sound velocity distribution.
iii. Difference of the calculated and measured sound fields is minimized by **optimizing** the sound velocity distribution.

2-1. Calculation of Sound Fields by Sectional NAH

In Fig.1, the origin is located at a center of ultrasonic transducer, and an ultrasonic wave is radiated in the direction of z-axis. In this paper, the transducer is circular, and a sound velocity distribution is uniform in x and y direction. Thus,

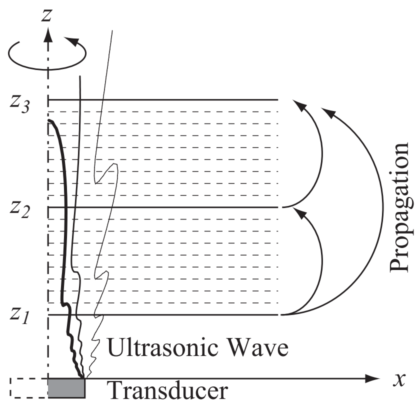

Fig. 1 Geometry of coordinate system, ultrasonic transducer, sound field, and measurement plane

the coordinate system is z-axial symmetry. Then, a two dimensional sound field at $z = z_1$ is expressed as $p(x, y, z_1)$, and sound field in wave number domain is expressed as $P(k_x, k_y, z_1)$. A relationship between the sound fields at $z = z_1$ and z_2 is given by

$$p(x,y,z_2) = p(x,y,z_1) * h(x,y,z_2 - z_1), \qquad (1)$$

where $*$ and h denote convolution integral and apropagation function. Here, the propagation function in wavenumber domain H can be expressed as

$$H(k_x,k_y,z_2 - z_1) = \exp[ik_z(z_2 - z_1)], \qquad (2)$$

$$k_z^2 = k - k_x^2 - k_y^2, \qquad (3)$$

where k is wavenumber [2)], which must be constant in ordinary NAH theory.

Heretofore, NAH method is used for calculation of the wave propagation. Then, we consider that inverse analysis of NAH is used for determination of the propagation function and the sound velocity [3)]. However, only constant sound velocity is obtained by inverse analysis.

Here, we consider a sound velocity only varies in z direction. Then, a space between planes at $z = z_1$ and $z = z_2$ is discretized into many sections as shown in Fig. 1 so that the sound velocity in each section becomes approximately uniform. We call this method sectional NAH (SNAH). The propagation function in SNAH is expressed as

$$H(k_x,k_y,z_2 - z_1) = \prod \exp(ik_z d_z) = \exp\left(id_z \sum k_z\right), \qquad (4)$$

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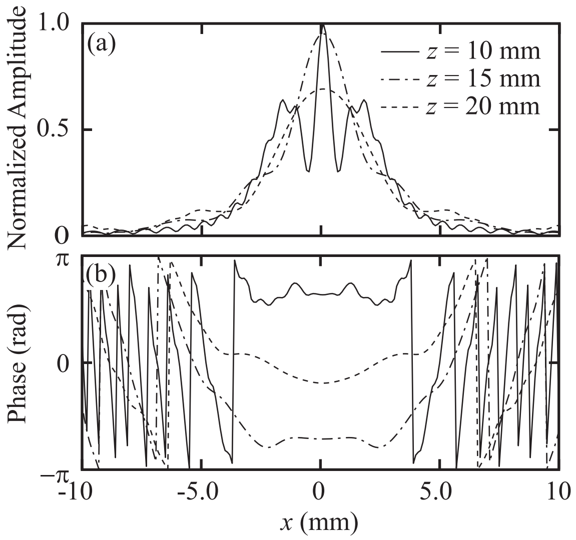

Fig. 2 Sound fields on x axis for estimation of sound velocity (a): normalized amplitude; (b): phase.

where, d_z is the step size of discretization in z axis. For accuracy of calculation, it is necessary that quadrature, like as Simpson's rule, is used for calculation of propagation function.

2-2. Estimation of Sound Velocity Using Global Heuristic Search

Here, we propose a use of optimization for estimating a continuous sound velocity distribution. A coordinate system is shown in Fig. 1. Firstly, two dimensional sound fields at $z = z_1$ and $z_3$are measured for estimation of sound velocity distribution in a range from $z = z_1$ to $z = z_3$. Then, an initial sound velocity distribution is determined randomly. With the initial sound velocity distribution, a sound field at $z = z_3$ is calculated from the measured sound field at $z = z_1$ using SNAH. If the sound velocity distribution is equal to the actual sound velocity distribution, the sound field at $z = z_3$ calculated using SNAH is equal to the measured sound field at $z = z_3$. Thus, the actual sound velocity distribution is estimated by optimization: the sound velocity distribution is optimized to minimize a difference of the calculated and measured sound fields.

In fact, it is necessary that sound fields at $z = z_1$, z_2 and z_3 are measured because a solution of optimization do not converge with two measured sound fields. The sound field at $z = z_3$ is calculated from $z = z_1$ and z_2, and the sound field at $z = z_2$ is calculated from $z = z_1$. An evaluation function for the optimization is the sum of difference of sound fields in real part respectively. Optimization coefficients are representative values of sound velocity distribution, and the sound velocity distribution is interpolated for calculating the sound field using SNAH. SA and GA, which are the global heuristic search, are used to optimize without falling into local solutions.

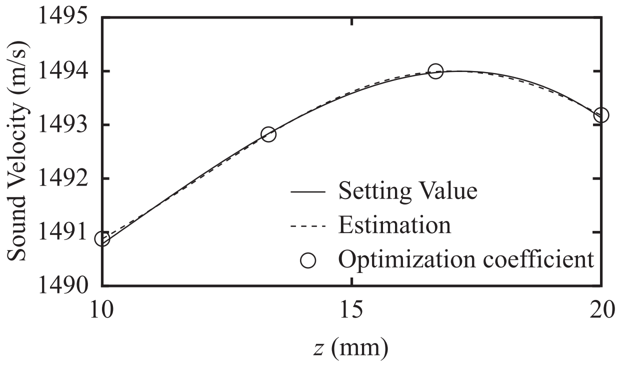

Fig. 3 Estimation result of sound velocity distribution using SNAH, SA, and GA

3. Simulation

We validate this method by a simulation. In the simulation, an ultrasonic wave is radiated into water from a circular transducer with diameter of 5.0 mm driven at 1.0 MHz. A sound velocity is given as Gaussian distribution curve in z- direction, and a range of estimation of sound velocity distribution is from z = 10 mm to 20 mm. Then, two-dimensional sound fields at z = 10, 15, and 20 (mm) are calculated as measured sound fields using SNAH in region of 20 × 20 mm^2. The space between z = 10 mm and z = 20 mm is discretized into 2000 sections. **Fig. 2** shows the sound fields at z = 10, 15, and 20 (mm) on x-axis. These sound fields are used for estimation of the sound velocity distribution. Then, sound velocities at z = 10, 13, 17, and 20 (mm) are used for optimization, and a sound velocity distribution is interpolated to 200 points with cubic spline function for using SNAH. **Fig. 3** shows the estimated result using SA and GA. The estimated result well agrees with the defined value.

4. Conclusion

We proposed a method for estimation of a sound velocity distribution using SNAH, SA, and GA. The estimated result well agreed with the defined value, and validity of our proposal method was confirmed by the simulation. Our technique is expected to be applied to determine three-dimensional sound velocity distribution with scanning transducer or transducer array.

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