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Introduction of Irregularly Arranged Array in Reflection Point Search by Rectangular Sound Source
矩形音源による反射点探索における不規則配置アレイの導入

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1. Introduction

Rectangular transducers are widely used as ultrasonic measuring devices and imaging equipment as elements of the sound sources. Rectangular transducers have four vertices and four sides. A spatial impulse response of a rectangular sound source changes complicatedly depending on the order in which edge waves from these vertices and sides and direct waves from the sound source surface arrive at the observation point[1]. And, the waveform acquired by a rectangular sound source changes depending on the position of the observation point, subject to the spatial impulse response. An application of this complicated change to the reflection point search is proposed using a single rectangular sound source[2,3] or a rectangular array sound source with a small number of elements[4-9].

In the conventional methods using these sound sources, when the reflection point is around the perpendicular from the center of the sound source to the observation space, which the direct wave from the surface of the sound source reaches, the arriving reflection waveform is strongly influenced by the direct wave. This is considered to be one of the reasons why good search results of reflection points cannot be obtained in that region.

In this study, as a method of reducing the influence of direct wave, an array sound source in which each element is arranged irregularly is introduced. Numerical calculations of cross-correlation coefficients are performed to investigate the improvement of the reflection point search results.

2. Method of Reflection Point Search

The configuration of a sound source with irregularly arranged rectangular array elements and a reflection point P is shown in **Fig. 1**. The sound source is assigned to a plane perpendicular to the z-axis, and the center of the sound source element for the transmission of the acoustic wave (indicated as T in Fig. 1) is the origin of the coordinates. Elements for receiving acoustic waves (indicated as R_n in Fig. 1) are arranged with irregular directions and distances around the transmitting element. The center of each receiving element is expressed as (x_{offn}, y_{offn}). The dimension of each element is $a \times b$. The position

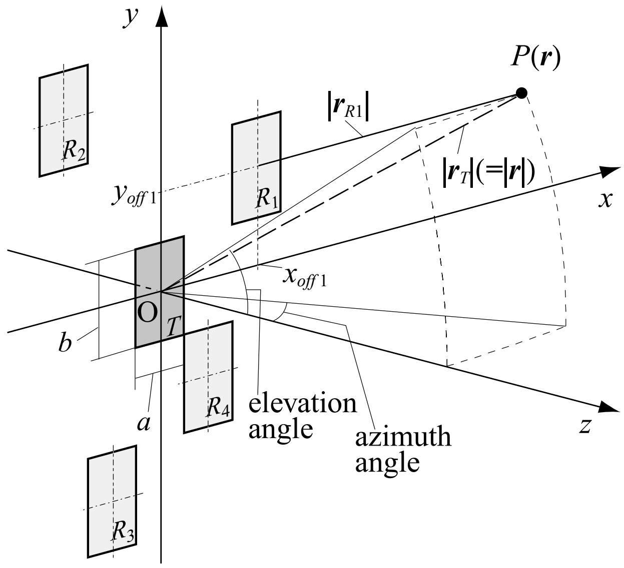

Fig. 1　Configuration of a sound source with irregularly arranged rectangular array elements and a reflection point P.

of the reflection point is indicated by $P(\boldsymbol{r})$. In the calculation result showing in the following section, $\boldsymbol{r}$ is expressed using the distance from the center of the transmitting sound source element ($|\boldsymbol{r}|$), the azimuth angle, and the elevation angle.

When the sound source element for transmission T is driven with uniform velocity $v(t)$, and when the wave radiated from the sound source is reflected at P, the output $e_n(\boldsymbol{r}, t)$ of the reflected wave received by the receiving element R_n is expressed as[10]

$$e_n(\boldsymbol{r},t) = -\frac{k\rho A}{2c} v(t) * \frac{\partial}{\partial t} h(\boldsymbol{r}_T,t) * \frac{\partial}{\partial t} h(\boldsymbol{r}_{Rn},t), \quad (1)$$

where k is the proportionality constant, ρ is the density of the propagation medium of the sound wave, A is the area of the region in which the reflection point contributes to the reflection, c is the velocity of sound, $h(\cdot)$ is the spatial impulse response of the sound source, and ∗ denotes the convolution integral. Additionally, $\boldsymbol{r}_T$ and $\boldsymbol{r}_{Rn}$ represent the positions of the reflection points from the center of the transmission (T) and reception (R_n) sound source elements, respectively.

The rise time of the reflected wave is measurable. Therefore, the value of $|\boldsymbol{r}|$ can be determined in the range expressed as

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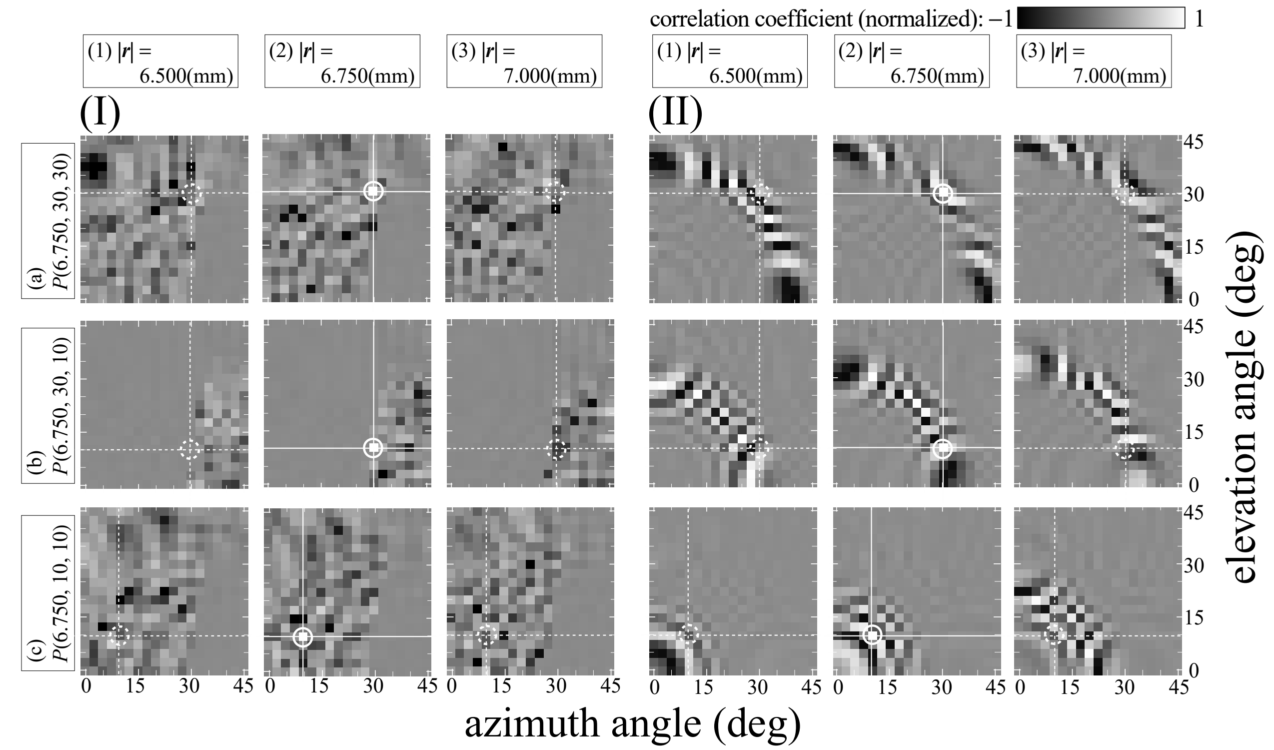

Fig. 2 Calculation results of cross-correlation coefficients at three reflection points: (I) using irregularly arranged rectangular array sound source; (II) using single rectangular sound source.

$$\frac{cT}{2} < |\boldsymbol{r}| < \frac{cT}{2} + \sqrt{\left(|x_{offn}| + \frac{a}{2}\right)^2 + \left(|y_{offn}| + \frac{b}{2}\right)^2}, \quad (2)$$

where T is the rise time of the reflected wave, and c is velocity of sound. When the value of $\boldsymbol{r}$ is set at an appropriate interval in the range of $|\boldsymbol{r}|$, the spatial impulse responses $h(\boldsymbol{r}_T, t)$ and $h(\boldsymbol{r}_{Rn}, t)$ corresponding to each $\boldsymbol{r}_T$ and $\boldsymbol{r}_{Rn}$ can be obtained. Since $v(t)$ is known, the output waveform $e_n(\boldsymbol{r}, t)$ in eq. (1) at each $\boldsymbol{r}$ can be calculated. By deducing the cross-correlation coefficient between the waveform obtained by the calculation and the original (acquired) reflected wave in the sequential order, it becomes possible to estimate the position of the reflection point P.

3. Numerical Calculations

The results of numerical calculations by the irregularly arranged rectangular array sound source are shown in **Fig. 2**(I). The results are obtained by calculating convolution integral in eq. (1) and the cross-correlation coefficient at time zero with the calculation result for the points around the reflection points sequentially. The dimensions of the sound source used in the calculation are $a = 6.450$ mm, and $b = 10.050$ mm. The centers of the receiving elements R_n are $(x_{off1}, y_{off1}) = (2a, b)$, $(x_{off2}, y_{off2}) = (-2a, -2b)$, $(x_{off3}, y_{off3}) = (-a, -2b)$, and $(x_{off4}, y_{off4}) = (a, -b)$, respectively. The convolution integral and the correlation coefficient are calculated in each receiving element separately, and the average is taken. For the comparison, the calculation results by a single rectangular sound source which has the dimension of $2a \times 2b$[2)] are also shown in Fig. 2(II).

In Fig. 2(I), the remarkable fluctuations of the correlation coefficient that appear in Fig. 2(II) are suppressed. Compared with the conventional method, it is considered that the proposed method is effective for improving search results.

4. Summary

In the reflection point search by rectangular sound sources, the irregularly arranged rectangular array sound source was introduced. From the calculation results of the correlation coefficients, it was shown that the influence of the direct wave which deteriorated the search results by the conventional method is suppressed.

In order to obtain better search results, it is considered necessary to further consider the number and arrangement of elements.

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