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Sound Source Localization Using a Pair of Microphones with Time Reversal Wave on Multi-layer Simulation

時間反転波の複層レイヤー伝搬計算による一対のマイクロフォンを用いる音源位置推定

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1. Introduction

In the last few decades, the method of acoustic field imaging / sound source localization has been actively researched[1-3]. It is well-known that time reversal wave simulation is useful for such objectives as a result of recent computational progress. The time reversal waves are simulated by simulation methods for wave propagation (*e.g.* FDTD, TLM) and the use of the GPU (Graphics Processing Unit) for the acceleration of the simulation is especially researched in resent years[4]. Although the sound source position is useful for target sound enhancement by using reflected sounds, it is often moving, such as human speaking. In order to improve the accuracy of sound source localization, a number of microphones or the simulation with the few velocity dispersion (such as the simulation governed by high-order difference equation if we use differential method) is required. Consequently, the measurements in specialized environment or calculation with high-power computers are desired to estimate the exact sound source position.

The purpose of this paper is to develop the method of sound source localization using a pair of microphones. Authors has been developed the localization method of reflective boundaries using an arbitrary sound source[5, 6]. In this paper we aim to develop the method of sound source localization applying the relation between the microphones and boundaries. Two techniques are proposed in this paper, the correction coefficient for acoustic field imaging to resolve the effect of a small numbers of microphones and the multi-layer wave simulation to resolve the velocity dispersion.

2. Sound Source Localization

2.1 Principles of time reversal wave simulation

FDTD (Finite Difference Time Domain) method is widely used for wave simulation. The sound pressure, $p_{i,j}^k$, and the particle velocities, $u_{x;\,i,j}^k$, $u_{y;i,j}^k$, on the grid point ${}^t(i,j)$ for each time step k are calculated as follows, which are originated from the initial parameters $(k=0)$.

$$p_{i,j}^{k+1} = p_{i,j}^{k} - K\Delta t\left(\frac{u_{x;\,i,j}^{k}-u_{x;\,i-1,j}^{k}}{\Delta h}+\frac{u_{y;\,i,j}^{k}-u_{y;\,i,j-1}^{k}}{\Delta h}\right) \quad , (1)$$

$$u_{x;\,i,j}^{k+1} = u_{x;\,i,j}^{k} - \frac{\Delta t}{\rho}\cdot\frac{p_{i+1,j}^{k+1}-p_{i,j}^{k+1}}{\Delta h} \quad , \qquad (2)$$

$$u_{y;\,i,j}^{k+1} = u_{y;\,i,j}^{k} - \frac{\Delta t}{\rho}\cdot\frac{p_{i,j+1}^{k+1}-p_{i,j}^{k+1}}{\Delta h} \quad , \qquad (3)$$

where Δt and Δh denote the time and the spatial step, K and ρ denote the bulk modulus and the medium density, which determine the wave propagation velocity $\left(c=\sqrt{K/\rho}\right)$, respectively.

With propagating the time reversal wave from the position of the microphones, we can visualize the sound source position on the time integral of the power of sound. However, the time reversal wave sometimes does not converge at the correct sound source position. This is because of the velocity dispersion in the time reversal wave simulation depends on the direction of propagation.

2.2 Corrective coefficient for acoustic field image

Since the time reversal waves converge near the microphones if we use a small number of microphones, we introduce a correction coefficient, $D_{i,j}$, to correct diffusional decay of the time reversal wave and it provides a distinct peak at the sound source position. Given the time integral of sound pressure, $P_{i,j} \equiv \sum_t \left|p_{i,j}^t\right|^2$, the corrected $\tilde{P}_{i,j}$ is defined as,

$$\tilde{P}_{i,j} \equiv P_{i,j}/D_{i,j} \quad , \qquad (4)$$

$$D_{i,j} = \sum_{m_s\in\mathcal{M}_n} 1/\left\|\underline{m}_s - {}^{t}(i,j)\right\|^2, \qquad (5)$$

$$\mathcal{M}_n = \left\{\underline{m}_1,\cdots,\underline{m}_n,\underline{\acute{m}}_1,\cdots,\underline{\acute{m}}_n,\underline{\grave{m}}_1,\cdots,\underline{\grave{m}}_n\right\} \quad , \qquad (6)$$

where $\underline{m}_n$, $\underline{\acute{m}}_n$ and $\underline{\grave{m}}_n$ denote the positional vectors of the n-th microphone and the mirror images of $\underline{m}_n$ due to reflective boundaries, respectively.

2.3 Multi-layer finite difference wave simulation

Figure 1 shows the diagram of the calculation process of the multilayer wave simulation. Firstly, we calculate the sound pressures, $p_{i,j}^k$ and $p'^{\,k}_{\chi,\psi}$, for each grid point (i,j) on the orthogonal grid and grid point (χ,ψ) on the oblique grid which is slanted from the grid of (i,j).

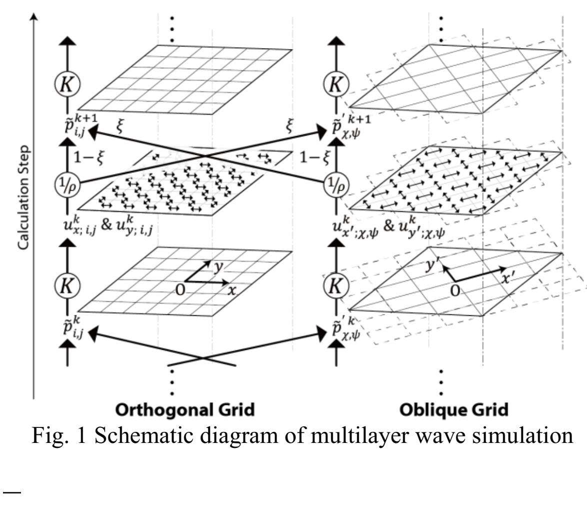

Fig. 1 Schematic diagram of multilayer wave simulation

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Table 1 Experimental Parameter

Position of the microphones $\underline{m}_1, \underline{m}_2$	$\begin{pmatrix}-5.0\\0.0\end{pmatrix}, \begin{pmatrix}5.0\\0.0\end{pmatrix}$ mm	
Calculation area	100×100 mm^2	
Spatial step Δh	1.0 mm	
Time length	1.0 ms	
Time step Δt	1.0×10^{-3} ms	
Sound source	Up-chirp, Down-chirp (Minimum wavelength: $10\Delta h$)	
Spec of the PC	CPU :	Intel Core i5-3570K (3.8 GHz, 4 cores)
	GPU :	NVIDIA GeForce GTX 670 (1.058 GHz, 1,344 cores)

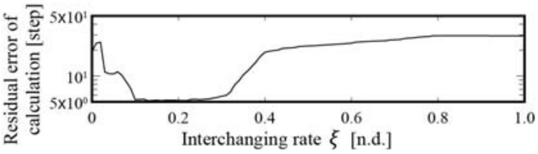

Fig. 2 Relation between the error and the interchanging rate ξ

Secondly, interchanged sound pressures, $\tilde{p}_{i,j}^{k}$, $\tilde{p'}_{\chi,\psi}^{k}$, with the interchanging rate, ξ, calculated as,

$$\tilde{p}_{i,j}^{k} = (1-\xi)p_{i,j}^{k} + \xi\left(\frac{p'^{k}_{\chi,\psi} + p'^{k}_{\chi-1,\psi} + p'^{k}_{\chi,\psi-1} + p'^{k}_{\chi-1,\psi-1}}{4}\right), \quad (7)$$

$$\tilde{p'}_{\chi,\psi}^{k} = \begin{cases} (1-\xi)p'^{k}_{\chi,\psi} + \xi\left(\frac{p^{k}_{i+1,j} + p^{k}_{i,j}}{2}\right)\Big|_{\chi+\psi\in 2\mathbb{Z}}, \\ (1-\xi)p'^{k}_{\chi,\psi} + \xi\left(\frac{p^{k}_{i,j+1} + p^{k}_{i,j}}{2}\right)\Big|_{\chi+\psi\in 2\mathbb{Z}+1}. \end{cases} \quad (8)$$

This linear interpolation even ups the velocity dispersions.

3. Evaluation

We had some experiments to evaluate the performance of the proposed method. **Table 1** shows the experimental conditions. We use $\xi = 0.14$ from the result of the prior wave propagation calculations in which the received sounds were generated by ray theory (**Fig. 2**). Two sound sources were localized at $\underline{s}_1 = (s, 50)$ mm as moving sound source and $\underline{s}_2 = (-25, 50)$ mm as fixed sound source. **Figure 3** shows the results in case $s = 20$ mm as an example. Especially, **Fig. 3 (d)** shows the result of the proposed method and **(e)** shows the result calculated with a narrow spatial step whose computing time was aimed nearly equals to the proposed method. Moreover the estimation error for each s is shown in **Fig. 4**. Although artifacts appear in the 45 degrees direction to the grids for each result, we can only find them near the reflective boundaries at the result of the proposed method. Moreover, definite peaks appear on the result of proposed method compared to others. The computing time for each method are shown in **Fig. 5**. Since the calculation time of **(d)** the proposed method and **(e)** are almost same, the proposed method enables the beneficial use of the calculation resources whether it is calculated by CPU or GPU. Therefore, the utility of the proposed method was confirmed with the use of sound source localization using a few numbers of microphones.

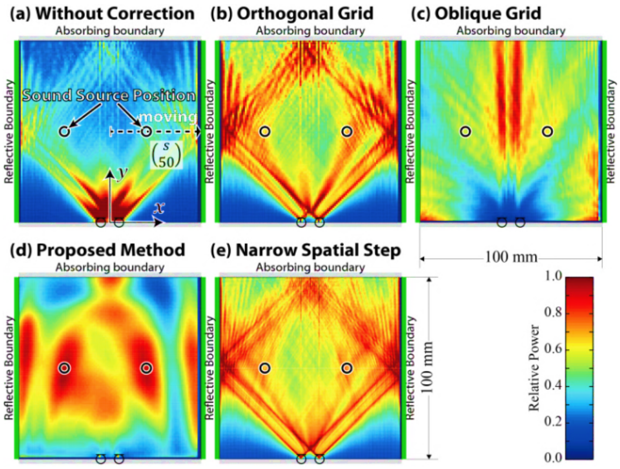

Fig. 3 Results of imaging $P_{i,j}$ in case $\underline{s} = (20, 50)$ **(a)** Without the correction coefficient **(b)** The grid was set along the spatial shape **(c)** The grid was set oblique angles to the spatial shape **(d)** Proposed method (Interchanging (b) and (c) while calculating) **(e)** Calculated with narrow spatial step (the calculation time was aimed nearly equals to (d))

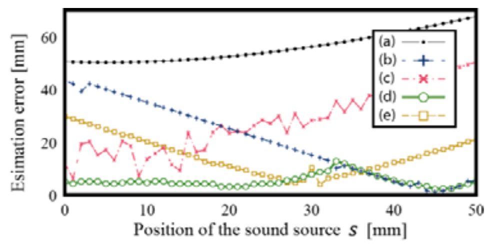

Fig. 4 Estimation errors for each method

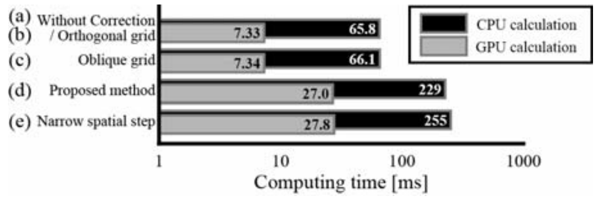

Fig. 5 Calculation time for each method

4. Conclusion

The purpose of this paper was to develop the method of sound source localization using a pair of microphones in reflective environments. Two techniques are proposed (the corrective coefficient for acoustic field imaging and the multilayer wave simulation) and the utility of them were evaluated through some experiments. As a result, it was confirmed that the accuracy of the proposed method is superior to conventional methods. For future works, authors are planning to reveal the detail characteristics of the proposed method.

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