Auralization of municipal public address announcements by applying geometrical sound simulation and multi-channel reproduction techniques

Junichi Mori*, Sakae Yokoyama, Fumiaki Satoh and Hideki Tachibana

Municipal public address system (M.P.A. system) for disaster prevention is an important system for supplying information outdoors. The speech intelligibility of the M.P.A. system, however, tends to be deteriorated by long-pass-echoes due to reflections from the surrounding buildings and the sounds from the loudspeakers covering other sub-areas. When designing such a M.P.A. system, effective tools for prediction of outdoor sound propagation are needed. For this aim, the authors have been investigating the application of the sound simulation technique based on geometrical acoustics. In addition, auralization is also desirable to subjectively assess the speech intelligibility of the M.P.A. system in acoustical design. Therefore, the authors are developing a simulation technique in which the sounds calculated by the geometrical simulation are reproduced through a 6-channel reproduction system, by which 3D information can be aurally realized. In this paper, the outline of this simulation method and some examples of its application are presented.

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INTRODUCTION

In Japan, municipal public address (M.P.A.) system is widely used to transmit various kinds of speech information to communities. In this system, speech announcements such as disaster-prevention, evacuation-order and crime-prevention are sent out simultaneously from loudspeakers located at multiple points in a certain area. The speech intelligibility of the M.P.A. announcements, however, tends to be deteriorated by multi-pass echo with long time delay due to reflections from nearby buildings and the sounds from the loudspeakers covering other sub-areas.

To mitigate such problems, it is necessary to consider the directional characteristic of the loudspeakers and their disposition in the covering area and reduce dominant reflections as far as possible. Therefore, for the design of a M.P.A. system, it is desirable to establish effective tools for predicting outdoor sound propagation. For this aim, we have been investigating the applicability of the computer modeling technique based on geometrical acoustics [1-2]. In addition, it is also desirable that the speech intelligibility of M.P.A. announcement can be assessed by auditory experiment, in which 3-dimensional information could be realized because the extent of deterioration of speech intelligibility by discrete multi-pass echoes might depend not only on the magnitude and delay time but also on the arriving direction of the echoes. In this study, therefore, a simulation method combining the computer modeling based on geometrical acoustics and 6-channel recording/reproduction technique was examined.

PRINCIPLE OF 6-CHANNEL RECORDING/REPRODUCTION TECHNIQUE

In this study the 6-channel recording/reproduction technique [3-7] is applied to investigate auditory impression of M.P.A. announcement. The principle of this technique is as follows.

The receiving system consists of six uni-directional microphones combined at every 90 degrees in the horizontal and vertical planes with a constant distance from the origin of the orthogonal coordinates. Under the assumption that all of the six microphones have an ideal cardioid directional characteristic expressed by Eq. (1) and the same phase characteristic, and the separation distance is sufficiently small compared to the wave length of the sound, the sound pressures sensed by respective microphones facing ±/− directions of x, y, z axes are expressed by Eq. (2) to Eq. (7) under the incidence condition of the sound shown in Fig. 1 (a).

\[
D(\theta) = \frac{1 + \cos \theta}{2} \quad (1)
\]

\[
p_{xs} = A_{xs} \cdot p_0 = \frac{1 + \sin \varphi \cos \theta}{2} p_0 \quad (2)
\]

\[
p_{ys} = A_{ys} \cdot p_0 = \frac{1 + \sin \varphi \sin \theta}{2} p_0 \quad (3)
\]

\[
p_{zs} = A_{zs} \cdot p_0 = \frac{1 + \cos \varphi}{2} p_0 \quad (4)
\]

\[
p_{xc} = A_{xc} \cdot p_0 = \frac{1 - \sin \varphi \cos \theta}{2} p_0 \quad (5)
\]

\[
p_{yc} = A_{yc} \cdot p_0 = \frac{1 - \sin \varphi \sin \theta}{2} p_0 \quad (6)
\]

\[
p_{zc} = A_{zc} \cdot p_0 = \frac{1 - \cos \varphi}{2} p_0 \quad (7)
\]

where, \( p_0 \) is the sound pressure of the incidence sound.

**FIGURE 1.** Sound incidence on an orthogonal coordinates and a 6-channel microphone set.
When reproducing these signals from six loudspeakers orthogonally combined in an anechoic room as shown in Fig. 2, the sound pressure $p$ at the origin is expressed as follows.

$$p = p_{x_0} + p_{y_0} + p_{z_0} + p_{y_0} + p_{z_0} = 3p_0$$  \(8\)

That is, the sound pressure at the origin is in proportion to the incidence sound omni-directionally.

As for the particle velocity components in $x$, $y$, $z$ directions, the following equations are obtained.

on $x$-axis: $p_{x_0} - p_{y_0} = \sin \phi \cos \theta \cdot p_0 \equiv \rho \cdot u_x$ \(9\)

on $y$-axis: $p_{y_0} - p_{y_0} = \sin \phi \sin \theta \cdot p_0 \equiv \rho \cdot u_y$ \(10\)

on $z$-axis: $p_{z_0} - p_{z_0} = \cos \phi \cdot p_0 \equiv \rho \cdot u_z$ \(11\)

In Eqs. (9), (10) and (11), $u_x$, $u_y$, $u_z$ are the particle velocity components of the incidence sound in $x$, $y$, $z$ axes, respectively. Thus, the particle velocity vector (accordingly, sound intensity vector) at the origin can be obtained from the outputs of the six microphones as a vector quantity.

Figure 1 (b) shows the 6-channel microphone set combined six 1/2 inch cardioid-type microphone units with separation distance of 55 mm. An example of the 6-channel reproduction system constructed in an anechoic room is shown in Fig.3. Though the principle mentioned above is explained for the center point of the reproduction system, we can have considerably accurate sound source localization when listening to the reproduced sound at the center of the system.

In this study applying the 6-channel technique, the impulse response calculated by computer modeling as mentioned below is divided into six channels by considering the arriving time and the arriving direction $(\theta$ and $\phi$). The 6-channel impulse response is convolved with a dry source (M.P.A announcement) and the synthesized sounds are reproduced by the 6-channel reproduction system as shown in Fig. 2. By doing so, the direct sound and successive discrete sounds (reflections from nearby buildings and sounds from the loudspeakers covering other sub-areas) can be heard with 3-dimentional information.

**FIGURE 2.** 6-channel recording/reproduction technique applied in this study.

**FIGURE 3.** 6-channel reproduction system constructed in an anechoic room (Chiba Institute of Technology).
CALCULATION OF OUTDOOR SOUND PROPAGATION IN M.P.A. SYSTEM

As a computer modeling software based on geometrical acoustics, ODEON [8-12] which was mainly developed to investigate the room acoustics is used in this study. In the modeling of buildings in the area under investigation, their shapes and sizes were approximated based on the measured values using a laser-range-finder. As the absorption coefficient of the boundary surfaces, the values shown in Table 1 were assumed for all frequency bands.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Absorption coefficient [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building surfaces</td>
<td>2.5</td>
</tr>
<tr>
<td>Ground surfaces</td>
<td>10</td>
</tr>
<tr>
<td>Surrounding boundaries</td>
<td>100</td>
</tr>
</tbody>
</table>

The loudspeaker system used in the M.P.A. system under this study is a set of four horn-type loudspeakers as shown in Fig. 4. For the modeling of this type of loudspeaker system in the calculation, the measurement data of sound pressure directional characteristic in six octave bands from 250 Hz to 4 kHz for a horn-type loudspeaker (TOA: TC-730M) shown in Fig. 5 was used. In the modeling, the directional characteristics of four loudspeakers were combined orthogonally.

In the calculation of the 6-channel impulse responses, the omni-directional impulse response and the arriving direction of the impulses calculated by the image source method of ODEON was used. The magnitude of each impulse was calculated using the arriving direction by considering the directionally of the hypothetical loudspeaker system.

![FIGURE 4. Loudspeaker system of M.P.A system.](image)

![FIGURE 5. Directional characteristic of loudspeaker (TOA:TC-730M) measured in an anechoic room.](image)

<table>
<thead>
<tr>
<th>Components</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of rays</td>
<td>10,000,000(Max value)</td>
</tr>
<tr>
<td>Transition order</td>
<td>10(Max value)</td>
</tr>
<tr>
<td>Max. reflection order</td>
<td>2,000(default)</td>
</tr>
<tr>
<td>Scattering of the surfaces</td>
<td>Neglected</td>
</tr>
</tbody>
</table>
CASE STUDY

The field measurement of the M.P.A. system was performed in the area shown in Fig. 6. In this area, four loudspeaker systems are distributed at a height of about 15 m above the ground. From those systems, a female announcement telling the crime-prevention for 30 seconds (speech rate is about 2.45 mora/seconds) is sent out at 5 P.M. every day. In the measurement, three receiving points (M1, M2 and M3) were chosen as shown in the figure and the announcement was recorded on a multi-channel digital data recorder through the 6-channel microphone set and an omni-directional microphone of a sound level meter.

As a result of the measurement, the omni-directional impulse responses measured through the microphone of the sound level meter and those measured through the 6-channel microphone set are compared in Fig. 7 (a) and (b). These impulse responses were obtained by calculating the cross-correlation function between the original source signal of the announcement and each sound received by each microphone for the three octave bands from 500 Hz to 2 kHz and the Hilbert-transform was applied to detect the envelope [2]. Here, regarding the results obtained by the 6-channel microphone set, the cross-correlation function was calculated for each microphone and the results were added according to Eq. (8). As a result, the impulse responses obtained by the two methods are in fairly good agreement for the three receiving points.

The impulse responses calculated by the computer modeling are shown in Fig. 7 (c). To compare these results with the measurement results mentioned above, the relative magnitude and delay time of the dominant impulses are in considerably good coincidence for the three receiving points.

To see the arriving direction of the dominant discrete sounds, the sound intensity vectors were obtained from the measurement results through the 6-channel microphone set according to Eqs. (9) to (11). Also for the results of computer modeling, the intensity vectors were calculated in the same way. As a result, the results of the measurement and the calculation correspond very well as shown in Fig. 8.
FIGURE 7. Echo-diagrams obtained by field measurement of Cross-Spectrum method and computer modeling.

(a) Results measured through microphone of sound level meter
(b) Results measured through 6-channel microphone set
(c) Results calculated by computer modeling

FIGURE 8. Sound intensity vectors obtained by field measurement and computer modeling (The alphabets marked in the figures are corresponded to those shown in Fig. 7, and the loudspeaker system nearest to the receiving point is positioned to 0 degree direction.).
AUDITORY EXPERIMENTS

To examine the effectiveness of the 3-D sound field simulation technique combining the geometrical sound simulation and the 6-channel reproduction technique, auditory experiments were performed in two steps as follows.

Experiment-1: Basic Study

As the first experiment, the perception of the direction of a long delayed sound was examined in a very simple situation. The calculation condition is shown in Fig. 9, in which the hypothetical sound source and the receiving point were assumed to be separated by 80 m and a reflecting surface was assumed at a position 100 m apart from the center of the sound source and the receiving point. By turning the sound source and the receiving point, the angle of the direct sound and the reflection changed from 0 to 330 degrees at every 30 degrees and 6-channel impulse responses were calculated for each condition according to Eqs (2) to (7). As a test sound, a female announcement made by “Voice Text Japanese Editor” for 20 seconds (speech rate is about 3.55 mora/seconds) was convolved with the impulse responses and reproduced from the 6-channel reproduction system.

In the auditory experiment, the test subject sat facing the direction of the direct sound and asked to judge the direction of the reflection. The test sounds for respective directions were reproduced twice in random order. During the judgment, the subject was allowed to move his/her head to detect the reflection. Eleven university students participated in this experiment.

The experimental results for all the subjects are shown in Fig. 10. In this figure, the horizontal axis is the simulated direction angle of the reflection and the vertical axis is the perceived direction and the area of a circle is proportional to the number of the responses. In the result, it is seen that almost all circles are plotted on the 45 degrees line; it indicates that the direction of reflection can be correctly judged by the 6-channel reproduction technique.
Experiment-2: Simulation of M.P.A. announcement

In the second experiment, a M.P.A. announcement received at the three points chosen in the case study mentioned above and the sounds synthesized by the 6-channel technique including the directional information for the corresponding receiving points were used and hearing difficulty of the announcement were examined by auditory experiment. As for the synthesized sounds, the dry source of the announcement was convolved with the calculated 6-channel impulse responses for each receiving point and therefore the background noise was not included.

The test sounds were reproduced from the 6-channel reproduction system so that the sound levels at the hearing point were adjusted to be almost the same levels in the actual field. The test subject was asked the hearing difficulty for each sound in six step categories. The hearing test was performed for the recorded sounds and the synthesized sounds separately. Each test sound was reproduced twice in random order. During the judgment, the subject was allowed to his/her head in this case, too. Nine university students participated in this experiment.

The experimental results are shown in Fig. 11 (a) for the real recordings and Fig. 11 (b) for the synthesized sounds. In these results, the vertical axis indicates the mean value of the score for hearing difficulty judged by all of the subjects, obtained by assuming equal intervals in the ordinal scale. In the figures, the bar indicates the standard deviation. To compare the two results, it is seen that the differences of the mean score are in good resemblance.

As for the sound at M2 point, it was reported by many subjects that the sound with a long delay-time of about 2.2 seconds might increase hearing difficulty and this point was examined by eliminating the sound from the synthesized test sound. The result of this additional experiment is shown in Fig. 11 (b) and it is seen the score of hearing difficulty lowered by one step.

![FIGURE 11. Experimental results on hearing difficulty of a M.P.A. announcement. (Categories: 1; “not difficult to hear at all”, 2; “A little difficult to hear”, 3; “Moderately difficult to hear”, 4; “Very difficult to hear”, 5; “Extremely difficult to hear, 6; “The contents cannot be understood at all”).](image)

CONCLUSIONS

The M.P.A. system is important for the transmission of acoustic information in local areas. To make the system effective all the more, it is necessary to obtain high speech intelligibility by considering the sound system and the way of speech synthesis. For the design of the system, it is desirable to have effective experimental techniques by which the auditory sensation can be correctly realized. For this aim, a sound simulation method using computer modeling based on geometrical acoustics and 6-channel reproduction technique has been investigated in this study. As a result of the auditory experiments, it has been found that the method is effective to simulate the sound propagation from a M.P.A. system with 3-dimensional information and can be used in subjective experiment to examine the speech intelligibility.
ACKNOWLEDGMENTS

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REFERENCES