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Evaluation of isotropy of sound field in a room based on the decay-canceled sound intensity

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Abstract

Isotropy is one important element for evaluating diffuseness of a sound field. Later reflected sounds refer to reflected sounds with a longer delay of more than 80 ms. In particular, reflected sounds with a very long delay are called “reverberation tails.” Thus far, it is not clear whether a sound field has characteristic arrival directions for the reverberation tail as the reverberation tail shows not significant characteristics owing to diffusion. The purpose of this study is to develop a technique for analyzing the spatio-temporal structure of reflected sounds in the reverberation tail in order to clarify whether there are significant characteristics on arrival directions of reflected sounds in the reverberation tail. In this study, the decay-canceled instantaneous sound intensity (DC-II) is proposed for evaluating the isotropy of a sound field, especially in the reverberation tail. The C-C method, which has been developed by the authors [Proc. INTER-NOISE 2008, T. Hanyu], was employed to measure the instantaneous sound intensity. We investigated the DC-II in several sound fields. As results, the DC-II showed that sound fields have significant characteristics on the arrival directions of late arriving reflected energy, namely the reverberation tail.

Keywords: Isotropy, Sound field, Decay-canceled sound intensity, Diffuseness, C-C method
1 Introduction

In the acoustic design of concert halls, the arrival direction of early reflected sounds is an important factor affecting parameters of spatial impressions, such as the apparent source width [1,2]. In fact, each concert hall has characteristic arrival directions for the early reflected sounds. Early reflected sounds generally refer to the reflected sounds that have a shorter delay of less than 80 ms from the arrival time of the direct sound. On the other hand, later reflected sounds refer to reflected sounds with a longer delay of more than 80 ms. In particular, reflected sounds with a very long delay are called “reverberation tails.” Thus far, it is not clear whether a concert hall has characteristic arrival directions for the reverberation tail as the reverberation tail shows not significant characteristics owing to diffusion. The purpose of this study is to develop a technique for analyzing the spatio-temporal structure of reflected sounds in the reverberation tail in order to clarify whether there are significant characteristics on arrival directions of reflected sounds in the reverberation tail. This analysis technique is based on the C-C method (named so as it involves a pair of cardioid microphones) [3, 4], which measures the instantaneous sound intensity and the decay-canceled impulse response [5].

In this study, a calculation method is introduced for the decay-canceled instantaneous sound intensity [6], which is an application of the decay-canceled impulse response. Significant reflected sounds in the reverberation tail are detected using the decay-canceled instantaneous sound intensity. Finally, results are measured in actual sound fields using the developed method.

2 Decay-canceled instantaneous sound intensity

2.1 Calculation of the decay-canceled instantaneous intensity

There are various methods for measuring the instantaneous sound intensity. The C-C method, which was previously developed by the author [3], is used in this study. The C-C method uses plural cardioid microphones such as a four-channel system in which each microphone is located at the apex of a tetrahedron and directed toward the tetrahedron center of gravity or a six-channel system in which each microphone is located on three-dimensional orthogonal axes and directed toward the origin. The intensity decay curve $I_s(t)$ is calculated from the instantaneous sound intensity $I(t)$ as follows:

$$I_s(t) = \int_t^\infty |I(t)| \, dt.$$  \hspace{1cm} (1)
Level of the decay curve, $IL(t)$, is expressed as follows:

$$IL(t) = 10 \log_{10} I_s(t) \ .$$  

(2)

Using $I_s(t)$, the decay-canceled instantaneous intensity can be obtained using

$$I_g(t) = \frac{I(t)}{I_s(t)} \ .$$  

(3)

Next, the calculation of the instantaneous intensity decay rate $A_I(t)$ is performed as follows:

$$A_I(t) = \frac{1}{\tau_2(t) - \tau_1(t)} \int_{\tau_1(t)}^{\tau_2(t)} I_g(t)dt \ .$$  

(4)

As shown in Figure 1, $\tau_1(t)$ and $\tau_2(t)$ are defined as the times when the decay levels are $+5 \, \text{dB}$ and $-5 \, \text{dB}$ relative to the decay level at time $t$. Figure 1 shows an example of the decay ratio calculation for two cases with the same time window setting; one case is for a steep slope while the other is for a shallow slope. The width of the time window changes automatically depending on the slope of the decay curve. A direct sound is not influenced by the room absorption. Therefore, $A(t)$ is calculated only after the level of the decay curve becomes $-10 \, \text{dB}$ relative to the direct sound level. For all $A_I(t)$ values before this level, the $A_I(t)$ at $-10\, \text{dB}$ is used.

Figure 1: Example of the decay ratio calculation.
Using $A_i(t)$, the normalized decay-canceled instantaneous intensity can be obtained:

$$I_b(t) = \frac{I_i(t)}{A_i(t)} = \frac{I(t)}{A_i(t) A_s(t)}.$$  \hspace{1cm} (5)

By this normalization, the time average of the magnitude of this vector $|I_b(t)|$ is always equal to 1. Here, $I_b(t)$ represents the relative magnitude and direction of the instantaneous intensity to the average decay curve of the intensity.

2.2 Calculation of the virtual sound sources

Using $I_b(t)$, the spatio-temporal structure of reflected sounds can be calculated as follows:

$$S(t) = \frac{I_b(t)}{|I_b(t)|} \times ct.$$ \hspace{1cm} (6)

where $c$ is the velocity of sound, $t$ is the time that the sound wave travels from the sound source, and $S(t)$ is the three-dimensional position vector.

The instantaneous intensity vectors are normalized by taking the absolute value of the instantaneous intensity multiplied by the distance that the sound wave travels from the source. These vectors $S(t)$ describe the spatio-temporal structure of the instantaneous sound intensity. This spatio-temporal structure is considered as a virtual sound source distribution. By combining the decay-canceled instantaneous intensity $I_b(t)$ and the spatio-temporal structure of instantaneous sound intensity, the significant reflected sounds can be detected in the reverberation tail. A particular threshold $k$ is set for $I_b(t)$. When $I_b(t)$ exceeds $k$, the instantaneous intensity is considered as a significant reflected sound. If $k$ is set higher, only the reflected sounds with large energy would be detected. Accordingly, the value of $k$ can be changed based on the magnitude of energy of the reflected sounds that are to be detected.

2.3 Measurement results of the decay-canceled intensity in actual sound fields

Figure 2 shows the sound fields which are examined in this study, a reverberation chamber, a concert hall and a classroom. The capacities of the concert hall and classroom are 511 and 200 persons, respectively. The reverberation chamber is a rectangular room ($W \times D \times H = 5m \times 4m \times 3m$). The concert hall is a shoebox-shaped hall, which is used mainly for chamber music. The back wall of the hall is absorptive. The reverberation times in the reverberation chamber at the 500-Hz and 2-kHz octave bands are 8.1 s and 4.0 s, respectively, and those of the concert hall are 1.7 s and 1.9 s, and those of the classroom are 0.6 s and 1.2 s, respectively.
Figures 3, 4 and 5 show impulse responses and the orthogonal components of the normalized decay-canceled instantaneous intensity in each sound field. Note that the sign of the intensity components represent the propagation direction of the sound energy. Thus, positive X-, Y- and Z-component values represent the energy from the left-hand side of the hall, the back of the hall, and the floor, respectively.

The reverberation chamber results (Figure 3) show that no anomalous reflected sounds occur. In particular, the absolute values of the positive and negative intensities are almost same on average. Therefore, this chamber can be considered as an isotropic sound field. The concert hall results (Figure 4) show that although no anomalous reflected sounds occur, the sound energy is biased in the Y- and Z-directions. In particular, the absolute values of the negative intensities are larger than those of the positive intensities for both the Y- and Z-components. These results mean that the sound energy reflected from the front and ceiling is larger than that reflected from other directions. It should be noted that this imbalance of reflected energy continues until the reverberation tail. As shown in the classroom results (Figure 5), the Y-component repeatedly indicates large positive and negative intensity values. This means that the flutter echo continues until the reverberation tail in the longitudinal direction of this room.

2.4 Results of the virtual sound source distribution in actual sound fields

Figure 6 shows the results of the virtual sound source distribution analysis for three sound fields. In this analysis, the threshold of $I_h(t)$ was set to 4. This threshold is 6 dB larger than the average intensity decay curve. Only the values of $I_h(t)$ that exceed the threshold are transformed to virtual sound sources through equation (6). Moreover, virtual sound sources far from the origin indicate that the reflected sound arrives later than those sources near the origin.

In results of the reverberation chamber, the virtual sound sources are distributed over a wide range uniformly. These results mean that this reverberation chamber is almost isotropic sound field. In the concert hall results, the reflected sound energy from front of the hall and the ceiling is larger in the reverberation tail. The back wall of this hall is absorptive, and the audience seats are upholstered. The use of these absorptive materials is the reason for the continued imbalance of the reflected sound energy until later part of the impulse response, i.e. the reverberation tail. In the classroom results, the virtual sound sources can be calculated longitudinally in a linear fashion. Using the virtual sound sources, the flutter echo can be clearly confirmed to continue until the reverberation tail in longitudinal direction of this room.
Figure 3: Impulse responses and the orthogonal components of the normalized decay-canceled instantaneous intensity in the reverberation chamber.
Figure 4: Impulse responses and the orthogonal components of the normalized decay-canceled instantaneous intensity in the concert hall.
Figure 5: Impulse responses and the orthogonal components of the normalized decay-canceled instantaneous intensity in the classroom.
Figure 6: Virtual sound source distribution of 2kHz octave band in each sound field
3 Conclusions

In this study, the decay-canceled instantaneous sound intensity was proposed for evaluating the isotropy of a sound field, especially in the reverberation tail. Reverberation tails in investigated sound fields showed significant characteristics of their arrival directions. The concert hall results showed that the sound energy reflected from the front and ceiling is larger than that reflected from other directions. Especially, it should be noted that this imbalance of reflected energy continues until the reverberation tail. Before this study, these characteristics had not been clarified. Thus, the imbalanced influences on the subjective effects in the reverberation tail have also not been clarified. Therefore, these influences will be studied in a future work.

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References


