SPATIAL DECOMPOSITION AND BEAMFORMING FOR PREDICTING 3D ROOM ACOUSTICS IN CONCERT HALLS

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1 INTRODUCTION

Our work involved the development and implementation of a measurement system to analyze room acoustics. Existing methods define the characteristics of a room by analyzing the impulse responses within the room in the temporal domain. A swept sine signal and an omni-microphone are typically used to generate the impulse response that is used to measure standardized acoustic parameters [1, 2]. This method has the advantage of calculating the acoustic parameters of the room with high stability. In contrast, neither directional nor spatial information, which is required for investigating the sound paths and reflection surfaces in a room, is well defined. The spatial distribution of sound has to be considered in room acoustical design with regard to auditory perception [3]. Previous studies have proposed methods for spatial analysis in which multiple microphone arrays such as spherical, 6-channel, and B-format microphones are used [4-7], whereas visualization methods, which involve multi-dimensional data, remain problematic because of the complexity of the data. Although some methods for visualization were previously suggested [4-7], it is still need to be developed.

In this study, the characteristics of the room acoustics were investigated by analyzing the 3D room impulse responses measured in an actual chamber hall. A 32-channel spherical microphone array was used as the measurement system and reflections from the lateral walls and ceiling were visualized in temporal and spatial domains on video using plane wave decomposition and adaptive beamforming. This measurement technique suggests synthesizing spatial impulse response (SIR) to analyze the directional room acoustic parameters such as the clarity of the sound.

2 SOUND FIELD SYNTHESIS

Sound field synthesis, which is based on the Kirchoff-Helmholz integral [8], computes the sound field on a real or imaginary surface, whereupon the remainder of the sound field can be determined mathematically, and this would enable the plane wave decomposition and beam forming to be determined. Three techniques, namely adaptive beam forming, minimum variance distortionless response (MVDR), and sound field extrapolation, were used to obtain a signal for each direction, an approach referred to as SIR.

A spherical microphone array was used in this study to capture the sound field on a rigid real surface. Theoretically, continuous sound field properties are required on a spherical surface; in contrast, our 32-channel array yields values at discrete spatial sampling points. A spatial Fourier transform technique with spherical microphone arrays (Eigenmike, mh-acoustics, USA) was used in the sound field synthesis to decompose the sound field into spherical harmonics. The spherical harmonics form the angular portion of a set of solutions of the Laplace equation. The selection of higher order harmonics enables a higher directional selectivity of the array to be obtained.

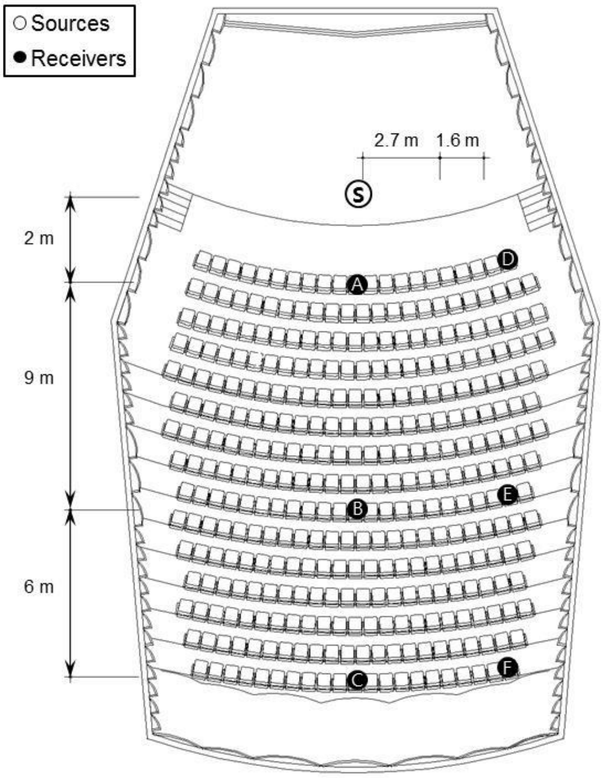
In conventional beamforming, commonly known as delay and sum beamforming, once the array geometry is fixed and the steering direction is determined, the characteristics of the beam pattern remain fixed. Therefore, readjustment of the beam-pattern would require physical changes to the microphone array geometries which is not possible [9]. To resolve this problem, adaptive beamforming, capable of responding to the frequency bands, was considered by using the MVDR beamformer [10] instead of simple spatial filters. This beamformer generally uses a finite impulse response filter to constrain the desired signal using unity gain while minimizing the filter output energy. This technique was developed to detect the direction of arrival of a desired signal during array processing.

3 METHODOLOGY

3.1 Measurement Setup

Measurements were conducted in the Sejong chamber hall with a seating capacity of 433, shown in Figure 1a, located in Seoul, South Korea. The hall is reverse-fan shaped and has tilted side walls designed with saw-tooth-type diffusers (1D corrugations) to provide diffusive reflections. The structural length and the depth of the diffusers vary from 0.3 to 1.2 m. The measurements were conducted according to the scheme shown in Figure 1b.

(a)



(b)

Figure 1. Measurement of real hall using spherical microphone: (a) Sejong chamber hall and (b) measurement positions (○: source, ●: audience receiver).

3.2 Sound Energy Map

The reflections in the time domain were investigated in each of the three directions by synthesizing and transforming the 32 signals from the spherical microphone into 180 × 360 signals, for a total of 64,800 signals. The algorithm which was used for the analysis was developed with MATLAB. The method enables the time range for the analysis to be selected, with a minimum range of 3 ms due to data quantity limitations in the spatial Fourier transform. A color image contour was selected to display the 3D directions based on the sound level. The Mollweide projection method, which is also known as the elliptical or homolographic method, was selected. In addition, the panoramic view at the receiver position was superimposed upon the color map contour was used to facilitate comprehension of the design component located in the direction of reflections, as shown in Figure 2.

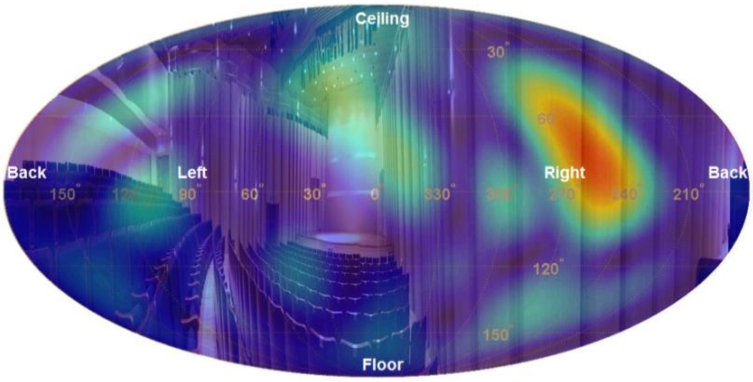


Figure 2. Example of sound energy map at position E (time interval of 61 ms to 64 ms after direct sound)

3.3 Spatial Impulse Response (SIR)

When performing acoustic measurements in a room with the aim of conducting an analysis, impulse responses containing all of the frequency components and energy distributions in the time domain are required to quantify the acoustic characteristics. In this study, impulse responses were generated in all directions by decomposing the signal and by steering the signal in a particular direction, known as SIR. Figure 3a shows the sound energy map for the interval 0 to 80 ms at position E. As an example, directions 1 and 2 were selected as representing the minimum and maximum levels. These two directions can be used to generate and compare the SIRs as shown in Figure 3b. The SIR has a high resolution with 1 degree in regard to all directions.

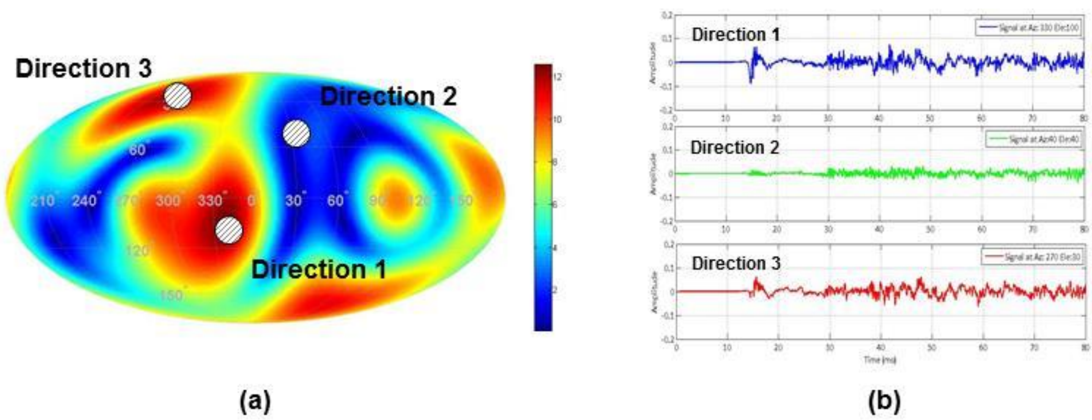


Figure 3. Example of SIRs for three directions at position E.
(a) Sound energy map for 0 to 80 ms and (b) SIR in each direction

4 RESULTS

4.1 Acoustic Visualization

A dynamic view was obtained by producing videos for the temporal range 1 – 80 ms, as shown in Figure 4, which displays the dynamic change in spatial reflection depending on the sound level. This video contains 80 frames presented in time intervals of 1 ms, each of which represents the sound level accumulated for 5 ms. The 703 SIRs were plotted in the temporal domain to allow a comparison of the differences between traditional impulse responses and the sound energy map. For example, at position A in the frame from 13 to 18 ms, reflections from the left rear wall of the audience area appear after all the other reflections (Figure 4a). Between 33 and 38 ms, the reflections are almost above the second order, implying that these reflections originate from the right wall of the stage (Figure 4b).

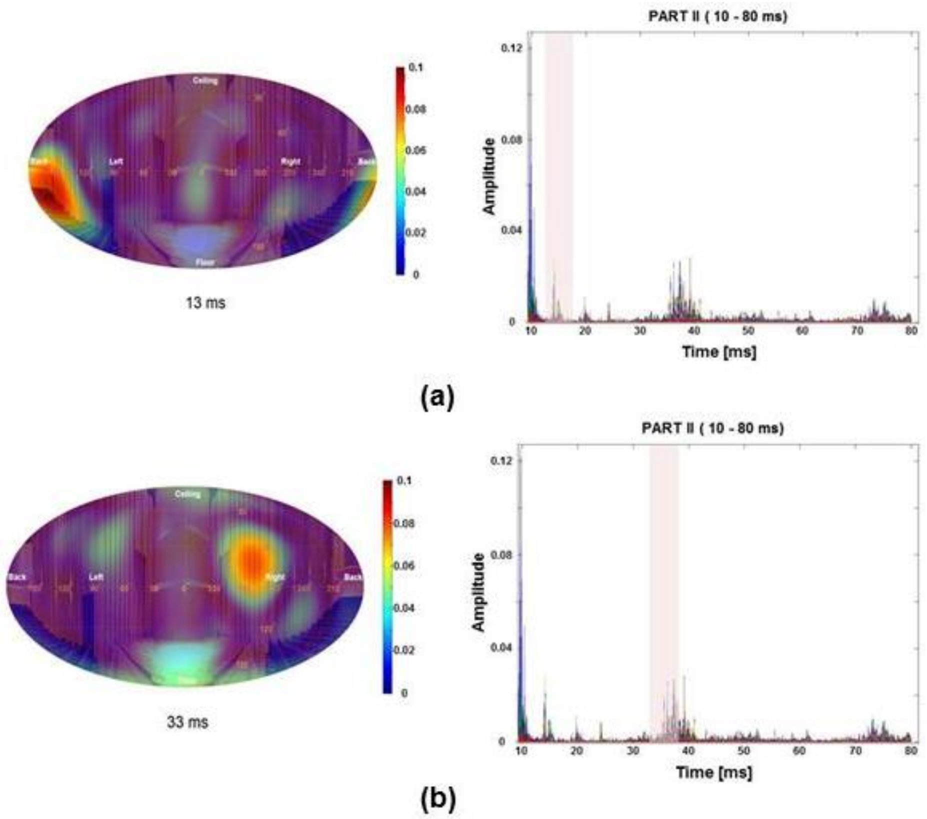


Figure 4. Example of acoustic visualization at position A. (a) 13 to 18 ms and (b) 33 to 38 ms

4.2 Directional Early Reflections

C_{80} was considered along the 3D directions using SIR to analyze the spatial acoustic parameters. A polar diagram was used to show the spatial energy distribution along the three planes X-Y (floor plan), X-Z (longitudinal section) and Y-Z (cross section). The hall plans were superimposed upon the polar diagram, as shown in Figure 5. Moreover, the average, maximum, and minimum value of the 12 directions in each plane was plotted using a red line, black triangle, and white circle, respectively, to compare the value as a function of direction. The data from the acoustic parameters, measured using the omni-directional, were added to the plot as a grey dotted line to compare our results with those from this different measurement system.

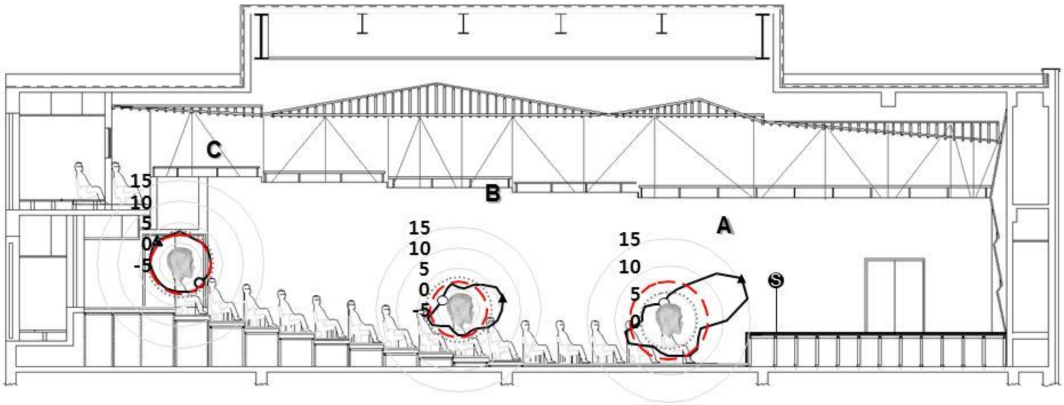


Figure 5. Results of C_{80} in longitudinal section

5 SUMMARY

In this study, acoustic measurements were conducted using a 32-channel spherical microphone in a chamber hall and assessed using the proposed spatio-temporal analysis and display method. The directions of the sound amplitude were plotted in three dimensions using a color contour map combined with a panoramic view at the listener's location. Interval data were displayed in video format at 1 ms intervals. A multi-channel microphone was used to measure the impulse response. These measurements were subjected to a spatio-temporal analysis, the results of which only show the direction of reflections with energy. Traditional acoustic parameters such as energy decay and temporal energy distribution are important indicators that quantify the acoustic quality of a room; however, these parameters were not treated spatially in previous studies. The results of the tests were displayed on a polar diagram which was combined with the floor plan and sections of the hall.

6 REFERENCES

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