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Applicability of locally reacting boundary conditions to porous material layer backed by rigid wall: Wave-based numerical study in non-diffuse sound field with unevenly distributed sound absorbing surfaces

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A B S T R A C T

To clarify the applicability of locally reacting boundary conditions in wave-based numerical analyses of sound fields in rooms, we numerically analyzed a non-diffuse sound field in a room with unevenly distributed sound absorbing surfaces and investigated the differences between the extended and local reactions. Each absorbing surface was a porous material layer backed by a rigid wall. Simulations were performed by the fast multipole boundary element method, a highly efficient boundary element method using the fast multipole method. At low frequencies, the extended and local reactions yielded similar reverberation decay curves because of the influence of the room. However, when the random incidence absorption coefficients were small at low frequencies or frequencies were high, the difference was greater than expected from the corresponding Eyring decay lines. We conclude at high frequencies, the locally reacting boundary conditions lead to a longer reverberation time than that expected from the absorption coefficient differences between the extended and local reactions. These differences were similar in sound-pressure-level and sound-intensity-level distributions, and in the oblique incidence absorption coefficient of the absorbing surfaces, but were increased at low frequencies.

1. Introduction

In accurate analyses of sound fields in architectural spaces using wave-based numerical methods, we must consider the extended reaction of the boundaries, specifically, sound propagation into and behind the walls. However, when the walls and their backs are composed of various materials, modeling becomes difficult. In addition, because architectural spaces are large, numerically analyzing the backs of wall surfaces incurs a significant computational cost.

Computational simulations in architectural acoustics have remarkably advanced in recent years [1]; however, for the above-mentioned reasons, most acoustics researchers adopt locally reactive boundary conditions with reflection/absorption characteristics defined by surface impedance. Similarly, in wave-based numerical studies on techniques for measuring surface impedance, absorbing surfaces are often treated by local reactions [2–5]. However, whether local reactions degrade the computational accuracy remains unclear. It is important to clarify the range over which the local reaction ensures computational accuracy, particularly in wave-based numerical analyses, which are regarded as highly accurate.

To investigate this issue, some previous studies have focused on the absorbing surfaces themselves. Jeong compared the random incidence absorption coefficients in the extended and local reactions using five wave-propagation models for porous materials [6]. Later, Jeong and co-authors experimentally validated the difference between the extended and local reactions [7]. According to the Miki model [8], Yasuda et al. theoretically organized the oblique and random incidence absorption coefficients of a porous material layer backed by a rigid wall using simple parameters such as the material thickness and airflow resistivity [9]. However, for understanding the difference between the local and extended reactions in room acoustics, surrounding environments, which influence the incidence condition of sound waves, should be considered. Franzoni and Elliot employed an angle-by-angle approach for rectangular enclosures. When the absorptive material was treated as bulk reacting (extended reacting) rather than point reacting (locally reacting), the fit to the experimental results improved [10]. Hodgson and co-authors showed that applying the local and

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extended reactions in rooms causes widely different results in a combined beam-tracing and transfer-matrix model [11,12]. In the field of wave-based computational acoustics, some practical studies have focused on different types of effective surface impedance at random/field incidence. Otsuru and co-authors analyzed the sound field in an irregularly shaped reverberation room with an absorbing material using the time-domain finite element method (FEM). When the ensemble averaged surface impedance at random incidence [13] was applied to the absorbing surface rather than the surface impedance at normal incidence, the fit to the experimental results improved [14,15]. Aretz and Vorländer analyzed the sound field in an irregularly shaped room with three absorbing walls using the frequency-domain FEM. When a porous PU foam with a strong angular dependence of impedance was assumed for the absorbing surfaces, the simulations with field incidence impedances showed comparably good results to those obtained with a three-dimensional FE absorber model (an extended reacting model) [16]. However, one reason for the effective functioning of the random/field incidence surface impedances in these studies is that the analyzed sound fields were relatively diffused because of the room shapes. To generalize these results, further studies are required.

Generally, the extended and local reactions are inconsistent when a sound wave intercepts an absorbing surface at an angle far from the surface normal. Such situations easily occur in rooms with unevenly distributed absorbing surfaces, such as absorbing ceilings and/or floors. In such a non-diffuse field, many incidence waves are oblique to the absorption surfaces. Oblique incidence slows the reverberation decay, because normal modes nearly parallel to these surfaces tend to remain after other modes decay. Building on the analyses of the relative diffuse fields cited above [14–16], the analysis of an extreme non-diffuse field can help clarify the error range (particularly the upper limit) of the local reaction in wave-based simulations of room acoustics. The findings of this analysis are directly applicable to rooms in which wide areas of the ceiling and/or floor are absorptive but the walls are reflective, such as classrooms and banquet halls.

Here we thoroughly investigate the difference between extended and local reactions in a wave-based numerical analysis of non-diffuse sound fields. The simulation environment is a room with unevenly distributed sound absorbing surfaces. Each surface is composed of a porous material layer backed by a rigid wall. The sound field analysis is accomplished by the fast multipole boundary element method (FMBEM) [17,18], a highly efficient boundary element method (BEM) using the fast multipole method (FMM). In this steady-state numerical method, we can simulate the frequency characteristics of the absorbing surfaces in detail. From the frequency responses obtained by the FMBEM, we can calculate and compare the reverberation decay curves, sound pressure level distributions, and sound intensity level distributions. Especially, we relate the simulated acoustic characteristics in the room to those of infinite-plane absorbing surfaces. As an offshoot of the investigation, we also reveal the reverberation decay phenomena in non-diffuse sound fields.

Section 2 of this paper presents the investigated analysis room model and numerical procedures, and validates the procedures for obtaining the reverberation decay curves from the steady-state numerical results. In Section 3, we compare the numerical results of virtual materials with different boundary conditions but the same normal incidence absorption coefficient. We also discuss the applicability of the real-number surface impedance (surface resistance), which is often used because complex-number data are missing. In Section 4, we confirm the observations of the previous section in a similar investigation on real materials. Section 5 summarizes the paper.

2. Investigation setup

2.1. Analysis model

The analysis model is a $(8.7 \times 5.1 \times 3)$-m^3 rectangular room with unevenly distributed sound absorbers (see Fig. 1). A point source is located at (2, 2.55, 1.2), with a sound pressure amplitude of 1.0 Pa at a point in a 1-m distance. Throughout this paper, all distances in parentheses are in meters.

2.2. Boundary conditions

The entire floor and ceiling surfaces are absorptive. The other surfaces are reflective with a real-number surface impedance corresponding to the normal incidence absorption coefficient $\alpha_n = 0.05$.

2.3. Numerical procedures

All numerical calculations in the steady-state sound field analysis were performed using FMBEM.

2.3.1. Sound field analysis with FMBEM

There are two kinds of FMBEM—one each for low [18] and high frequencies [17]. We adopt the latter. The boundary elements are constant and rectangular, and their width is $<1/6$ of the analysis wavelength. For extended reacting absorbing surfaces, we apply the domain decomposition method [19,20], treating sound fields in porous materials as sub-domains. The linear system is iteratively solved by GPBiCG [21] with ILUT$(10^{-5}, 50)$ preconditioning [22] and a stopping criterion of $\varepsilon = ||\mathbf{b} - \mathbf{Ax}||/||\mathbf{b}|| = 10^{-6}$. Here $\mathbf{A}$ is the system matrix, $\mathbf{b}$ is the right-hand-side vector, and $\mathbf{x}$ is the unknown vector of the linear system. The interval of the analyzed frequencies is 0.25 Hz, unless noted otherwise. From the single-frequency results, the sound-pressure and sound-intensity levels of the 1/3-octave bands are obtained by summing the energy and active intensity vectors, respectively.

2.3.2. Calculation of reverberation decay curves

The frequency responses obtained by the FMBE analysis are processed through 1/3-octave band filters, and transient responses are obtained by an inverse fast Fourier transform. The transient responses are time-delayed to satisfy the law of causality, and reverberation decay curves for the 1/3-octave bands are obtained by the integrated impulse response method.

2.4. Validation of numerical procedures

To validate the above procedures for obtaining reverberation decay curves, we compare the obtained curves with those of the

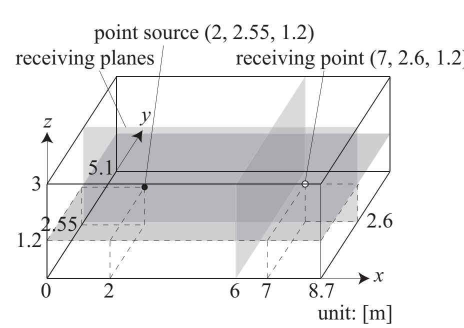

Fig. 1. Analysis model with absorptive floor and ceiling, and reflective walls.