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Recent advances in building acoustics: An overview of prediction methods and their applications

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ABSTRACT

This paper presented an overview of the prediction methods used in building acoustics. The methods reviewed were based on analytical models, empirical models and numerical models. This review found that the analytical models had made significant contributions to the research literature in building acoustics in the past three years. Numerical models or experimental models were commonly used to verify the analytical models. Besides, the prediction methods used in building acoustics are those used for prediction in room acoustics and for air-borne sound, structure-borne sound, and duct-borne sound. Many of the literature found in this review were related to the prediction of sound in room acoustics and for air-borne sound.

1. Introduction

Acoustics can be defined as the generation, transmission, and reception of energy in the form of vibrational waves in matter [1]. It is the scientific study of sound, which is the pressure fluctuation or disturbance sensed by the human ear or measured by a microphone at a point in space. In contrast, noise is regarded as "unwanted" sound. Building acoustics refers particularly to the acoustics issues in buildings, such as room acoustics. To assess the acoustical environment or apply possible noise control measures, it is essential to have appropriate and accurate methods for predicting the level and spectral content of the sound in buildings. There are many facets to the field of building acoustics and many publications on building-related acoustics issues. Rather than being an inclusive literature review of building acoustics, this paper mainly reviews studies related to the prediction methods used in building acoustics published within the past three years in English-language journals. The aim is to provide an overview of the recent advances in building acoustics and the methods used for predicting sound fields in buildings. These methods are classified as those used for prediction in room acoustics and for air-borne sound, structure-borne sound, and duct-borne sound.

2. Overview of prediction methods used in room acoustics

Apart from experimental methods, three modeling methods are widely used in room acoustics: wave-based acoustical methods, geometrical acoustics methods and diffusion equation methods. In wave-based acoustical methods, acoustics quantities are completely defined as functions of space and time in a homogeneous and bounded space. The numerical methods usually applied to approximate the wave equation governing sound propagation in rooms are the finite difference method and the finite element method. The wave-based acoustical methods are efficient in handling conditions of which rooms are small compared to the wave length, with simple shapes and well-defined boundary conditions. Workload of numerical calculations grows rapidly as a function of the frequency [2], and other methods such as geometrical acoustics methods may be applied to handle high frequency simulations. Geometrical acoustics methods are also called ray acoustics methods. In these methods, the high-frequency sound in air is imagined as traveling in a straight line directly from the sound source to the receiver. The image source method, ray tracing, and beam tracing methods can be classified as geometrical acoustics methods. The acoustic diffusion equation model is an energy-based model that is successfully applied in room acoustics for predicting the late part of the decay [3]. It is based on the analogy between sound energy density and a density of sound particles traveling at velocity c along straight lines [4]. Some researchers reviewed those

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methods utilized in room acoustic simulations [2,5]. Hornikx et al. [6] conducted a case study of two selected rectangular shaped sports halls. A diffuse field method, a geometrical acoustics method and a wave-based acoustical method were used in predicting the sound pressure level and reverberation time. Simulation results of the wave-based acoustical method agree well with the measurement results.

2.1. Wave-based acoustical method

The wave-based acoustical method is based on the theory of acoustic wave. The fundamental equation governing the propagation of sound in air is the wave equation. The wave equation with scalar parameter is given by:

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0 \quad (1)$$

where p is the sound pressure, c is the velocity of sound. With an analytical method, standing-wave frequencies existing in rectangular rooms can be derived. However, when the room shape and boundary conditions are complicated, numerical methods must be used to obtain approximate solutions. These numerical methods include the finite element method and the finite difference method. There are less recent works about utilizing the finite element method in room acoustics than the finite difference method. The following part in this section is mainly about the finite difference method utilized in wave-based acoustical models.

Analysis of the finite difference method starts with the formulation of a wave equation, which has a vector formulation and scalar formulation. Botts and Savioja [7] compared these two schemes and demonstrated the way to integrate vector formulation with the more efficient scalar formulation. Boundary conditions are of importance in the finite difference method. Bilbao [8] demonstrated the potential of the finite difference time domain—the reduced type of finite volume method used to handle complex geometries and boundary conditions. Some researchers investigated the use of various source models. Other researchers [9–11] investigated sourced excitations in the finite-difference time-domain method. Escolano et al. [12] proposed the use of a general minimum-phase filter to alleviate the problem caused by simplification from the 3-D to the 2-D simulation model. Botts and Savioja [13] investigated eigenvalue decompositions of finite difference operators that are used for room acoustics simulation or virtual acoustics. Their investigation gave insights into solution behavior and stability.

2.2. Geometrical acoustical methods

Practical application of the wave equation turns out to be complicated, except for small enclosures and low frequencies [14]. The geometrical acoustics method, a much simpler description of the propagation of sound than the wave-based acoustical method, is more suitable to be applied to large spaces and high frequencies than the wave-based method. Simplifications in the geometrical acoustics method neglect wave-based phenomena such as diffraction and interferences. Many recent studies in the geometrical acoustics method are about wave-based phenomena such as diffraction [15–19].

Fig. 1 is a schematic diagram showing how the image source method works. The point labeled S is the source point, that labeled S_i is the first-order image source point, and that labeled R is the location of the receiver.

Allen and Berkley were the first to show that for the special case of a rigid rectangular room the mirror source method yields an equivalent result to the solution of the Helmholtz equation [20]. Borish [21] developed the image source method by extending its application to handling arbitrary polyhedral with any number of sides. In the beginning, applications of the image source method to the prediction of room acoustics have assumed that boundaries are smooth. Scattering from rough surfaces was modeled by using random-incident scattering coefficient [22] and digital filtering approach [23].

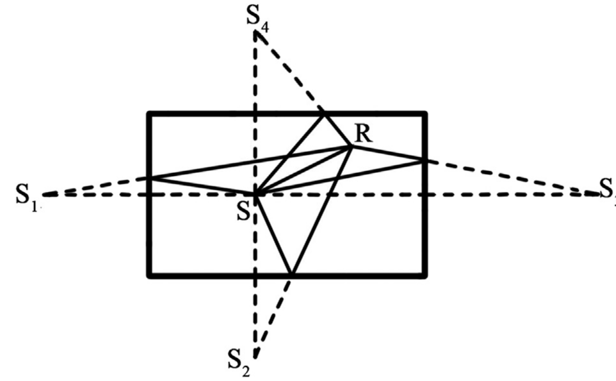

Fig. 1. Sound transmission in a two-dimensional room: sound travels from the source and the first-order image source.

Aretz et al. [20] quantified errors in using the image source method in simulations of damped rectangular rooms. Their research results can provide some suggestions about how to choose reasonable reflection orders, frequency and angle-dependent complex reflection factors when utilizing the image source method with realistic boundary conditions.

In 1968, the paper titled "Calculating acoustical room response by use of a ray tracing technique" was published by Krokstad et al. [24]. It is the first paper that presented the computerized ray tracing technique for finding the impulse response in any 3D models of rooms [25]. In 1989, Vorländer [26] presented a new method that is based on the ray tracing method and the image source method. This method results in solving high-accuracy impulse response of rooms and analyzing room response in the frequency domain. Some recent works in ray tracing focused on developing fast sound propagation algorithms for interactive scenes [19,27,28]. Chevret and Chatillon [16] applied diffraction theory and the ray tracing model to the prediction of noise in open-plan offices. For traffic noise break-in, Chen et al. [29] recently incorporated a space partitioning method into the 3-D ray tracing method.

In the area of beam tracing method, some recent works [30–32] focused on the influence of boundary conditions on the prediction results. In the work of Siltanen et al. [33], they presented a way to introduce incoherent reflections in a beam tracer algorithm. Sikora et al. [34] developed a beam tracing with the refraction method to examine the possibility of creating the beam tracing simulation of sound propagation in environments with piecewise non-homogenous media.

In reality, purely specular reflections do not occur in rooms. The acoustical radiosity, a type of geometrical acoustics methods, is based on purely diffuse reflections. For rooms with complex geometries, the acoustical radiosity should be solved numerically. Nosal [35] and Zhang [36] conducted works to improve algorithms and decrease computational load in the acoustical radiosity simulation. To model both specular and diffuse reflections, some researchers used hybrid models. Kutruff [37] solved the combination of the image source method and the acoustical radiosity for the stationary propagation of sound in a flat room analytically.