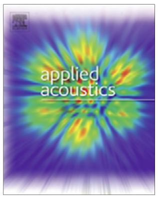
Applied Acoustics 73 (2012) 1029–1044

Contents lists available at SciVerse ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust



Experimental and numerical study on the propagation of impulsive sound around buildings

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ARTICLE INFO

Article history:
Received 29 August 2011
Received in revised form 7 April 2012
Accepted 16 April 2012
Available online 11 May 2012

Keywords:
Outdoor sound propagation
Impulsive sound
Sonic boom
Geometrical acoustics
Biot–Tolstoy–Medwin method
Boundary element method
Isolated buildings
Multiple buildings

ABSTRACT

Propagation of impulsive sound around buildings and induced structural loading are investigated experimentally and numerically. Experiments were conducted on a rectangular building at Virginia Tech using sonic booms generated by shaped charges with an explosive weight of 0.78 kg, constructed from detonation cord. These experiments were simulated with a three-dimensional numerical model, in the context of geometrical acoustics (GA), by combining the image source method for the reflected field (specular reflections) with an extension of the Biot–Tolstoy–Medwin (BTM) method for the diffracted field. In this model, it is assumed that the acoustic propagation is linear and that all surfaces are acoustically rigid. This numerical model is validated against a boundary element (BE) solution and experimental data, showing a good overall agreement. The key advantages of this GA modeling approach for this application include the ability to model large three-dimensional domains over a wide frequency range and also to decompose the sound field into direct, reflected, and diffracted components, thus providing a better understanding of the sound-propagation mechanisms. Finally, this validated numerical model is used to investigate sound propagation around a cluster of six rectangular buildings, for a range of elevated source positions simulating sonic booms from aircraft.

1. Introduction

A considerable amount of work has been devoted to modeling sound propagation around building structures in both rural and urban settings. In the military, many localization techniques for enemy threats such as snipers rely on the sensing of the acoustic signals as well as an accurate knowledge of the multiple sound propagation paths [1]. This knowledge is also crucial in the assessment of non-audible stand-off distances for military equipment. Civil applications mainly include the propagation and reduction of road-traffic noise and airport community noise. Another problem of interest is the impact of sonic booms at the ground level for envisioned civil transport.

Recent advances in the development of a quieter supersonic transport have opened the possibility of commercial supersonic flights over land, which are currently banned by aviation authorities. For the ban to be lifted, the sonic booms the aircraft generate at supersonic speed must be acceptable by populations at the ground, in particular inside buildings. Experimental studies have been the only means by which the human reaction to interior noise induced by sonic booms could be assessed. Recently, fighter jets were used to generate sonic booms and excite residential houses that were appropriately instrumented to record their vibro-acoustic responses and were occupied by test participants to conduct subjective studies on loudness [2,3]. However, the resources required to fuel and maneuver a supersonic aircraft are prohibitively expensive. In addition, there is a degree of control lost to the realm of far-field outdoor acoustics. For instance, atmospheric effects along the propagation path, such as wind, temperature gradients, and humidity are unavoidable over such long distances. The alternative is a numerical tool that can predict all the physics along the propagation path of the sonic boom from outdoors to a listener inside a building. This paper is focused on the simulation of outdoor sound propagation and induced structural loading. This simulation tool could be used in combination with a vibro-acoustic model such as the one developed by Remillieux et al. [4] to predict sound transmission into buildings at low frequencies.

Prediction of sound propagation around buildings and induced structural loading due to impulsive noise, e.g. sonic booms and explosions, is a challenging problem. Many effects must be accounted for, in particular multiple reflections on surfaces and diffraction from edges. Numerical tools for outdoor sound propagation are typically based on finite-element (FE), boundary-element (BE), finite-difference time-domain (FDTD), energy, and geometrical-acoustic (GA) methods. Because of the relatively large size of

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0003-682X/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apacoust.2012.04.011

the outdoor environments usually considered, e.g. building structure(s) standing on a ground, many of these tools cannot achieve satisfactory performance in terms of computational speed and accuracy over a wide frequency range.

Propagation of acoustic pulses has been investigated for the case of a right angle wall [5], including non-line-of-sight (NLOS) configurations, and in urban settings [6,7]. The mechanisms of multiple reflections and diffraction occurring in urban settings due to the presence of buildings are described using experimental measurements and 2-D FDTD simulations. In the simulations, the acoustic domain was invariant in the vertical direction. Similarly, Cho and Sparrow [8] have used a 2-D FDTD model to study the interaction of sonic booms with a residential building structure. They identified a ‘‘building spiking’’ effect that they attributed to the presence of roof overhangs and the frequency dependent nature of diffraction. In this case, the acoustic domain was invariant along one horizontal direction of the building. Numerical methods such as FDTD and FE methods require discretization of the domain with the constraint that the element size must be a fraction of (typically one-tenth of) the shortest acoustic wavelength. Then, the problem consists of solving very large matrix systems, thus making numerical simulations computationally intensive. For this reason, FE and FDTD simulations are usually limited to 2-D or small 3-D acoustic domains, so that the frequency range of the simulations is reasonable. These methods also possess the disadvantage of not fulfilling the Sommerfeld radiation condition when dealing with infinite domains. As a result, there can be artificial reflections at the remote exterior discretized boundary coming back into the acoustic domain. Note that these effects can be greatly reduced by using absorbing boundary conditions or perfectly matched layers (PMLs). However, this technique was not implemented in the work of Cho and Sparrow [8]. Instead they used rigid boundaries and a sufficiently large domain.

An alternative to FE and FDTD methods is a GA model combined with a model for edge diffraction. Many combinations are possible through various available models for edge diffraction. The problem of diffraction of transient sound from an edge has been extensively studied since the late 1950’s. A number of models have been proposed in both the frequency and time domains. The most popular frequency-domain formulation is the Geometrical Theory of Diffraction (GTD) proposed by Keller [9], which extends geometrical optics by the inclusion of additional diffracted rays to describe the diffracted field. This theory possesses two limitations. Firstly, the solutions of the incident and reflected fields are discontinuous across the boundaries of the specular and shadow zones. Secondly, the diffracted waves become infinite in these two regions. To address the first limitation, several theories have been developed such as the Uniform Asymptotic Theory of Diffraction (UATD) [10] and the Uniform Geometrical Theory of Diffraction (UTD) [11]. However, due to the asymptotic nature of the solutions, these methods are only applicable in the mid- to high-frequency ranges. A time-domain formulation for the case of an infinite wedge irradiated by a point source was first proposed by Biot and Tolstoy [12] using explicit analytical impulse response (IR) solutions. This method provides an exact solution and thus is not restricted to high-frequencies. The BT method was later extended to finite wedges [13] and to handle multiple diffractions using a ‘‘discrete Huygens interpretation’’ [14]. More recently, the Biot–Tolstoy–Medwin (BTM) method was reformulated by Svensson et al. [15] to give the solution for the first order diffraction from a finite edge as a line integral along the edge, based on secondary edge sources with analytical directivities. Like GTD, the BTM solution suffers from singularities near the boundaries of the specular and shadow zones. This limitation was addressed by deriving an analytical expansion of the integrand, which gives a continuous IR across these zones [16].

The extension of the time-domain BTM method as formulated and implemented by Svensson et al. [15] in conjunction with the image method will be used in this paper to predict the sound field around buildings. It is demonstrated that this approach is accurate and computationally efficient.

This paper is organized as follows. Section 2 describes experimental results on the propagation of a simulated sonic boom from a blast event to a rectangular test structure. The mechanisms of non-linear wave propagation near the blast event and scattering of sound around the test structure are examined. Section 3 presents the GA model combined with the BTM method for edge diffraction used to predict the sound propagation around buildings and the induced structural loading. This modeling approach is validated against a BE solution and experimental data. Section 4 studies the relation between the position of an elevated source and the sound field in a small cluster of rectangular buildings. Section 5 reports the main conclusions of this study.

2. Experimental study for an isolated building

2.1. Experimental apparatus

Experiments were conducted at Virginia Tech to measure the sound propagation around and induced structural loading on a rectangular building structure due simulated sonic booms [17]. Fig. 1 is a photograph of the test structure consisting of a single room with two double-panel glass windows and a wooden door. Stud-framed floor, ceiling, and side walls forming the structure were built following standard construction techniques, using dimensioned lumber, sheathing, sheetrock, and bat fiber–glass insulation. The door was mounted to a wall adjacent to that with the windows. The finished structure had exterior dimensions of 4.9 × 2.8 × 3.1 m. The structure was extensively instrumented with microphones and accelerometers to record its vibro-acoustic response.

The layout of exterior microphones mounted on the exterior surfaces of the structure is displayed in Fig. 2a. In this figure, the center surface corresponds to the top (roof) of the structure and the other views are unfolded from this surface. The microphones used for experimental validation are circled in red and are located

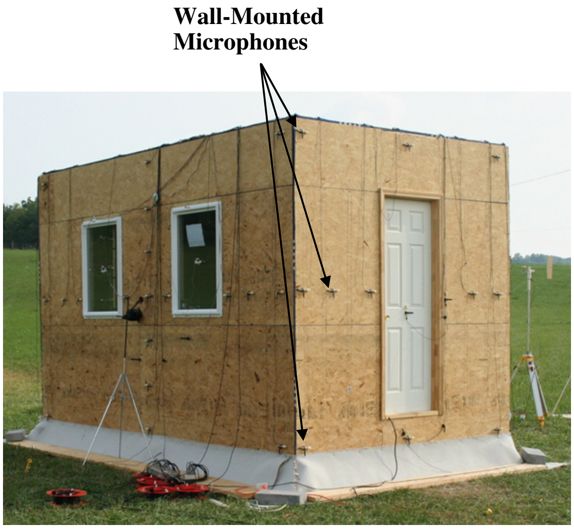

Fig. 1. Photograph of the test structure consisting of a single room made of stud-framed walls with two double-panel glass windows and a wooden door. The finished structure had exterior dimensions of 4.9 × 2.8 × 3.1 m. The structure was extensively instrumented with microphones and accelerometers to record its vibro-acoustic response.