Applied Acoustics 129 (2018) 1–12

Contents lists available at ScienceDirect

Applied Acoustics

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

A frequency domain finite element solver for acoustic simulations of 3D rooms with microperforated panel absorbers

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ARTICLE INFO

Article history:
Received 31 August 2016
Received in revised form 28 June 2017
Accepted 11 July 2017
Available online 20 July 2017

Keywords:
Room acoustics
Microperforated panel
Finite element method
Frequency domain
Absorption

ABSTRACT

Microperforated panel (MPP) absorbers, which provide broadband sound absorption without the use of fibrous materials, have favorable material properties that support recyclability, flexibility of design, hygiene demands, and cleaning. Many earlier studies have specifically examined the development of absorbers themselves. However, to use the absorption performance of MPP absorbers sufficiently in room acoustic applications, it is beneficial to develop accurate prediction methods of sound fields in rooms with MPP absorbers. Such methods are expected to be useful for room acoustics design and absorber design tools. This study constructs a frequency domain finite element (FE) solver for acoustic simulations of a practical sized room with MPP absorbers. Then the accuracy and effectiveness are evaluated. In the FE solver, spatial domains are discretized by fourth-order accurate FEs in terms of dispersion error, and MPP absorbers are modeled using first-order hexahedral limp MPP elements that can deal with sound propagation in the backing structure of absorbers. First, the accuracy of present FE solver is demonstrated using impedance tube problems in comparison with conventional second-order accurate FEs. Results show higher convergence of solutions for the present FE solver. Then, exploration of an iterative solver for efficient multi-frequency analyses reveals that the recently developed CSQMOR is a faster and more stable solver. Finally, comparison with a conventional surface impedance model based on a locally reacting assumption confirms the effectiveness of present FE solver by presenting the importance of dealing with the incident angle dependence of reactance of a rigid-backed air cavity in the modeling of single-leaf MPP absorbers.

1. Introduction

Sound absorbers play an important role in controlling reverberation and improving speech intelligibility in rooms. Various absorbers include porous absorbers, plate/membrane type absorbers, and Helmholtz resonators, each having their unique absorption characteristics. A microperforated panel (MPP) is a thin panel with submillimeter perforations. The panels are made out of arbitrary materials such as metal and plastic. Actually, MPP absorbers have received considerable attention in recent years because they have more broadband sound absorption than conventional perforated panel absorbers, without the use of porous materials. They also have great value from perspectives of recyclability, designability, hygiene demands, and cleaning. Various MPP absorbers have been developed with these attractive features. The typical configuration is placing an MPP in front of a rigid backed air cavity to form a Helmholtz resonator [1,2]. However, the absorption characteristics show frequency-selective behaviors. Additionally, its bandwidth with high absorption is not so wide for general purpose absorbers. For these reasons, many studies have been conducted to broaden the absorption bandwidth [1,3–8]. Multi-layer constructions [1,3,5,6] and the parallel arrangement of MPP absorbers with different cavity depths [4,7,8] exemplify such wideband MPP absorbers.

However, to use the absorption performance of MPP absorbers sufficiently or to use them appropriately in room acoustic applications, it is beneficial to develop accurate prediction methods of sound fields in rooms with MPP absorbers based on wave acoustics. For example, installing absorbing materials in rectangular rooms such as classrooms and offices frequently engenders non-diffuse sound fields. It is difficult to predict such sound fields using a diffuse field theory such as Sabine and Eyring reverberation formulas [9,10]. In such a non-diffuse sound field, wave-based prediction methods such as finite element method (FEM) can be useful to explore the optimum sound absorber location. Furthermore, the development of accurate wave-based methods enables us to evaluate the absorption performance of MPP absorbers in actual

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http://dx.doi.org/10.1016/j.apacoust.2017.07.008

installed conditions. That is useful to elucidate in situ absorption performance of MPP absorbers and to develop further high-performance MPP absorbers.

In wave-based methods, a surface impedance model based on the assumption of local reaction is usually used to model absorbers simply. However, that model might produce inaccurate results when surface impedance of absorbers depends strongly on incidence angles. In such cases, a proper absorber model that can deal with frequency and incident angle dependence of surface impedance i.e., an extended reacting model, is necessary for accurate sound field analyses. Such a model can be constructed by dealing with sound propagation inside absorbers. Although wave-based predictions of sound fields in practical sized rooms with the appropriate absorber model have been regarded as difficult because of their high computational cost, recent advances in computer technology present the possibility of such prediction [11,12].

Recently, the authors presented a frequency domain finite element (FE) formulation for acoustics simulations of rooms with MPP absorbers [11]. In that formulation, MPP itself is assumed as a locally reacting material because MPP is too thin, but sound propagation in the backing structure can be treated appropriately by introducing boundary conditions in both MPP surfaces. Therefore, the absorption model is the extended reacting model, with validity shown through two-dimensional numerical experiments based on an impedance tube method for measuring normal incidence absorption characteristics. This study also presented theoretical memory requirements for three-dimensional analyses, which revealed that sound field predictions of practical sized rooms are within the scope of analyses. However, the FE formulation has not yet been applied to three-dimensional analyses and calculations of transient responses, which are important for room acoustic applications.

As described in this paper, a frequency domain FE solver for acoustic simulations of 3D room with MPP absorbers is developed. The purpose of this paper is to show the accuracy and effectiveness. First, first-order eight-node hexahedral MPP elements are derived for modeling MPP absorbers in three-dimensional analyses. Detailed discretization procedures to solve sound fields in rooms are also presented, including the explanation of fourth-order accurate eight-node hexahedral FEs for spatial discretization. Secondly, the accuracy is shown through impedance tube problems. Then, a proper iterative solver is explored for performing multi-frequency analyses efficiently. Finally, the importance of dealing with the incident angle dependence of surface impedance is demonstrated to underscore the effectiveness of the present FE solver. An earlier report of the literature [13] presents the importance as preliminary results for two-dimensional steady-state sound fields. The presented paper provides more detailed discussion related to three-dimensional analyses including transient sound fields.

2. Theory

2.1. FE model of MPP

In the present MPP elements, an MPP is assumed as limp. The effect of microperforation is modeled using Maa's impedance model [1]. Two material parameters are used to construct the elements: the surface density M_{MPP} and acoustic impedance Z_{MPP} of MPP. The resulting matrix expression of MPP elements is also presented explicitly for convenience.

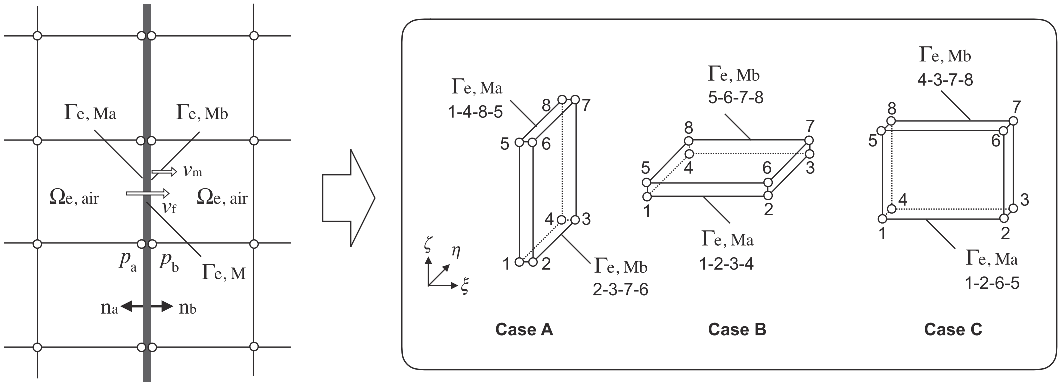
Fig. 1(a) and (b) present an FE model of an MPP and three cases of eight-node hexahedral MPP elements with different absorbing surfaces, where $\Omega_{\mathrm{e,air}}$ and $\Gamma_{\mathrm{e,M}}$ represent the air element and MPP element derived with contribution from both boundary surfaces of MPP $\Gamma_{\mathrm{e,Ma}}$ and $\Gamma_{\mathrm{e,Mb}}$. In addition, p_{a} and p_{b} represent the sound pressures at both sides of MPP. In addition, v_{f} and v_{m} represent the average particle velocity over a tube cross-section and vibration velocity of MPP. $\mathbf{n}_{\mathrm{a}}$ and $\mathbf{n}_{\mathrm{b}}$ are the normal vectors at the boundaries. As presented in Fig. 1(b), the three cases with different absorbing surfaces exist in the MPP elements for three-dimensional analyses. For example, in Case A, the absorbing surfaces of MPP, $\Gamma_{\mathrm{e,Ma}}$ and $\Gamma_{\mathrm{e,Mb}}$ respectively consist of nodes 1–4–8–5 and 2–3–7–6, where the number is element node numbers in the local coordinate (ξ, η, ζ) system. Considering cases A–C in the MPP elements is important for implementation because locations of element components in the resulting matrix differ among the cases.

2.2. Boundary conditions of MPP surfaces

Regarding boundary conditions of MPP, a vibration boundary is assumed in the boundary surfaces of the MPP element $\Gamma_{\mathrm{e,Ma}}$ and $\Gamma_{\mathrm{e,Mb}}$, as described below.

$$\frac{\partial p}{\partial n} = \begin{cases} -i\omega\rho_0(v_{\mathrm{m}} + v_{\mathrm{f}}) & \text{on } \Gamma_{\mathrm{e,Ma}}, \\ i\omega\rho_0(v_{\mathrm{m}} + v_{\mathrm{f}}) & \text{on } \Gamma_{\mathrm{e,Mb}}. \end{cases} \tag{1}$$

Therein, i, ω, and ρ_0 respectively represent the imaginary unit, angular frequency, and air density. In this formulation, MPP itself is modeled as a locally reacting material because MPP is too thin, having less than 1 mm thickness. However, by introducing the boundary conditions into both surfaces of MPP, a sound field in



(a) FE model of MPP (b) Three cases of eight node hexahedral MPP elements

Fig. 1. FE model of MPP (a) and eight-node hexahedral MPP elements in three cases (b).