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Analytical modelling of sound transmission through finite clamped double-wall sandwich panels lined with poroelastic materials

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ABSTRACT

This paper addresses analytically the vibroacoustic problem of sound transmission across a rectangular double-wall sandwich panel clamp mounted on an infinite rigid baffle and lined with poroelastic materials. The wave propagation in poroelastic media is described by Biot's theory and the coupling methods between the poroelastic core and the panel determine the various configurations and associated boundary conditions. The modal superposition theory and the weighted residual (Galerkin) method are employed to account for the finite extension with the clamped boundary and to obtain a double-series solution of the problem through a matrix equation. The sound transmission loss (STL) of the structure is calculated for a single incident wave after validating the analytical model against previous theories and experiments. The numerical results show that the finite panel and clamped boundary influence the STL dominantly in the low-frequency range. The poroelastic materials exhibit strong damping effects on the resonances of STL spectra at high frequencies as well as panel vibrations and enhance significantly the sound insulation performance of the sandwich panel.

1. Introduction

Double-wall sandwich panels are extensively used in a variety of engineering applications (e.g. automotive, marine, aircraft and construction industries) due to their superior mechanical properties (stiffness-to-weight ratio, vibration damping, fatigue resistance, etc.) and sound insulation performance. Compared with the single-wall counterparts, the sandwich core sealed in between two facing plates results in the structural discontinuity and acoustic impedance mismatch of the panel system and hence the mechanical and sound insulation advantages. The vibroacoustic problem of sound transmission through a double-wall panel, involving the fluid-acoustic-structural coupling and sound transmission loss (STL) calculation, has attracted extensive research attention in literature for decades. Most of the studies were focused on laterally infinite panels, including the early works by Berenak and Work [1] and London [2] who developed simplified theoretical models for this problem. Many studies considered only the simple case of normal incident plane waves [1,3–5], while the sound transmission of random incidence in a diffuse field was also addressed [2,6,7]. A wide range of sandwich cores have been investigated for the double-wall panels, such as air cavity [8–10], corrugated core [11,12], periodically frame-stiffened core [13–18], and porous foam [7,18–21]. In order to optimise the STL of a double-wall structure under the weight and volume constraints, multilayered linings are applied to the panel that contains a combination of solid, fluid and porous components [22–24]. A review of this vibroacoustic problem and the theoretical and experimental approaches was given by D'Alessandro et al. [25].

For realistic double-wall panels with finite extent, the influence of boundary conditions and finite dimensions on the vibroacoustic behaviours becomes significant particularly at low frequencies [26–29], and hence accurate theoretical models are necessary in order to predict the STL of the finite-sized structures in practical applications. Numerous numerical studies on sound transmission through finite double-wall sandwich panels have been conducted using finite element method and boundary element method [30–35]. Theoretical and experimental methods were also proposed to address this problem, mainly focused on the simply supported boundary condition [36–39]; for example, Leppington et al. [38] modelled this problem analytically based on the modal superposition theory. In contrast, little attention has been received to another important boundary condition, i.e. the fully clamped boundary. Carneal and Fuller [36] proposed to increase the panel

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stiffness by an empirical factor of $\sqrt{2}$ for the analytical solution of the simply supported boundary condition in order to approximate the experimental results of the clamped boundary condition. A rigorous theoretical model was formulated by Xin et al. [27] for sound transmission through a finite double-wall panel with an air cavity and fully clamped on its edges using the modal superposition method. Xin and Lu [28] then compared the two different boundary conditions both theoretically and experimentally, and discovered dramatic discrepancies between them in terms of STL and panel vibration characteristics in the case of oblique sound incidence. Xin and Lu [40] also extended their analytical model to address sound transmission through clamped triple-wall panels with enclosed air cavities.

As far as sound insulation improvement is concerned, poroelastic materials among various sandwich cores have been widely applied in double-wall structures due to their excellent sound absorption capability. By employing Biot's theory [41] on wave propagation in a poroelastic medium, Bolton et al. [7] modelled analytically the problem of sound transmission through infinite double-wall sandwich panels lined with poroelastic materials and validated the theoretical model against their experimental results. Lee et al. [42] simplified Bolton's formulation by retaining only the energetically strongest wave among those propagating in the poroelastic material because the contribution of the shear wave to the transmission loss was found to be always negligible. Liu [21] extended the theoretical model of Bolton et al. [7] to address sound transmission across triple-wall panels with poroelastic linings. Also on the basis of Bolton's theory, Zhou et al. [20,24] investigated the effects of an external mean flow and extended the vibroacoustic problem to a three-dimensional one, and Liu and Sebastian [43] further considered the effects of an internal gap mean flow. Shojaeifard et al. [44,45] studied power transmission through infinite double-walled laminated composite panels using the classical laminated plate theory and Biot's theory [41] for wave propagation in the porous sandwich layer. Xin and Lu [18] and Meng et al. [19] adopted the equivalent fluid model [46–48] to study sound transmission through an infinite double-wall panel with and without rib-stiffened core, respectively, filled with porous sound absorptive materials. Enhanced sound insulation properties of the double-wall sandwich panels have been observed in all these previous works. Moreover, the influence of poroelastic materials was also investigated on sound transmission through infinite double-wall shell structures with similar conclusions [49–56].

Despite the notable enhancement of sound insulation performance by sound absorbing poroelastic materials, to the best of the authors' knowledge, no research efforts have been made to study the acoustic-structural behaviours of fully clamped double-wall panels of finite extent lined with poroelastic materials. Therefore, the aim of the present study is to develop an analytical model to solve this vibroacoustic problem on the basis of previous works [7,28]. A detailed derivation of the analytical solution to this problem is formulated in this paper (note that an outline of the current theoretical formulation has been recently presentated in Ref. [57]), taking account of both the finite extension with clamped boundary conditions and the boundary conditions at the panel/lining interfaces. The present study attempts to answer the following issues on sound insulation properties: (i) What are the effects of the finite extent and clamped boundary condition compared with an infinite sandwich panel? (ii) What are the benefits of the poroelastic lining in addition to an air cavity? Moreover, the validity of the theoretical model is verified by previously published theoretical and experimental data [7,28], and the effects of other representative parameters (i.e. incident angles, poroelastic foam thickness) are quantified in this work.

2. Description of the sandwich panel system

2.1. The clamped double-wall sandwich panel

A double-wall sandwich panel lined with poroelastic materials consists of two rectangular, isotropic, homogeneous and sufficiently thin plates commonly made of aluminium, as illustrated in Fig. 1. The two elastic plates are fully clamped along their edges to an infinite rigid acoustic baffle. In between, a layer of poroelastic materials superimpose air layer(s). The upper plate is excited by a plane harmonic sound wave and the convention $e^{i\omega t}$ is used with ω being the angular frequency and the symbol $i = \sqrt{-1}$. Without loss of generality, an incident sound wave of unit amplitude is assumed, and its incident direction is determined by the elevation angle ϕ and the azimuth angle θ (see Fig. 1). The vibrations of the upper plate are transmitted through the structure via the poroelastic medium and air layers to the bottom plate which induces pressure variations and thus a transmitted sound wave. The incidence field and transmission field separated by the infinite rigid baffle are assumed to be semi-infinite with identical air properties, i.e. air density ρ_0 and speed of sound in ambient air c_0. The panel dimensions are chosen as follows: a, b are the length and width of the panel, h_1, h_2 are the thicknesses of the upper and bottom plates, and H is the total thickness of the sandwich core (poroelastic and air layers) in between the two plates.

Two basic coupling methods for the poroelastic layer as a sandwich core of the double-wall panel were considered in previous studies [7,20,21,43]: (1) 'Bonded' (B), the poroelastic material is directly attached to the panel and (2) 'Unbonded' (U), the porous layer is separated from the panel by an air gap. Therefore, different configurations of the double-wall sandwich panel can be considered to superimpose the poroelastic and air layers. Bolton et al. [7] and subsequent researchers [20,21,43] studied three typical configurations, BB, BU and UU, as shown in Fig. 2. In order to have a benchmark for validation, the same configurations are considered in the present study. The BB (Bonded-Bonded) configuration is sandwiched with only a poroelastic core between the two facing plates, whereas the BU (Bonded-Unbonded) and UU (Unbonded-Unbonded) configurations present one and two additional air lay-

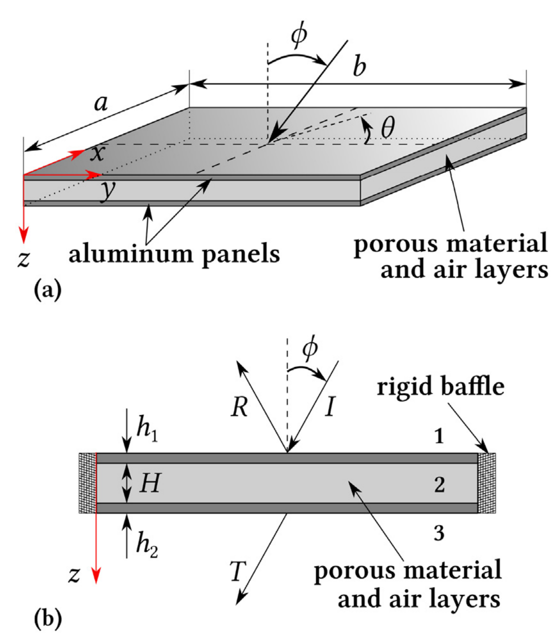

Fig. 1. Schematic of a clamped double-wall sandwich panel lined with poroelastic materials: (a) global view, (b) side view.