Journal of Sound and Vibration 425 (2018) 189–207

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Sound attenuation and absorption by micro-perforated panels backed by anisotropic fibrous materials: Theoretical and experimental study

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A R T I C L E I N F O

Article history:
Received 22 November 2017
Received in revised form 3 April 2018
Accepted 5 April 2018

Keywords:
Micro-perforated panels
Fibrous anisotropic materials
Sound attenuation
Sound absorption
Flow convective effect

A B S T R A C T

Enhancing the attenuation or the absorption of low-frequency noise using lightweight bulk-reacting liners is still a demanding task in surface and air transport systems. The aim of this study is to understand the physical mechanisms involved in the attenuation and absorption properties of partitions made up of a thin micro-perforated panel (MPP) rigidly backed by a cavity filled with anisotropic fibrous material. Such a layout is denoted as a MPPF partition. Analytical models are formulated in the flow and no-flow cases to predict the axial damping of the least attenuated wave in a MPPF partition as well as the plane wave absorption coefficient. They account for a rigid or an elastic MPP facing a bulk-reacting fully-anisotropic material. A cost-efficient solution of the propagation constant for the least attenuated mode is obtained using a simulated annealing search method as well as a low-frequency approximation to the axial attenuation. The normal incidence absorption model is assessed in the no-flow case against pressure-velocity measurements of the surface impedance over a MPPF partition filled with fibreglass material. A parametric study is conducted to evaluate the MPP and the cavity constitutive parameters that mostly enhance the axial attenuation and sound absorption properties, with special interest on the MPP airframe relative velocity. This sensitivity study provides guidelines that could be used to further reduce the search space in parametric or impedance optimization studies.

1. Introduction

Acoustic liners made up of porous materials or of perforated sheets backed by a cellular honeycomb core are well established methods for mitigating noise propagation in flow ducts such as in air conditioning systems and exhaust mufflers, but also in the nacelle of aircraft engines [1]. The former treatments are *a priori* "bulk-reacting" and allow wave propagation in the direction parallel to the liner surface. They provide good attenuation and absorption performance at high frequencies, but may cause environmental issues due to airborne fibre emissions and low durability. The latter treatments are locally-reacting

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https://doi.org/10.1016/j.jsv.2018.04.006
0022-460X/

narrowband resonators that can be tuned and optimized to efficiently dissipate noise at mid-frequencies. They are able to withstand harsh thermal and flow environments, but may be prone to generate pressure losses and flow-induced noise.

The use of resonators covered by micro-perforated panels (MPP) with sub-millimetric holes diameter present a light-weight alternative to fibrous materials and have shown to provide efficient sound absorption and attenuation in the low-to-medium frequency range due to the effective mass added by the micro-perforations as well as a small flow discharge. Since their proposal by Maa [2,3], they have been used in several areas such as in room acoustics where they can work either as absorbing resonators [4] or modal dampers [5], in the automotive industry and ventilating systems as dissipative duct mufflers [6] and also as noise barriers [7]. In a quiescent fluid, their absorption range can be broadened by inserting inner MPPs in the cavity with a positive gradient of their flow resistance [7], by backing the MPP by an irregular cavity [8], by parallel cavities of different depths [9] or by decreasing the MPP holes diameter and thickness [10]. Indeed, the half-absorption bandwidth of thin ultra-microperforated membranes with holes diameters down to 27 μm was able to span 3-4 octaves with an absorption peak value exceeding 0.85 [10]. Studies on the vibroacoustic properties of thin elastic MPPs facing an air cavity have shown that the MPP flexural vibrations can significantly enhance the absorption performance [11,12]. A relationship was found between the airframe relative velocity and the beneficial or detrimental effect of the first panel-cavity resonance onto the absorption values around the Helmholtz resonance [13,14].

The use of MPP partitions in aero-acoustic applications is more limited as their behaviour in presence of a grazing and bias flow is still a subject under study [15]. In particular, the micro-perforations are known to efficiently convert most of the turbulence into back-scattered sound for values of $St_h = fd_h/U_\infty$, the hole-based Strouhal number, typically greater than 0.1, with f the frequency, d_h the holes diameter and U_∞ the flow free-stream velocity [16–18]. Hence, MPPs in contact with flow may generate additional broadband and tonal noise, albeit at a frequency higher than that of perforated sheets. Optimum attenuation of MPP silencers for noise control in ducted flows has been achieved by partitioning the cavity length [6] and by matching the impedance of the locally-reacting MPP wall to an optimum impedance model [19,20], extended to the low frequency range [21]. The optimum acoustic resistance that maximizes the axial attenuation was found to be much smaller than the one used in room acoustics that maximizes the normal incidence absorption [22]. Recently, the absorption performance of locally-reacting MPP partitions in contact with a flow have shown to be of interest when used as external fuselage liners, for instance to dissipate the broadband multi-tonal interaction noise radiated from fuel-efficient aircraft open rotors [23].

Backing the MPP partitions with a porous material is another strategy to broaden the Helmholtz resonance and to damp the higher order absorption peaks provided that the MPP acoustic resistance is not too high to hinder the effects of the porous layer [24]. In this approach, the porous material is often considered as locally-reacting and characterized using the empirical Delany-Bazley model [25] or its low-frequency extension, the so-called Miki-Delany-Bazley (MDB) model [26], in terms of a single parameter: the normal flow resistivity. The Delany-Bazley model has however been used to predict sound attenuation by bulk-reacting liners made up of a perforated sheet covering a porous layer in which axial and transverse waves propagate in an equivalent fluid assumed to be isotropic [27]. More complex models of porous materials have been proposed involving a number of transport parameters [28] that are measured or determined from the material microstructure [29]. In practice, fibrous materials made up of a periodic network of natural [30], synthetic [31] or metallic fibres [29] exhibit anisotropic properties at macro-scale level or at least a weaker form of transverse isotropy when the fibres are grouped in layers. Tarnow [32,33] derived a 2D model for the anisotropic resistivities of a porous material to an air flow parallel with and perpendicular to a random lattice of collinear cylinders, simulating the geometry of glass wool fibrous material. This model was used in Ref. [34] to calculate the sound absorption and attenuation of unshielded fibrous materials with complex anisotropic bulk moduli, effective densities and arbitrary fibre orientation in contact with a uniform flow. This fully anisotropic (FA) model extends previous models that assumed a real homogenous bulk modulus of the duct lining material in the no-flow [35] and flow cases [36].

The current paper, companion to [34], aims at further generalizing the FA model to account for a partition made up of a thin MPP backed by a rigid cavity filled with a layer of anisotropic fibrous material. This layout constitutes a MPPF partition that can eventually be in contact with a uniform low-speed flow. This study shows how the constitutive parameters of both the MPP and the fibrous material enhance either the axial damping of the least attenuated wave or the normal incidence absorption coefficient in the MPPF partition. In Sec. 2, analytical models are delineated for the prediction of the attenuation and absorption properties of MPPF layouts in the no-flow and flow cases. In these formulations, an elastic MPP is coupled, on one side, with a rigidly-backed fibrous anisotropic material and, on the other side, with a uniform low-speed flow. In Sec. 3, the absorption model under normal incidence is assessed against pressure-velocity impedance measurements carried out in the no-flow case over a MPPF sample. Section 4 proceeds with parametric studies in order to examine the effects of the MPPF constitutive parameters and flow Mach number on either the axial attenuation or the normal incidence absorption properties. The last section summarizes the main outcomes of the work together with further research lines.

2. Modelling sound attenuation and absorption by a MPPF sample

The system under study is shown in Fig. 1(a). It consists of an unducted bulk-reacting MPPF partition of infinite extent along the x-axis, composed of a thin flexible MPP located at $y = d$ and separated from a rigid back wall by a layer of anisotropic fibrous material with thickness b. Acoustic waves ($e^{-i\omega t}$) propagate in both the porous and the fluid domains, the latter being either at rest or carrying a uniform flow of Mach number, $M = U_\infty/c_0$, with c_0 the sound speed. The overall transfer