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Sound attenuation and absorption by anisotropic fibrous materials: Theoretical and experimental study

Teresa Bravo [a, *], Cédric Maury [b]

[a] Instituto de Tecnologías Físicas y de la Información (ITEFI), Consejo Superior de Investigaciones Científicas (CSIC), Serrano 144, 28006 Madrid, Spain
[b] Ecole Centrale Marseille, Laboratoire de Mécanique et d'Acoustique (LMA), UPR–CNRS 7051, Aix Marseille Université, 38 rue Frédéric Joliot-Curie, 13013 Marseille, France

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ABSTRACT

This paper describes analytical and experimental studies carried out to examine the attenuation and absorption properties of rigidly-backed fibrous anisotropic materials in contact with a uniform mean flow. The aim is to provide insights for the development of non-locally reacting wall-treatments able to dissipate the noise induced by acoustic excitations over in-duct or external lining systems. A model of sound propagation in anisotropic bulk-reacting liners is presented that fully accounts for anisotropic losses due to heat conduction, viscous dissipation and diffusion processes along and across the material fibres as well as for the convective effect of an external flow. The propagation constant for the least attenuated mode of the coupled system is obtained using a simulated annealing search method. The predicted acoustical performance is validated in the no-flow case for a wide range of fibre diameters. They are assessed against impedance tube and free-field pressure-velocity measurements of the normal incidence absorption coefficient and surface impedance. Parametric studies are then conducted to determine the key constitutive parameters such as the fibres orientation or the amount of anisotropy that mostly influence the axial attenuation or the normal absorption. They are supported by a low-frequency approximation to the axial attenuation under a low-speed flow.

1. Introduction

The attenuation of sound waves by fibrous anisotropic materials in contact with an air flow is of high relevance to design parallel baffle silencers [1,2] or duct linings [3,4] that can be integrated into low noise HVAC (Heat, Ventilation and Air-Conditioning) or power plant duct systems. They should however comply with stringent environmental policy on low airborne fibres emissions, ease of maintenance, stable acoustical efficiency over a full life-cycle and no risk of damage when used as silencers in gas exchange systems of motor vehicles. To handle this type of problem, they can be shielded by micro-perforates. In this case, partitioned fibre-free dissipative silencers have been optimized under a low-speed flow to achieve high levels of attenuation (>30 dB) over more than one octave at mid-frequencies [5]. Free-surface fibrous anisotropic materials can also be partitioned by rigid walls perpendicular to their surface in order to achieve locally-reacting conditions and enhance peak attenuation at the lining weakly damped resonances [6]. At low frequencies, such linings showed greater

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* Corresponding author.
E-mail addresses: teresa.bravo@csic.es (T. Bravo), cedric.maury@centrale-marseille.fr (C. Maury).

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attenuation without partitions, e.g. for a bulk-reacting fibrous core. It is therefore of interest to understand how to use the bulk-reacting properties of non-isotropic fibrous materials to enhance their axial attenuation in flow ducts, especially in the low frequency range.

The properties of anisotropy may also improve the absorption of sound from existing sources in aeronautics and surface transport systems. For instance, future aircraft engines such as Contra-Rotating Open Rotors (CROR) generate broadband multi-tonal interaction noise impinging the fuselage from a wide range of incidence angles [7]. These emissions have to be reduced to meet the goals set by ACARE [8] that include a 10 dB abatement by 2020 in the perceived noise levels per airplane and per flight during take-off and landing. CROR noise is tackled by the use of external fuselage liners [9] made up of a honeycomb core shielded by a perforated sheet that is optimized to lower the drag and enhance the absorption. Bulk-reacting anisotropic material could be a potential solution for the core material of these absorbents, as shown from recent investigations on the use of bio-inspired fibres for aeronautic liners [10]. Transverse bundles of natural or synthetic reeds packed in a 5 cm depth cavity lead to higher normal incidence absorption between 400 Hz and 800 Hz than conventional double-degree-of-freedom perforates over honeycomb of equivalent thickness, the latter having typical maximum absorption values at 1.5 kHz. These properties were also observed under random incidence from absorption measurements of natural transverse reeds in a large reverberant room [11]. One also needs to optimize the bulk-reacting fibrous materials attached on the inner side of wheels tread in order to damp out the cavity acoustic resonances and reduce the transmission of tyre road noise to the vehicle cabin [12].

The main objective of this paper is thus to determine the most influent parameters constitutive of bulk-reacting anisotropic fibrous materials, eventually in contact with a uniform flow, in order to enhance the attenuation or absorption from external sound sources. Interaction of the material with the flow should not generate drag nor aerodynamic self-noise (airframe noise), but these points are out of the scope of this paper. Moreover, the material may be shielded by a microperforate. This configuration will be analysed in a forthcoming study.

Accounting for the effect of the material anisotropy and bulk-reaction can be done from either the capillary pore or fibres theories. The capillary pore approach was first developed by Rayleigh [13] who studied dissipation within an array of parallel cylindrical pores of small radii embedded in a rigid solid matrix. Subsequent theories generalized this approach and introduced phenomenological models for the effective density and bulk modulus of rigid frame porous materials assuming cylindrical pores, eventually slanted, with variable cross-sectional shapes [14]. These models require specific experimental characterization of the macroscopic bulk parameters such as dynamic tortuosity or their hybrid numerical computation from microscopic cell morphology such as the pores size and their connectivity [15]. However, when dealing with fibrous materials, it is not obvious how to define an “effective” pore radius from microscopic measurements of the fibres diameters and their mean distances. In order to avoid complex characterization of fibrous materials bulk parameters and to keep the model as self-contained as possible, the studied materials have been modelled in the framework of the fibres theory, e.g. as solid fibres in a fluid matrix. In this case, the flow resistivity [16] and dynamic compressibility [17] can be deduced from the microscopic fibres geometry.

Previous parallel fibre models considered arrays of cylindrical fibres freely suspended or fixed in the air. Early works by Kawasima [18] investigated the influence of fibre bonding on the sound absorption and showed that the thermal effects had a small contribution with respect to the viscous effects for materials with very high porosity. The absorption and attenuation properties of fibres of different radii, randomly distributed in planes parallel to the surface, have also been modelled by the Multiple Scattering Theory (MST) [19,20]. The scattering framework builds upon a cylindrical harmonic decomposition of the incident wave into multiply scattered dilatational, thermal and viscous waves in the fluid phase, and induced dilatational, thermal and shear waves in the solid phase, whose amplitudes are determined from suitable continuity conditions over the fibres boundaries. The MST is a fruitful model that allowed to predict normal incidence absorption through fibreglass materials, but also sound attenuation through trees with foliage canopy between 1 kHz and 10 kHz [21]. However, in its initial formulation, it does not account for propagation through anisotropic materials made up of fibres with an arbitrary orientation with respect to the material surface and in contact with a flow.

In what follows, Section 2 delineates an analytical model that predicts the axial attenuation and absorption of a rigidly-backed anisotropic material assuming parallel fibres of arbitrary orientation in contact with a uniform flow. In Section 3, the model is assessed against a set of in-duct and free-field absorption measurements carried out in the no-flow case on a number of anisotropic materials with small and large fibre radii. Section 4 determines the most influent constitutive parameters that enhance either the axial attenuation or the normal absorption properties of anisotropic fibrous materials with and without flow. Section 5 summarizes the main outcomes and points out a number of further research lines.

2. Modelling axial attenuation and sound absorption by anisotropic fibrous materials

The present approach describes the propagation of inhomogeneous waves in a uniform layer of anisotropic fibrous material, of thickness b, of infinite extent along the x-axis and in contact with a fluid flow, as shown in Fig. 1. The model predicts the axial attenuation (dB/m) and the absorption coefficient induced by the bulk-reacting liner. It generalises previous approaches that did not account for anisotropy and losses in the parallel- and cross-fibres flow resistivity and bulk moduli [3,22] or that were restrained to transversely isotropic materials with all fibres lying in planes parallel to the surface (Sec. 3.7 to 3.9 in Ref. [14]). Here, the parallel fibres are anchored to a rigid wall at $y = b + d$ and are inclined by an arbitrary angle,