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Microstructure representations for sound absorbing fibrous media: 3D and 2D multiscale modelling and experiments

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ABSTRACT

The paper proposes and investigates computationally-efficient microstructure representations for sound absorbing fibrous media. Three-dimensional volume elements involving non-trivial periodic arrangements of straight fibres are examined as well as simple two-dimensional cells. It has been found that a simple 2D *quasi*-representative cell can provide similar predictions as a volume element which is in general much more geometrically accurate for typical fibrous materials. The multiscale modelling allowed to determine the effective speeds and damping of acoustic waves propagating in such media, which brings up a discussion on the correlation between the speed, penetration range and attenuation of sound waves. Original experiments on manufactured copper-wire samples are presented and the microstructure-based calculations of acoustic absorption are compared with the corresponding experimental results. In fact, the comparison suggested the microstructure modifications leading to representations with non-uniformly distributed fibres.

1. Introduction

Sound propagation and absorption in air-saturated porous media with sufficiently stiff frame can be predicted using the so-called Johnson-Champoux-Allard (JCA) model [1–3] or its enhanced versions involving some improvements concerning viscous dissipation [4] and thermal effects [5–7]. Namely, Pride et al. [4] proposed a correction for the imaginary part of dynamic viscous permeability which is underestimated at low frequencies by the original Johnson-Koplik-Dashen model [2], whereas corrections for thermal effects involved introduction of a static thermal tortuosity [5] and a thermal analogue of permeability [6]. Finally, what resulted are precise semi-phenomenological models with rather large number of parameters, involving in the most advanced case: the open porosity, the (inertial) tortuosity, the static viscous permeability and its thermal analogue, the viscous and thermal characteristic lengths, and the static viscous and thermal tortuosities. Simpler phenomenological models do exist, in particular, the purely empirical models by Delany and Bazley [8] with important corrections and generalizations by Miki, namely: a correction for low frequencies [9], and a generalisation introducing porosity and tortuosity [10]. They are valid for some fibrous absorbent materials of very high porosity (originally they were proposed and validated for fibrous materials with porosity close to unity). The main material parameter is here the flow resistivity of fibrous material. More recently, an improved empirical model for fibrous materials was proposed by Voronina [11]. In general, more complex, general models (especially, the mentioned JCA model and its enhanced versions) are less restrictive, yet they involve many parameters related to the average geometry of porous or fibrous media. These parameters

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(usually referred to as *transport parameters*) can be in fact determined from microstructure of a porous (or fibrous) medium, and it seems that soon such microstructure-based approach should allow to design and optimise novel acoustic materials. Improvements in robust passive acoustic treatments are possible, although an active approach has been proposed [12].

Realistic microstructure-based calculations become now an important tool for prediction of attenuating performance of sound absorbing porous and fibrous media. Such an approach has been recently applied to various porous materials, namely: to open-cell aluminum foams [13,14], to perforated closed-cell metallic foams [15], to open-cell foams with microstructure represented by idealised packing of polyhedral periodic unit cells [16], to a fibrous material with hexagonal arrangement of fibres [17], to open-porosity ceramics [18] and other open-cell foams with spherical pores [19], to polyurethane foams in order to optimise their low frequency sound absorption by cell size control [20], to granular media with face-centred cubic packing [21] and also other packings of spherical grains [22,23], to granular media with double porosity [24], and to double porosity foams [25]. Moreover, various microstructure-based analyses have been also applied when studying wave propagation in poroelastic materials [26–29].

Nevertheless, the accuracy of such calculations strongly depends on a correct choice of representative micro-structural geometry of porous media, and that choice is constrained by some requirements, like: the periodicity, a relative simplicity of micro-geometric representations, and the size of elementary volume (or cell) which should be small enough to allow for the separation of scales [30].

One of important transport parameters is the static viscous permeability, and in particular, a dynamic generalisation of this parameter: the frequency-dependent and complex-valued dynamic permeability [2]. It was investigated by Johnson et al. [2], and also, for example, by Cortis and Berryman [31] in case of frequency-dependent viscous flow in channels with rough surfaces. The real part of this frequency-dependent function of dynamic permeability converges to the value of static permeability when the frequency tends to zero. Thus, the parameter of Darcy permeability forms a low-frequency limit of its dynamic generalisation, and therefore, it is used as an important reference parameter in the analytical approximating formulas for the dynamic permeability [2,1]. Microstructural influences on the permeability of fibrous media have been studied by many authors, for example: for media with uni- and bi-modal fibre size distribution [32,33], in case of 2D periodic fibrous representations [34], and using 3D imaging coupled with CFD simulations [35]. The role of microstructural parameters in radiative heat transfer through disordered fibrous media was investigated by Tahir et al. [36]. Koponen et al. [37,38] used the lattice-Boltzmann methods to study the interdependence of permeability, tortuosity, and porosity of random fibrous media. They confirmed that permeability exponentially depends on porosity over a large range of porosity, and proposed a modification of the Kozeny-Carman equation for permeability by involving the concept of effective porosity. Tomadakis and Robertson [39] compared diffusional and electrical estimates of viscous permeability and tortuosity of random fibre structures with analytical formulas and experimental results.

The acoustic attenuation of sound absorbing fibrous materials strongly depends on the dynamic resistivity to an oscillating air flow, which is directly related to the dynamic permeability. This matter was studied by Tarnow [40], who calculated the dynamic resistance for a 2D model of randomly placed cylinders (discs) with geometry simulating the geometry of a real fibrous material. Earlier, the same author [41] investigated the dynamic compressibility of air in fibrous materials, which was determined for 2D models with parallel cylinders: placed in a regular square lattice and placed randomly. Tarnow carried out also experimental investigations on the sound propagation in glass wool [42], and later in particular, he investigated the effect of fibre movements on the sound attenuation in this material [43].

Schladitz et al. [44] presented a method of design for a stacked fibre non-woven acoustic trim based on geometric modelling and flow simulations. The non-woven fabric was modelled by a macroscopically homogeneous random system of straight cylinders (tubes). Such geometric model was generated from stochastic geometry (obtained using image acquisition) by adapting the characteristic properties of the material (i.e., porosity, fibre size distribution). For the geometric model, the Stokes equations were solved with no-slip boundary conditions on fibre surfaces using the generalized lattice Boltzmann method. Numerical calculations allowed to determine the flow resistivity of the material, which was then used in the formulas of Delany–Bazley model [8] improved for low frequencies by Mechel [45] to predict the frequency-dependent acoustic absorption (these final results were confronted with measurements). The authors proposed a design procedure for a non-woven material with improved acoustic absorption properties as follows. First, the fibre thickness, porosity and anisotropy of the fibre system are modified. Then, the flow and acoustic simulations are performed for the new geometric sample. These two steps are repeated for various sets of parameters. Finally, the set of parameters for the geometric model leading to the best acoustic absorption is found.

Thermoacoustic properties of fibrous materials were studied by Jensen and Raspet [46]: they used computational fluid simulations to test the proposed models for propagation in porous materials with an ambient temperature gradient. These authors also used the lattice Boltzmann model for flow simulations and the geometric model used for the fibrous material was the same as the one used by Schladitz et al. [44].

The effect of some physical parameters on sound absorption properties of natural fibre mixed non-woven composites was studied experimentally by Küçük and Korkmaz [47]. Along with the sound absorption properties they measured thickness, weight per unit area, and air permeability for samples of eight different non-woven composites including different fibre types mixed with various ratios (for example, 70% of cotton and 30% of polyester fibres). They found in particular for such composites that the increase in amount of fibre per unit area resulted in an increase in sound absorption of the material. (Of course, it is within some reasonable limit of fibre amount, since on the other hand, too many fibres may eventually make the airflow resistivity too large and degrade the sound absorption.).