Bottom-up approach for microstructure optimization of sound absorbing materials

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BOTTOM-UP APPROACH FOR MICROSTRUCTURE OPTIMIZATION OF SOUND ABSORBING MATERIALS

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ABSTRACT
A major issue in building acoustics concerns the need to increase or adapt the absorption spectrum of commonly used sound absorbing materials. However, the most advanced models used to characterize and predict sound absorbing material performances are based on macroscopic parameters, which are inter-dependant, and do not take explicitly into account the local geometry description of the porous media, i.e. microstructure. For these reasons, optimizing sound absorbing material performances firstly relies on our ability to predict acoustic properties of porous media from the description of their local geometry, and secondly to propose pertinent physically realistic modifications of the microstructure having predictable impacts on the absorption spectrum. Starting from an open-cell foam sample having poor sound absorption properties, this paper exposes how the link between microstructure and macro-behaviour is achieved, and how its sound absorption is increased from the optimization of its microstructure.

INTRODUCTION
Does a periodic unit cell (PUC), whose microstructural parameters have been identified experimentally, might serve as a basis to model acoustic dissipation phenomena in open cell foams? How do acoustic properties depend on microstructural parameters? These are two of the many questions that are dominating studies of relationships between microstructure and acoustic properties of porous media such as open cell foams.

Such questions may be addressed in different manners. A common method consists in conducting a lot of laboratory measurements on samples of varying microstructural parameters[1,2]. Alternatively, in a search for a theoretical understanding, one may try to better understand the mathematical and physical basis of the macroscopic equations governing acoustic dissipation phenomena[3-7]. Finally, numerical studies based on simulations can be considered[8-13]. Each of these ways of considering these questions has advantages and disadvantages. Laboratory measurements are of indisputable values; however, their interpretation may be limited to a specific group of materials. Theoretical studies at the macroscopic scale are leading to robust models, but they also require measurements of non-independent macroscopic parameters. Numerical simulations usually attempt to bridge the gap between theory and experiments. They are nevertheless typically restrained by either the need to simplify geometry, physics, or both.

In recent years, another approach to the numerical study of acoustic properties of porous media has gained some interest. The idea is to numerically solve, in a microstructural configuration which consists of a Periodic Unit Cell (PUC), the linearized Navier-Stokes equation in harmonic regime with the local incompressibility condition[9] (viscous problem) and the linearized heat equation in harmonic regime[7] (thermal problem), with appropriate boundary conditions, and then to study how volume-averaged properties of the velocity and thermal fields relate to microscopic details of the geometry. Compared to macroscopic models, such an approach offers the ability to study the micro-physical basis of the acoustical macro-behaviour.

For the case of the viscous problem, solutions by finite element methods (FEM) have been investigated. Craggs and Hildebrandt[8] solved the viscous problem for specific cross-sections of uniform pores. Zhou and Sheng[9] treated the case of a cylindrical tube with sinusoidal modulation of its cross section, three-dimensional (3D) fused-spherical-bed and fused-diamond lattices. Firdaouss *et al.*[10] paid attention to a corrugated pore channel. Cortis *et al.*[11] studied the case of bi-dimensional (2D) configurations made of a square arrangement of solid cylinders. They were also interested by the corrugated pore channel[12]. Gasser *et al.*[13] treated the 3D case of the face centered cubic sphere packing.

Alternatively, the random-walker simulation method has been recently proposed by Lafarge[14] to provide an efficient resolution of the thermal problem. The principle of the method consists in simulating Brownian motion for a large number of the fluid-phase particles, and to link their mean free-paths to the thermal conduction properties of the confined fluid. An important point of the method is that, once the mean free path of a large number of particles has been estimated, the dynamic thermal response might be obtained for all frequencies. Contrary to finite element analysis, the solution has not to be computed at each frequency.

The random-walker simulation method has been implemented in two- and three- dimensions for computing the trapping constant of a 2D arrangement of overlapping fibres of circular cross-sections[15], and 3D digitalized geometries[16]. However, the trapping constant is only providing the asymptotic low frequency behaviour of the thermal problem. The first numerical simulations in harmonic regime have recently been proposed for the case of 2D regular and random arrangements of fibres with circular cross-sections[14]. This work has been newly extended to 3D PUC, and applied to the determination of the dynamic thermal characteristics of an open cell aluminium foam[17,18,19].

Starting from these micro-physical foundations, the aim of this paper is to illustrate the potential of such a bottom-up approach for microstructure optimization of sound absorbing materials. In the framework of this proceeding, we will focus on the viscous boundary value problem. The porous structure is a hexagonal lattice of solid fibres in air. For this simple geometry, it is shown how local geometry parameters are related to the absorption spectrum of the porous media. In particular, we will examine the influence of (i) the throat size (i.e. smallest distance between two fibres), (ii) the fibre radius at fixed throat size (i.e. the cellular size), and (iii) the cross-section shape of the fibres (i.e. 1-circle and 2-convex, 3-straight or 4-concave triangle).

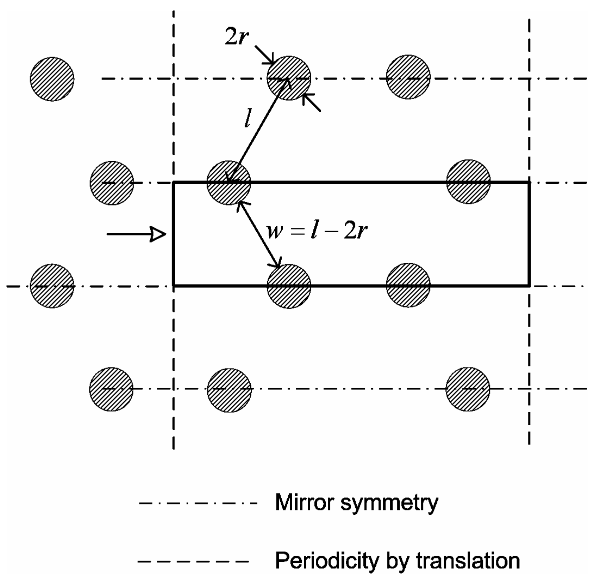

Figure 1.-Hexagonal porous structure

NUMERICAL CALCULATIONS

Model system

A typical two-dimensional hexagonal porous structure is depicted in Figure 1. It has an open cell structure where the cells have the shape of a hexagon. The fibre cross-sections form the nodes of the hexagons. The cross-sections of the fibres are circular for a porosity $\Phi \approx 0.85$ (or less). For a fixed thermal characteristic length Λ' (defined as twice the radio between the pore volume to wet surface ratio), when the cross section of the fibres changes from being circular to triangular, the porosity increases and the throat size *w* reduces.

Summary of numerical methods

The approximation is based on the assumption that the wavelength propagating though the fluid phase (air) of the porous structure is much larger than the pore (cell) size.

(1) The so called Poiseuille[20] and electric[21,22] boundary value problems have been solved using a commercial finite element code[23] on the hexagonal two-dimensional porous structure (cellular) for varying (i) throat sizes, (ii) cell sizes, and (iii) fibres cross-section shapes.

No-slip boundary conditions at the pore walls, and periodicity of the static velocity field were prescribed. Neumann boundary conditions on the fluid-solid interface, and periodicity on the inlet-outlet surfaces were used for the electric field. Generalized Neumann boundary conditions are set in the remaining borders due to the symmetries of the problems. The number of elements and their distribution in the fluid phase regions of the identified PUC were varied, with attention paid especially to the throat and the near-wall areas, to examine the accuracy and convergence of the field solutions. Up to a total of 5×10^4 elements were used to guarantee the variation of the solutions to within a few percent when the distribution and number of elements were varied.

(2) Macroscopic parameters are than derived from the flow field solutions by spatial averaging. The resistivity σ is computed from the static velocity field; the viscous characteristic length Λ and the tortuosity α_∞ are computed from the electric field as defined by Johnson *et al.*[3]

(3) Equations derived by Johnson[3], and Champoux and Allard[4,5] are used to relate the macroscopic parameters to the effective density and bulk modulus of a fluid filled porous medium. The absorption coefficient is then expressed from these quantities[5].

RESULTS AND DISCUSSION

We have derived the sound absorption coefficient of a two-dimensional hexagonal porous structure having a thickness of 25 mm for varying (i) throat sizes, (ii) cell sizes, and (iii) fibres cross-section shapes. The following results were obtained.

(1) The throat size *w* controls the sound absorption level; Figure 2. Note that an optimal throat size ($w \approx 70$ μm) corresponds to an intermediate resistivity ($\sigma \approx 26\,760$ N.m^{-4}.s; Figure 7).

(2) Pore size controls the frequency selectivity of the sound absorption spectrum (i.e. varying fibre radius R at constant throat size); Figure 3. Note that the optimal fibre radius ($R \approx$ 32 μm) minimizes the characteristic lengths ($\Phi \approx 0.862$, $\Lambda \approx 113$ μm, $\Lambda' \approx 200$ μm).

(3) At constant thermal characteristic length, a slight sound absorption enhancement is obtained with concave triangular cross-sections inscribed in the previous fibres; Figure 4. The throat size is thus reduced to keep Λ' constant ($w \approx 53$ μm). It is interesting to notice that during this process (from circular to concave triangular cross section), Λ is still minimized; Figure 5. The porosity and the resistivity are thus increased ($\Phi \approx 0.946$, $\Lambda' \approx 200$ μm, $\sigma \approx 34\,460$ N.m^{-4}.s, $\Lambda \approx 83$ μm, $\alpha_\infty \approx 1.06$).

Furthermore, it is interesting to notice that the reported values of the macroscopic parameters found with the optimal geometric configuration are those of a typical performing porous media such as a glass wool or a melamine foam.

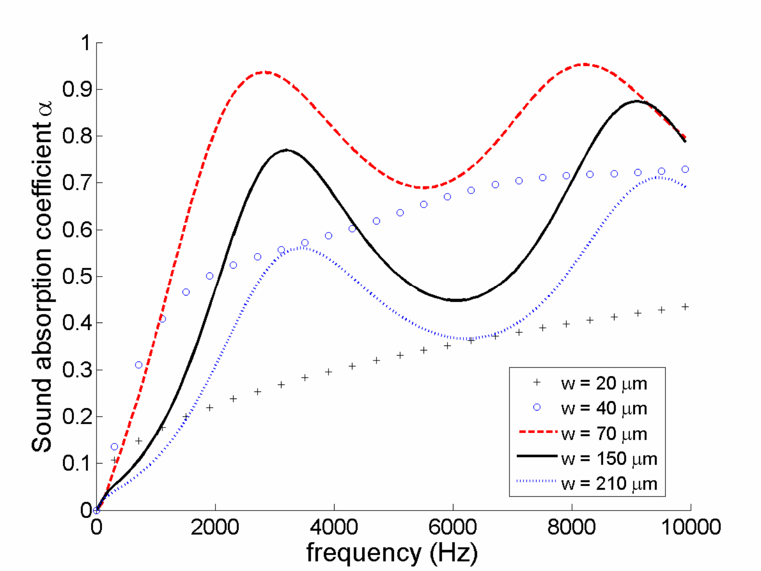

Figure 2.-Throat size effect on the sound absorption coefficient

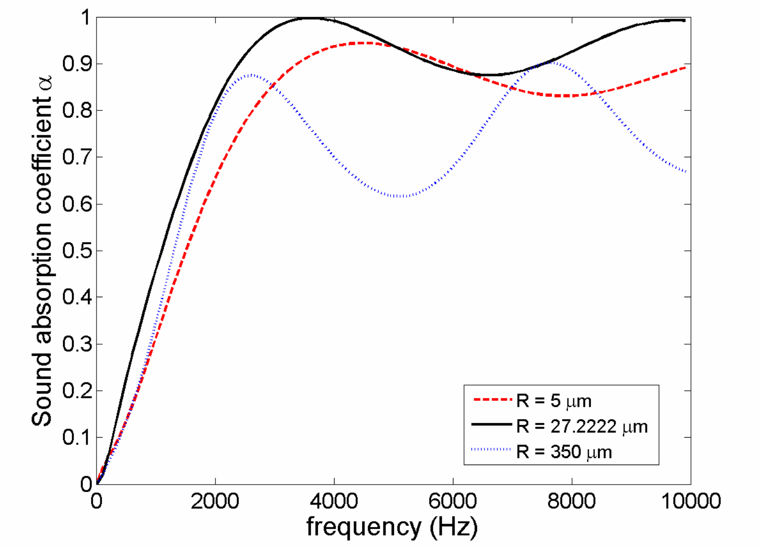

Figure 3.-Cell size effect on the sound absorption coefficient

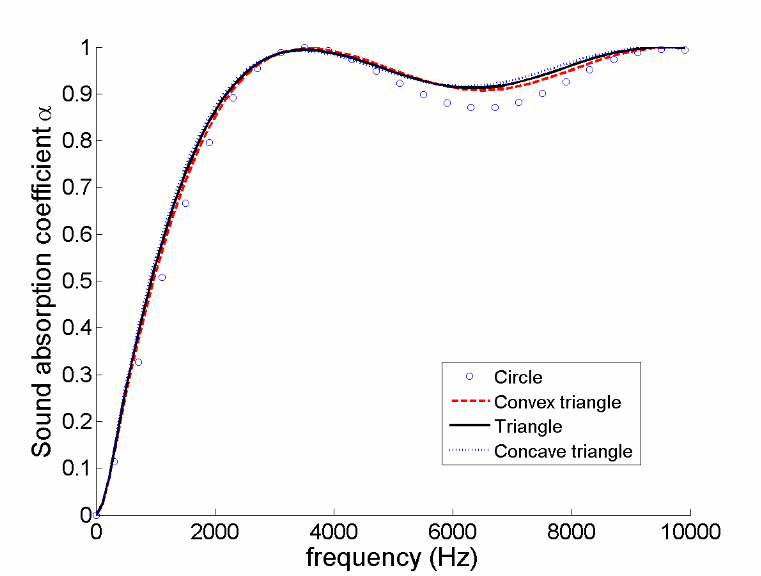

Figure 4.-Cross-section shape effect on the sound absorption coefficient

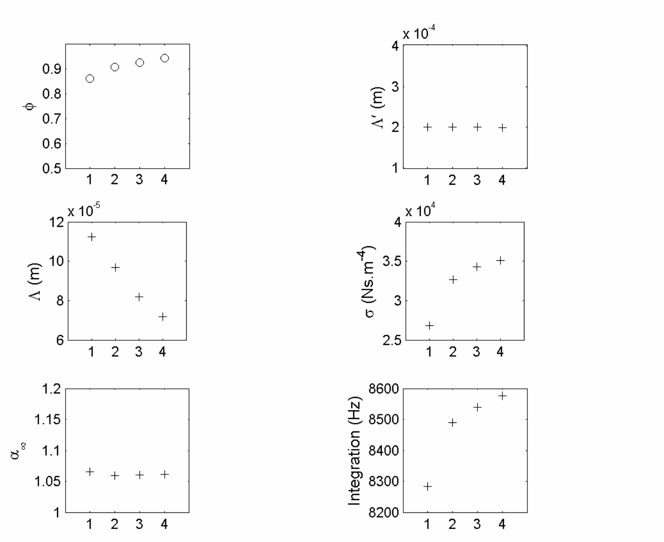

Figure 5.-Cross-section shape effect on macroscopic parameters
(1-circle and 2-convex, 3-straight or 4-concave triangle)

SUMMARY AND CONCLUSIONS

The results of our bottom-up approach for microstructure optimization of sound absorbing materials are summarized in this section. For a given fibre radius, an optimal throat size controlling the sound absorption level can be found, corresponding to an intermediate resistivity. By contrast, given an optimal throat size, the fibre radius (i.e. cell size) is essentially modulating the absorption curve. It is worth mentioning that the optimal absorption curve is the one which is minimizing the viscous characteristic length. And thus, this property can be used as a new criterion for sound absorption optimization. For a given thermal characteristic length, as the porosity increases from its circular cross-section value to its concave triangular cross section value, the throat size reduces with the viscous characteristic length, enhancing slightly the sound absorption coefficient of the porous structure. It is also worth mentioning that the macroscopic parameters found for the optimized porous structure are taking values commonly seen with performing sound absorbing materials such as a glass wool or a melamine foam.

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