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Design of metaporous supercells by genetic algorithm for absorption optimization on a wide frequency band

C. Lagarrigue *, J.-P. Groby, O. Dazel, V. Tournat

LUNAM Université, Université du Maine, CNRS, LAUM UMR 6613, Av. O. Messiaen, 72085 Le Mans, France

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ABSTRACT

The optimization of acoustic absorption by metaporous materials made of complex unit cells with 2D resonant inclusions is realized using genetic algorithm. A nearly total absorption over a wide frequency band can be obtained for thin structures, even for frequencies below the quarter wavelength resonances i.e., in a sub-wavelength regime. The high absorption performances of this material are due to the interplay of usual visco-thermal losses, local resonances and trapped modes. The density of resonant and trapped modes in this dissipative porous layer, is a key parameter for broadband absorption. The best configurations and critical coupling conditions are found by genetic algorithm optimization. Several types of resonators are included gradually in the studied configurations (split-rings, Helmholtz resonators, back cavities) with increasing complexity. The optimization leads to a metaporous structure with a 2-cm sub-wavelength layer thickness, exhibiting a nearly total absorption between 1800 Hz and 7000 Hz. The influence of the incidence angle on the absorption properties is also shown.

1. Introduction

Acoustic porous materials are widely used in noise control applications for their interesting sound absorbing properties in the middle and high frequency ranges (>1000 Hz) but they suffer from a lack of efficiency at lower frequencies [1]. These last decades, several ways to avoid the problem of absorption in the low part of the audible frequency range (<1000 Hz) have been proposed. The generally implemented solutions make use of multi-layer packages. This solution has limits at low frequencies while trying to keep the thickness of the treatment relatively small compared to the incident wavelength that has to be absorbed. Recently, new directions have been explored, based on combining resonant and scattering phenomena with the traditional viscous and thermal losses. Whatever the frequency is, the key is to excite modes of the structure that will trap the energy inside it for a long time and therefore enhance the absorption of the whole structure. Among different studied configurations, i.e., double porosity [2,3], dead-end porosity [4], multiple scattering [5], we focus here on configurations composed of periodic rigid inclusions and resonant inclusions embedded in a porous layer (often refereed as metaporous materials) [6–8].

The effect on the absorption properties of a periodic embedment of both non-resonant and resonant inclusions in a porous layer has been studied in two (or three) dimensions, when the porous layer is either backed by a rigid backing [6–9], possibly incorporating cavities [10], or radiating in a semi-infinite half-space [11] in the case of transmission problems. Different inclusion shapes have been studied [6,7,12,13] showing similar results at low frequencies. The enhanced absorption compared to simple porous media has been explained by the coupling of several phenomena: scattering by periodic inclusions and/or back cavities local resonances that trap the energy inside the inclusions or cavities, excitation of a localized mode that traps energy between the rigid backing and the inclusions, and excitation of the modified mode of the backed layer similar to Wood's anomaly. The rigid backing acts as a perfect mirror and allows interaction between the inclusion and its image to excite the trapped mode [6]. In these previous studies, the relatively simple configurations allowed for some analytical and semi-analytical modeling, together with numerical simulations and experiments. Consequently, the observed effects of perfect absorption (i.e. the absorption coefficient is 1), or nearly perfect absorption (the absorption coefficient is close to 1) for narrow frequency bands could be interpreted and associated to specific processes. The dependencies of the absorption properties on the metaporous cell parameters (such as the inclusion shape, size, position, and resonance frequency) could be interpreted and in some cases predicted and tailored.

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* Corresponding author.
E-mail address: clement.lagarrigue@univ-lemans.fr (C. Lagarrigue).

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Table 1
Supercells geometric parameters range values.

x_i (mm)	y_i (mm)	ϕ_i (rad)	r_i (mm)	e_i (%)
[4; 16]	[4; 16]	[0; 2π]	[2; 10]	[10; 90]

Table 2
Parameters used for the routines.

Routine	Selection	Mutation	Crossover	Sharing	Scaling
Type	Roulette	Multipoint	Non-uniform	Large exploration	Exponential
Parameter		3	$b = 1$	$\alpha = 0.8$ $\sigma = 0.95$	$q = 1$

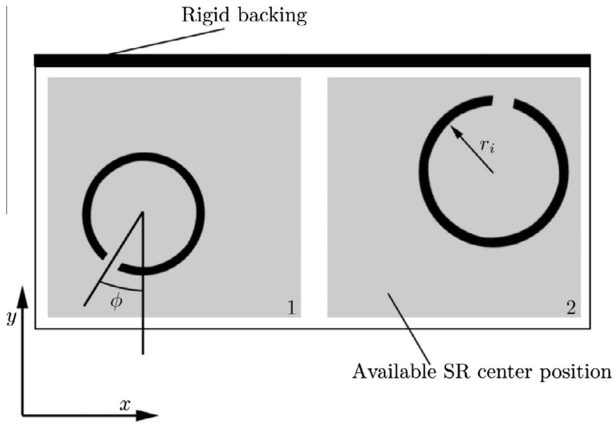

Fig. 1. Outline of a random unit cell.

Table 3
Parameters of the porous foam used in the article.

ϕ	α_∞	Λ (μm)	Λ' (μm)	σ (N s m^{-4})	f_v (Hz)
0.95	1.42	180	360	8900	781

In the present article, we propose a way to design metaporous materials able to strongly absorb the incident acoustic energy over a wide frequency band, for wavelengths in air larger than the material thickness. As mentioned previously, the density of modes trapping the energy inside the layer should be large enough in the frequency range of interest, which requires complex metaporous unit cells (or super-cells). The number of parameters defining the metaporous super-cell can consequently become large (all geometrical parameters of the inclusions and back cavities, parameters of the porous medium) and the effect of varying one of them on the absorption properties is unpredictable due to the influence on several coupled or competing absorption processes. In particular, the perfect absorption condition which can be analytically found in some configurations defined by only few parameters (see e.g. the one-dimensional case of a weakly lossy resonator, critically coupled to a waveguide cavity in [14], or the two-dimensional case of membrane resonator panel in [15]) is impossible to predict in the case of metaporous two-dimensional and three-dimensional super-cells composed of several resonators, back cavities and a porous material with frequency dependent acoustic properties. Therefore, in order to find metaporous super-cell configurations having high and broadband absorption, we make use of Genetic Algorithm (GA) optimization. In other words, we find empirically the metaporous super-cell parameters such that the different wave processes (scattering, trapped modes, local resonances and critical coupling, frequency dependent wave dissipation...) play together for high and broadband absorption.

The configuration analyzed in the following is composed of an infinite periodic set of two-dimensional (2D) metaporous super-cells. Each super-cell can contain 2D resonant inclusions embedded in a porous layer which is backed by a hard wall with or without resonant cavities. For the sake of clarity and to analyze the influence of each elements, we decided to make an incremental study where the complexity of the super-cells increases by the successive addition of ingredients. The optimization by the in-home genetic algorithm code begins with a previous configuration analyzed in [8] and evolves to account for more resonators per super-cells and a larger number of degrees of freedom.

2. Optimization by genetic algorithm

The genetic algorithm is set to find the configuration having the highest acoustic absorption in average over 80 points on the frequency range from 100 Hz to 7 kHz.

The geometry of the problem is two-dimensional and periodic, the inclusions being split-rings and 2D Helmholtz resonators and the cavities being 2D. The problem therefore reduces to the solution of the pressure field in the unit cell because of the periodicity and excitation by a plane incident wave. Bloch-Floquet conditions are applied to the left and right boundaries to consider the infinite periodicity as explained in [16]. For this to be correctly implemented, the two sides were discretized with similar nodes, i.e. identical vertical coordinates. All simulations are performed by considering a normal incident wave arising from a semi infinite space to the bottom of the cell. The top of the cell is considered perfectly rigid (Neumann type boundary condition). All the geometrical parameters are chosen by the algorithm except two: the thickness (20 mm) of the plate and the spatial periodicity (40 mm). The other parameters (summarized in Table 1) are set in a range of values that allow almost all configurations: where $i = 1$ or $2, x_i$ and y_i are respectively the longitudinal and the vertical position of the inclusion i, ϕ_i is the angular position of the slit, the origin is chosen centered on each inclusion and the direction is $-y, r_i$ is the internal radius of the inclusion and e_i is the thickness.

The program is coded in Fortran and uses classical minimum search (selection, mutation and crossover [17,18]) and fast convergence (sharing, scaling and elitism [17,19]) routines. Because of the possible high number of parameters, these routines are configured

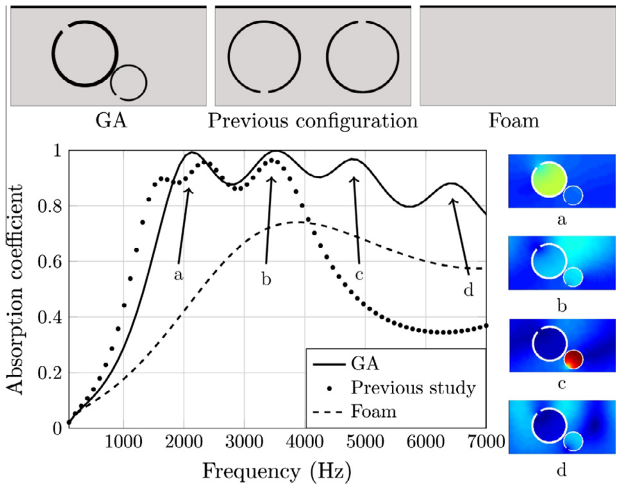

Fig. 2. Absorption coefficient for a super-cell composed of two split-rings.