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A microstructure material design for low frequency sound absorption

Thomas Dupont[a,*], Philippe Leclaire[a], Raymond Panneton[b], Olga Umnova[c]

[a] DRIVE EA1859, Univ. Bourgogne Franche Comté, ISAT, BP 31 - 49 rue Mlle Bourgeois, 58027 Nevers, France
[b] GAUS, Département de Génie Mécanique, Université de Sherbrooke, Sherbrooke J1K 2R1, Canada
[c] Acoustics Research Centre, University of Salford, Salford M5 4WT, United Kingdom

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ABSTRACT

The acoustic properties of an air-saturated porous material depend on its microstructure and the thickness of the sample. Thick samples of conventional acoustic materials are required to achieve good absorption at low frequencies. This study suggests a new micro-structure for the design of low-frequency resonant acoustic absorbers. A perforated material is studied, in which the main perforations are connected to a collection of periodically spaced very thin annular dead-end pores with respect to the lateral size, these absorbers are called multi-pancake materials. It is shown, that at low frequencies, the periodic array of annular dead-end pores increases the effective compressibility without modifying the effective dynamic density. Due to this effect, the first sound absorption peak appears at much lower frequency, compared to that of the structure without dead-end pores. A transfer matrix approach is proposed to model and optimize the absorber. Prototypes have been 3D printed and tested for sound absorption and transmission loss. This design allowed to design materials capable of producing absorption peaks at a few hundred Hz and constituted of a stacking of 10–20 annular dead-end pores, each dead-end having a thickness of the order of 1 mm or less so that the overall material thickness was of a few cm. A good agreement between the data and the model predictions is demonstrated.

1. Introduction

The acoustic properties of an air-saturated porous material depend on its microstructure and on the thickness of the sample [1]. Conventional acoustic treatments (such as foams or fibrous materials) of large thickness are required to achieve good sound absorption at low frequencies, which leads to a reduction of the air space volume and a significant increase of the material price. The purely reactive treatments (such as quarter wavelength resonator or Helmholtz Resonator [2]) or the reactive and resistive materials (such as a microperforated plate (MPP) [3] or a resistive film coupled with a macro-perforated plate [4]) backed by an air cavity can be used to improve the absorption at medium frequencies. However, a large depth cavity is still required to achieve low frequency absorption. Hence, the development of thin acoustic materials for low frequency absorption is an important challenge for the industry and is required in many applications, e.g. the acoustic liners for turbo fan engine [5], the passenger compartments, or the acoustic treatments of buildings.

To improve the absorption at low frequencies, Li et al. [6] proposed to add some extended tubes to MPP. Lagarrigue et al. [7] proposed to insert periodic lattice of resonators in rigid porous material. Boutin [8] proposed to use the homogenization method to model the acoustic of porous media with inner resonators. Based on Bradley's works [9], Leclaire et al. [10] have studied a structured perforated material containing periodically spaced dead-end (DE) pores (such as quarter wavelength or Helmholtz resonators). It has been observed that the presence of a periodic lattice of dead-end pores leads to the appearance of absorption peaks at low frequencies and at high frequencies (bandgap or stop bands for the sound transmission). Similar observations on other sound absorbing systems were reported by Groby et al. [11].

In Ref. [10], it has been proposed to model the resonant material with periodically spaced dead-end cavities by a transfer matrix approach or using low frequency asymptotic expansions. The presence of the network of DE pores has the effect, at low frequencies, of increasing the effective compressibility of the material without changing its effective dynamic density. This induces a decrease of the effective celerity of the material (Groby et al. [11] suggest calling this kind of material "slow sound material"). Due to this effect, the presence of a periodic network of pores significantly reduces the resonance frequencies of the material. This leads to the appearance of the absorption peaks at much lower frequencies without increasing the thickness of the resonant material. The model has been validated by numerical simulation and by comparing its predictions with measurements on prototype samples.

Based on this work, we propose a new type of microstructure design

* Corresponding author.
E-mail address: thomas.dupont@u-bourgogne.fr (T. Dupont).

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for low frequency resonant materials. In order to enhance the thermal effects at low frequencies and thus to decrease the first resonance frequency, the proposed microstructure is directly inspired by the design of heat exchangers. A perforated material with a periodic lattice of "pancake" cavities is designed and modeled. Here, "pancake cavities" is the name for very thin annular cavities (or ring cavities) with respect to the lateral sizes of the annuli, so that the ratio between annulus radius and thickness can be high (for example 40 or more). Another advantage of the ring cavities is that their volume can be significantly larger than that of the previously considered DE pores of Ref. [10], which is an advantage to reduce the frequencies of the absorption peaks. In the first part of the paper, the expressions of the low frequency approximation of effective parameters of this kind of material are presented and the design of the microstructure is proposed. Several prototypes are presented and the fabrication process is discussed. A model based on the transfer matrix formulation is described in the second part. The determination of the pancake cavity impedance is inspired by the work of Dickey and Selamet [12] on the acoustic behavior of a Helmholtz resonator with a "pancake" shape. Then, in the third part, numerical and experimental validations of the model are presented. A patent application has been filed on the thin multi-pancake resonant materials [13].

2. Material and methods

2.1. Proposed design for the microstructure of a resonant material

2.1.1. Low frequency approximation and effective parameters

An example of material with periodically distributed DE pores, proposed in Ref. [10], is presented in Fig. 1. When the distance between neighboring dead-end pores is small compared to the wavelength of sound in the main pore, the expressions for the effective density and compressibility of the material have been derived. A simple self-consistent model similar to a coherent potential approximation [14] has been used. For the design shown in Fig. 1, the low frequency expression of effective dynamic density ρ_e and effective compressibility C_e are given by the following equations [10]:

$$\rho_e = \rho_{mp}, \tag{1}$$

$$C_e = C_{mp} + C_{de}\frac{NA_{de}}{A_{mp}}\frac{d}{h}\left(\frac{\tan(k_{de}d)}{k_{de}d}\right), \tag{2}$$

where ρ_{mp} and C_{mp} are the effective density and effective compressibility of air in the main pore and ρ_{de} and C_{de} are the effective density and effective compressibility of air in DE pores, $k_{de} = \omega\sqrt{\rho_{de}C_{de}}$ is the wavenumber in DE pores, and ω is the angular frequency. These effective parameters can be expressed using an equivalent fluid model (for example JCA approach [1]). The geometrical parameters of the pores are: A_{mp} the cross-sectional area of the mean pore, h the periodicity, i.e. centre-to-centre distance between two neighboring DE pores, A_{de} and d are the cross-sectional area and the length of the DE pores. N is number of DE pores per period h.

Moreover, if $\mathrm{Re}\,(k_{de}d) \ll 1$ (very low frequency and/or short DE pores), the expression for the compressibility can be reduced to:

$$C_e = C_{mp} + C_{de}\frac{NA_{de}}{A_{mp}}\frac{d}{h} = C_{mp} + C_{de}\frac{V_{de}}{V_{mp}}, \tag{3}$$

with V_{mp} and V_{de} the total volumes of the main and of the DE pores per period h.

According to Eqs. (1)–(3), a periodic array of DE pores at low frequencies does not modify the effective density of air in the main pore, but it increases significantly its effective compressibility. That means that the periodic array of DE pores has a significant influence on thermal effects in the thermal boundary layers near the DE pore walls as the effective compressibility ($C_e = 1/K_e$ with K_e the effective Bulk modulus) is generally associated to them [15].

Moreover, the low frequency approximation of the effective sound speed is given by:

$$c_e = \frac{1}{\mathrm{Re}(\sqrt{\rho_e C_e})} \xrightarrow[\mathrm{Re}(k_{de}d)\ll 1]{} \frac{1}{\mathrm{Re}\left(\sqrt{\rho_e\left(C_{mp} + C_{de}\frac{V_{de}}{V_{mp}}\right)}\right)}, \tag{4}$$

It is clear from this equation, that periodic array of DE pores decreases sound speed in the material.

If we consider a quarter-wavelength thickness L material with straight main pores only, the first resonance frequency is given by:

$$f_{res1} = \frac{c_{mp}}{4L}, \tag{5}$$

where c_{mp} *is* the effective sound speed in the main pore. If a periodic array of lateral DE pores is added, the effective sound speed c_e is given by Eq. (4), and the first resonance frequency is modified as follows:

$$f_{res1}^{*} = \frac{1}{4L}\frac{1}{\mathrm{Re}\left(\sqrt{\rho_e\left(C_{mp} + C_{de}\frac{V_{de}}{V_{mp}}\right)}\right)}, \tag{6}$$

Thus periodic array of DE pores reduces the first resonance frequency in a significant way.

2.1.2. Proposed design

Based on the low frequency model presented in the previous section (Eqs. (3) and (6)), it is proposed here to optimize the microstructure of the DE pores in order to achieve the first resonant frequency (of perforated material) as low as possible without changing the main pore geometry and the sample thickness. It follows from (Eq. (6)), that in

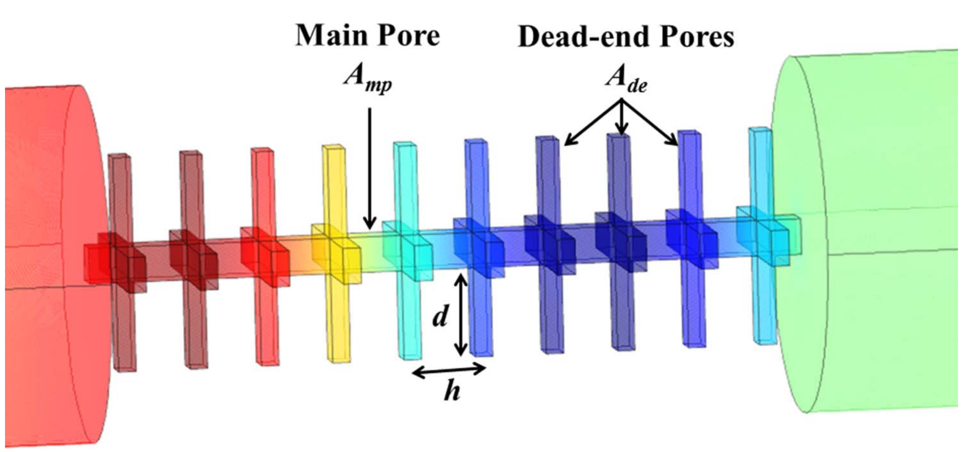

Fig. 1. Main pore (with a cross-sectional area A_{mp}) with periodically arranged dead-end pores, $N = 4$ identical dead-end pores with cross-section area A_{de} and length d per period h. The dead-end pores are located at "nodes".