Journal of Sound and Vibration 418 (2018) 221–239

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Acoustics of permeable heterogeneous materials with local non-equilibrium pressure states

Rodolfo Venegas [*], Claude Boutin

Université de Lyon - Ecole Nationale des Travaux Publics de l'Etat, LGCB/LTDS UMR-CNRS 5513/CeLyA, Rue Maurice Audin, 69518 Vaulx-en-Velin, France

ARTICLE INFO

Article history:
Received 9 June 2017
Revised 4 November 2017
Accepted 8 November 2017
Available online XXX

Keywords:
Sound propagation
Heterogeneous materials
Homogenisation
Pressure diffusion

ABSTRACT

The key idea developed in this work is the enforcement of local non-equilibrium pressure states in permeable materials by means of introducing geometrical and/or material heterogeneities. The two-scale asymptotic method of homogenisation is used to derive the macroscopic equations that describe sound propagation in the investigated class of materials. This allowed us to conclude that, at the leading order, the macroscopic fluid flow is mostly determined by that occurring in the most permeable fluid network. In contrast, the effective compressibility of the saturating fluid is modified by the non-equilibrium pressure states occurring in the different much less permeable local heterogeneities of the materials. The theory is exemplified by introducing an analytical model for the acoustical properties of a perforated microporous matrix with cylindrical microporous inclusions co-axially inserted in the perforations. The experimental validation of the theory is also provided.

1. Introduction

This paper investigates sound propagation in gas-saturated permeable heterogeneous media in which local non-equilibrium pressure states are present. This class of materials is characterised by a highly permeable pore fluid network and two (or more) much less permeable local heterogeneities. The key idea developed in this paper is the enforcement of local non-equilibrium pressure states by means of introducing geometrical and/or material heterogeneities. It will be shown that this leads to enhanced sound attenuation caused by mechanisms of diffusive type. These act in addition to the well-known mechanisms of sound energy dissipation associated with gas viscosity and thermal exchanges between the gas and solid frame of the material (see e.g. Refs. [1–4]).

Heterogeneous materials presenting a single non-equilibrium pressure state at the local scale display unconventional macroscopic acoustic behaviour. For example, in double porosity materials with highly contrasted permeabilities [5], such as meso-perforated foams [6,7], the foam matrix experiences a non-equilibrium pressure state imposed by the uniform pressure on its common interface with the pore fluid network (i.e. meso perforations). This occurs when the mass flux pulsed from the foam matrix on its common interface with the pore fluid network is of one order smaller than the mass flux generated by the carrying wave in the meso perforations. Under this condition, the macroscopic fluid flow is mostly determined by the fluid flow in the most permeable fluid network and the macroscopic mass balance becomes modified by the non-equilibrium pressure state occurring at the local scale. Such a modification is largely determined by a pressure diffusion phenomenon that leads to an increase of sound attenuation in a wide frequency band centred at the characteristic frequency associated with it. Pressure diffusion has also been observed in packings of porous grains [8], while in double porosity sorptive material [9] a similar phenomenon

---

[*] Corresponding author.
E-mail addresses: rodolfogustavo.venegascastillo@entpe.fr (R. Venegas), claude.boutin@entpe.fr (C. Boutin).

https://doi.org/10.1016/j.jsv.2017.11.013

occurs. In the latter case, however, mass diffusion affected by sorption is responsible for the modification of the macroscopic mass balance. Recently, it has been evidenced theoretically and experimentally that the local non-equilibrium states present in triple porosity sorptive media are characterised by pressure and mass diffusion, being both affected by sorption [10].

Let us also mention the works [11] and [12] where porous composites are studied and [13] where sound absorption of multi-layered porous materials with meso-perforations is numerically investigated. As in double porosity media, these works only considered a single local non-equilibrium pressure state when dealt with materials with highly contrasted permeabilities.

This work introduces the notion of enforcing multiple local non-equilibrium pressure states in permeable heterogeneous media and can be considered as a generalisation of the theory of acoustics of double porosity media [5,6].

The paper is organised as follows. The macroscopic equations describing sound propagation in porous media that can support multiple local non-equilibrium pressure states are derived in Section 2 using the two-scale asymptotic method of homogenisation [4,14]. The analysis of the effective parameters associated with the upscaled model is presented in Section 3. An analytical model that allows us to exemplify the theory is introduced in Section 4, followed by examples of the behaviour of the acoustical properties. We then validate the theory experimentally and summarise the main findings in the conclusions.

2. Sound propagation in permeable heterogeneous materials - theory

2.1. Geometry and main assumptions

We consider a periodic rigid-frame permeable heterogeneous material saturated with a Newtonian fluid. Fig. 1 shows a diagram of the scales of the material and its relevant geometrical descriptors. The macroscopic characteristic length L is related to the sound wavelength λ through $L = \lambda/2\pi$ and largely exceeds all other characteristic lengths of the material.

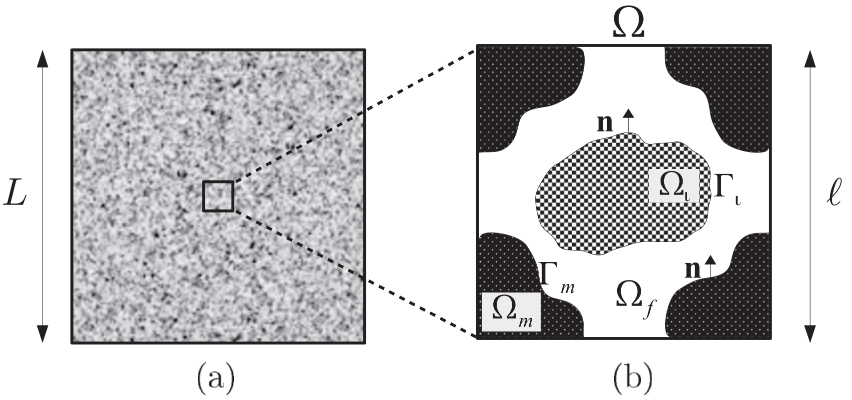
The representative elementary volume (REV) of the material is denoted as Ω. This is constituted by the volume of the pore fluid network Ω_f and the volume of the local heterogeneities Ω_m and Ω_ι. To simplify the presentation, these will be referred to as matrix (subscript m) and inclusion (subscript ι) microporous materials, respectively. Their solid parts are assumed perfectly impervious to gas transport.

The characteristic length associated with the pores (or the period of the material) is denoted as ℓ, while that of the pores in the matrix and inclusion microporous materials as l_m and l_ι, respectively. These lengths are of the same order of magnitude, i.e. $O(l_m) = O(l_\iota)$, and are both much smaller than the characteristic pore size, i.e. $l_i << \ell$, where the subscript $i = m, \iota$ is used to index the matrix and inclusion microporous materials. This indexing will be used throughout the paper, unless otherwise stated.

Because of the separation of scales between the characteristic pore size ℓ and micropore sizes l_i, the microporous materials Ω_i, having porosities ϕ_i, are modelled as equivalent Darcy media with known complex-valued frequency-dependent viscous permeability tensors $\mathbf{k}_i(\omega)$ and effective compressibilities $\mathsf{C}_i(\omega)$. The volume fraction occupied by the pore fluid network is equal to the mesoporosity, i.e. $\phi_p = \Omega_f/\Omega$, while the volume fractions occupied by the microporous materials are represented by $\varphi_i = \Omega_i/\Omega$. Hence one has that $\phi_p + \sum_i \varphi_i = 1$ and the total porosity of the material is $\Phi = \phi_p + \sum_i \varphi_i \phi_i$. Furthermore, the disparity in length scales between the macroscopic characteristic length associated with the acoustic phenomenon and the period of the material provides a small parameter $\varepsilon = \ell/L << 1$.

2.2. Governing equations at the pore scale and physical analysis

The equations that describe the oscillatory flow of a compressible fluid saturating the pore fluid network Ω_f are [1,3,15] the linearised equations of conservation of momentum (1), mass (2), and energy (3), and the equation of state (4). The physical



(a) (b)

Fig. 1. Diagram of the macroscopic (a) and local (b) scales of a permeable heterogeneous material. The local scale features a representative elementary volume (REV) Ω that comprises a pore fluid network Ω_f and local heterogeneities Ω_m and Ω_ι. The interfaces between the pore fluid network and the local heterogeneities are Γ_m and Γ_ι, and $\mathbf{n}$ is the outward-pointing normal vector.