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Computational homogenization of sound propagation in a deformable porous material including microscopic viscous-thermal effects

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ABSTRACT

Porous materials like acoustic foams can be used for acoustic shielding, which is important for high-tech systems and human comfort. In this paper, a homogenization model is proposed to investigate the relation between the microstructure and the resulting macroscopic acoustic properties. The macroscopic absorption ability is due to the microscopic viscous-thermal coupling between an elastic solid skeleton and a gaseous fluid in the associated Representative Volume Element (RVE). The macro-to-micro relation is realized through the boundary conditions of the microscopic RVE, which relies on the macroscopic solid deformation and fluid pressure gradient. By assuming that the variation of the macroscopic energy per unit volume equals the volume average of the variation of the microscopic energy, the macroscopic solid stress and fluid displacement can be calculated from the corresponding microscopic quantities. Making additional assumptions on this approach, Biot's poroelastic theory is recovered. A case study is performed through the simulations of sound absorption in three porous materials, one made from aluminum and two from different polyurethane foams. For simplicity, an idealized partially open cubic microstructure is adopted. The homogenization results are evaluated by comparison with Direct Numerical Simulations (DNS), revealing an adequate performance of the approach for the studied porous material. By comparing the results of different solid materials, it is found that the solid stiffness has a limited effect when resonance does not occur. Nevertheless, due to the absence of the microscopic fluctuation, Biot's model with the parameters obtained from the homogenization approach predicts a higher resonance frequency than the DNS, whereas a full homogenization modification improves the prediction.

1. Introduction

Passive sound absorbing porous materials, such as acoustic foams, can be used in acoustic shielding applications to improve the sound absorption performance. Models of acoustic porous materials can be classified as equivalent fluid models

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for motionless solid skeletons or fluid–solid coupled models. In the equivalent fluid model, acoustic properties depend on the effective density and the effective bulk modulus of the fluid in the porous material. Several models of this type have been proposed. For example, Zwikker and Kosten derived an analytical model from studying the case of a cylindrical pore, where viscous and thermal effects are both considered [1]. Another widely-accepted semi-phenomenological model is the Johnson–Champoux–Allard–Lafarge (JCAL) model which combines the Johnson–Koplik–Dashen (JKD) model and the Champoux–Allard–Lafarge (CAL) model. By introducing the concept of a viscous characteristic length, the JKD model gives an analytical expression matching the low- and high-frequency limiting effective density involving the static permeability and the tortuosity at infinite frequency [2]. Analogously, Champoux and Allard introduced a thermal characteristic length and derived an analytical expression for the effective bulk modulus by assuming circular-cylindrical pores [3]. The Champoux–Allard model was further developed for more general pores by introducing the static thermal permeability [4]. Conventionally, the above non-acoustical parameters are obtained from experiments [5–8], showing satisfactory results for wool materials [9] and fibrous materials [10]. Besides, an idealized unit cell representing the microstructure of the porous material can be constructed based on geometrical parameters obtained from microstructure characterization techniques [11–14]. The non-acoustical parameters can be linked to the representative unit cell through these semi-phenomenological models using (semi-)empirical relations [13] or calculated numerically by solving a steady Stokes problem, an electric conduction problem and a thermal conduction problem of the unit cell [11,12]. Justifications of these computational schemes can be obtained, clarified and developed by applying the asymptotic homogenization method to the fluid domain in the porous material [15–18]. Following an electromagnetic-acoustic analogy and an ensemble-averaging concept, a nonperturbative homogenization method was developed to allow for both temporal and spatial dispersion effects in fluid-saturated rigid-framed porous media [19].

A limitation of the equivalent fluid models is the lack of solid motion, which is important in vibro-acoustic problems [20] and which may be added as a refinement. Furthermore, although the sound absorbing behavior is often believed to be mainly governed by the local visco-thermal dissipations of the fluid, in particular for some partially-reticulated foams, the vibration of the pore membranes is observed to have a significant influence [21] and the consideration of the solid elastic properties can improve the agreement with experimental measurements [22]. Therefore, a fluid–solid coupling model should be considered when the solid motion is not negligible. The most famous coupling model is probably Biot's model, based on Biot's poroelastic theory [23–26], describing the coupling between the macroscopic fluid and solid displacement fields with effective parameters that are dependent on the corresponding microstructure. It can be easily expanded for anisotropic materials [27,28] and implemented in a finite element context [29–33]. Biot's model includes the effects of the microstructure implicitly through the effective parameters: the viscous coefficient and the added density are mainly determined by the effective fluid density; the elastic coefficients are related to the effective bulk modulus of the solid skeleton and the fluid through three *gedanken* experiments for isotropic porous materials [34]. A widely accepted method for obtaining the effective fluid properties involved in Biot's model is a direct application of equivalent fluid models such as the JCAL model [35–39]. There are also other analytical models to obtain Biot's parameters, such as Pride et al.'s model [40] and Wilmanski's model [41]. On the other hand, many fluid–solid coupling models have also been studied by taking into account the microstructure explicitly. For example, the asymptotic homogenization method has been applied to a porous material including an elastic solid skeleton and a compressible viscous gaseous fluid, each with a linearized behavior [42–45,15]. By considering the porous material as a mixture of a solid and a fluid, a set of macroscopic thermodynamically consistent constitutive equations can be obtained, while applying volume integration on the microscopic mass and momentum conservation equations [46–48].

Recently, the authors proposed a multiscale homogenization approach to obtain Biot's parameters from the corresponding microstructure by adopting the computational homogenization framework [49]. The proposed homogenization method is based on the scale separation principle that is also a fundamental assumption in the asymptotic homogenization method. However, it does not require lots of mathematical derivations and assesses the macroscopic influence of the complex microstructure straightforwardly. Furthermore, instead of a direct volume-averaging [40,46–48] or an ensemble-averaging [19], the upscaling from the microscopic scale to the macroscopic scale is realized through energy consistency of the two scales in the proposed method. It gives a good description of the viscous fluid–solid coupling effect in porous materials under isothermal conditions for the microscopic RVE. However, to agree with Biot's theory, the microscopic solid fluctuations were ignored in the approach, which may lead to an inaccurate description of the macroscopic properties. Moreover, the thermal effect is also very important for acoustic porous materials, particularly at low frequencies [1,3,4].

In this paper, extensions of the homogenization approach are proposed at both the macroscopic and the microscopic scales. Instead of Biot's poroelastic theory, the general formulations of momentum conservation of the solid and mass conservation of the fluid are adopted for the description of the macroscopic problem. Considering the linearity of the problem, an enhanced homogenization is obtained and it is compatible with Biot's poroelastic theory only when the microscopic fluctuations of the solid and the average of the microscopic fluid dilation are negligible. Through numerical examples of a simple unit cell with several different solid materials, it is shown that the incorporation of the microscopic fluctuations is crucial for a correct description of the effective solid density. A comparison with the results of Direct Numerical Simulation (DNS) shows that this new model gives a more accurate result when resonance occurs. Besides, in the microscopic RVE, the non-uniform thermal field is considered by applying the set of linearized Navier–Stokes–Fourier equations in the fluid [50] and allowing the thermal diffusion in the solid. The classical description of the non-isothermal

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