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Investigation of the effects of the microstructure on the sound absorption performance of polymer foams using a computational homogenization approach

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ABSTRACT

In this paper, a computational homogenization approach is exploited to study the effects of the microstructure of polymer foams on their acoustic properties. A Kelvin cell with partially-open thin membranes is adopted to represent the microstructure of the foam. By applying the homogenization approach, the effective material parameters are obtained based on a microscopic representative volume element (RVE) subjected to different loading conditions. Geometrical properties, including the opening and the thickness of the thin membranes and the cell size, are investigated. It is shown that when the opening of the membranes or the cell size are smaller, the sound absorption performance at low frequencies can be improved, at the expense of the mid-high frequency performance. Moreover, the optimal opening and optimal cell size for best sound absorption performance depend on the target frequency range. The effect of solid properties, including the stiffness and the loss factor, are also discussed. For low-stiffness materials, local resonance of the solid frame greatly affects the effective fluid density and the frame-borne wave, whereas global resonances can be utilized to improve the absorption performance in a specific frequency band.

1. Introduction

Acoustic porous materials, such as acoustic foams, are widely used as sound absorbers. Their sound absorption performance is strongly related to the underlying microstructure. For open-cell foams, an important factor of the performance is the cell size triggering the viscous effects. For example, by investigating 12 fully reticulated polyurethane (PU) foams, Cummings and Beadle discussed the relationship between the flow resistivity and the cell size (Cummings and Beadle, 1993). Han et al. tested several open-cell Al foams under different conditions and found that the foam samples with the smallest pore size of 0.5 mm exhibit the best absorption capacities when there is no air gap behind the sample (Han et al., 2003). For partially-open and fully-closed foams, thin membranes or thick walls exist in the faces of cells (Yasunaga et al., 1996). In this case, the opening of the membrane or the wall is important for the absorption. Lu et al. discovered that the sound absorption performance of Al foams can be enhanced by drilling holes in the cell wall (Lu et al., 1999). Moreover, based on the microstructure characterization of 15 PU foams, Doutres et al. discussed the effects of membranes in the cells and they pointed out that the presence of membranes enhances the viscous effects in the foams (Doutres et al., 2011). Furthermore, compared with fully-closed foams, Zhang et al. observed that the sound absorption performance of PU foams was improved for the low-mid frequency range by using an open cell structure (Zhang et al., 2012).

The cell size and its distribution are the results of many controlling factors, depending on the fabrication processes, such as foaming with inert gases, centrifugal casting, powder metallurgy, 3D printing, etc. For example, Zhou et al. fabricated a polymer foam, in which the cell size gradually changed from 20 to 100 μm, via supercritical carbon dioxide foaming (Zhou et al., 2011). Ghaffari Mosanenzadeh et al. applied a combination of a particulate leaching technique and a compression molding method to closely control the cell structure of open-cell foams with a graded cell size changing from 200 μm to 600 μm (Mosanenzadeh et al., 2015). It is also reported that ultrasound can be applied for a better control and monitoring of the production process (Torres-Sanchez and Corney, 2008; Torres-Snchez and Corney, 2009; Zhai et al., 2008; Wang

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et al., 2011). Moreover, it was shown that the opening ratio of the membranes is influenced by the concentration of the reactants (Zhang et al., 2012).

To understand effects of the microstructure, many methods or models have been developed. When the solid deformation can be ignored, effective fluid models and their derivatives can be applied (Zwikker and Kosten, 1949; Attenborough, 1983; Wilson, 1993, 1997; Wang and Lu, 1999). Among them, the Johnson-Champoux-Allard-Pride-Larfarge (JCAPL) model (Johnson et al., 1987; Champoux and Allard, 1991; Pride et al., 1993; Lafarge et al., 1997) is noteworthy, providing an adequate description of the effective density and the effective bulk modulus of the fluid. By using a numerical microstructure-based approach to obtain the non-acoustical parameters used in the JCAPL model, Perrot et al. discussed the effects of throat size, pore size and cross-section shape on the sound absorption performance of porous fibrous materials (Perrot et al., 2008) and also evaluated the approach on foams with experimental measurements (Perrot et al., 2012). By following the same approach, Hoang and Perrot studied the effects of the thin membranes (Hoang and Perrot, 2012) and Zieliński discussed the influences of a microstructure with randomly-distributed spherical pores (Zieliński, 2015). On the other hand, the non-acoustical parameters can also be obtained by using semi-phenomenological models. For instance, Doutres et al. proposed a 2-parameter model and a 3-parameter model for fully-open and partially-open foams respectively (Doutres et al., 2013) and used their models in a corresponding sensitivity study (Doutres et al., 2014). Moreover, Yang et al. developed an empirical model based on a simple cubic unit cell (Yang et al., 2015).

The solid deformation cannot be ignored in vibro-acoustic problems or when the material has a relatively low stiffness, such as for polymers. Considerable work has been done by focusing on mechanical properties of polymer foams (Srivastava and Srivastava, 2014). By coupling the fluid and the solid, Biot's poroelastic theory (Biot, 1962) is nowadays widely adopted in vibro-acoustic problems (Albert, 1993; Bolton et al., 1996; Kang and Jung, 2001; Göransson, 2006; Tsay, 2006; Leroy et al., 2009). The effective parameters required in Biot's theory can be linked to the microstructure by using a direct volume average (Pride et al., 1992) and semi-phenomenological scaling laws (Göransson, 2006; Lind-Nordgren and Göransson, 2010). Nevertheless, the total microscopic mechanical energy is not consistent with the macroscopic mechanical energy in the direct volume average method (Gao et al., 2015). The semi-phenomenological scaling laws can only be applied for a specific type of microstructure since they are usually derived for simplified geometries only (Gibson and Ashby, 1999).

To overcome these shortcomings, homogenization methods based on the scale separation principle can be applied without using semi-phenomenological or empirical relations. For example, the asymptotic homogenization method has been applied to porous materials (Sanchez-Palencia, 1980; Burridge and Keller, 1981; Auriault et al., 1985; Yamamoto et al., 2011). As an alternative, the authors proposed a computational homogenization approach for acoustic porous materials in earlier work (Gao et al., 2015, 2016a). It straightforwardly assesses the macroscopic influence of the microstructure by considering the viscous-thermal gaseous fluid flowing in an elastic solid frame. By using Kelvin cells with thin membranes, a comparison with experimental measurements showed the versatility of this approach (Gao et al., 2016b).

Particularly, polymer foams of a solid material with a low stiffness cannot be considered as rigid. The influence of the microstructure of these foams should be investigated by considering both the flowing fluid and a deformable solid. The purpose of the present paper is to employ the recently presented computational homogenization approach to obtain insights in the role of various morphological characteristics and solid properties for sound absorption of polymer foams based on isotropic Kelvin cells. The influences of the geometrical properties and the solid properties are investigated by focusing on the effective material parameters involving both mechanical and acoustical properties of polymer foams. For the geometrical properties, earlier investigations on these factors (Perrot et al., 2008, 2012; Hoang and Perrot, 2012; Zieliński, 2015; Doutres et al., 2013, 2014) were based on the JCAPL model, in which the solid deformation is not considered. In this paper, the effects of the thin membrane and the cell size are analysed systematically by applying the homogenization approach to the corresponding Kelvin cells. Thereafter, influences of solid properties, including the Young's modulus and the loss factor are discussed and particular attention is paid to the case of a low-stiffness solid with strong fluid-solid coupling effects. Significant phenomena, such as absorption peaks triggered through global resonance and anomalous behaviour induced by local resonance, are observed in the investigation.

2. Homogenization approach

When an acoustic wave is propagating in a porous material, two coupled problems at different scales can be considered: at the macroscopic scale, the porous material is replaced by an equivalent homogeneous medium, whereas at the microscopic pore scale, the material is intrinsically inhomogeneous. In the homogenization approach, the macroscopic characteristic length related to the external excitation is assumed to be much larger than the microscopic characteristic length, i.e. the two problems at the macro- and micro-scales can be separated. The two problems are studied in the frequency domain and the time derivative is replaced by $j\omega$ where j is the imaginary unit and ω is the angular frequency. At the macroscopic scale, the solid displacement $\boldsymbol{u}^s_M$ and the fluid pressure p^f_M are chosen as the macroscopic field variables. Momentum conservation of the solid and mass conservation of the fluid govern the macroscopic behaviour:

$$\boldsymbol{f}^s_M = \boldsymbol{\nabla}_M \cdot (\boldsymbol{\sigma}^s_M)^{\mathrm{T}}, \quad \text{and} \quad \varepsilon^f_M - \boldsymbol{\nabla}_M \cdot \boldsymbol{u}^f_M = 0. \tag{1}$$

Here, the operator $\boldsymbol{\nabla}_M$ represents the spatial gradient at the macroscopic scale. In the first equation, $\boldsymbol{\sigma}^s_M$ is the macroscopic Cauchy stress of the solid and $\boldsymbol{f}^s_M$ is the inertial force exerted on the solid. In the second equation, ε^f_M is the macroscopic volumetric change of the fluid and $\boldsymbol{u}^f_M$ is the fluid displacement.

In the microscopic representative volume element (RVE), the solid and the fluid are coupled through a continuous interface condition. In the solid, conservation of linear momentum is applied for the mechanical problem and Fourier's law is adopted for the thermal diffusion:

$$\begin{aligned} -\omega^2 \rho^s_0 \boldsymbol{u}^s_m &= \boldsymbol{\nabla}_m \cdot \boldsymbol{\sigma}^s_m \\ \rho^s_0 C^s_p j\omega\theta^s_m &= -\boldsymbol{\nabla}_m \cdot \left(-k^s \boldsymbol{\nabla}_m \theta^s_m \right). \end{aligned} \tag{2}$$

Here, ρ^s_0 is the static density of the solid; $\boldsymbol{\sigma}^s_m$ is the microscopic Cauchy stress of the solid; C^s_p is the thermal capacity at constant pressure; θ^s_m is the temperature difference of the solid; and k^s is the thermal conductivity of the solid. The isotropic linear elastic constitutive law is applied, and thermal expansion effects are