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Design optimization of porous fibrous material for maximizing absorption of sounds under set frequency bands

Shutian Liu, Wenjiong Chen, Yongcun Zhang *

State Key Laboratory of Structural Analysis for Industrial Equipments, Dalian University of Technology, Dalian, China

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ABSTRACT

In this paper, a methodology is proposed for designing porous fibrous material with optimal sound absorption under set frequency bands. The material is assumed to have a rigid frame and a hexagonal arrangement of fibers, and the analytical model derived by Johnson, Champoux and Allard ("JCA model") is used to investigate the influences of the micro-structural parameters (fiber radius r and gap w) on sound absorption performance, and the macro-acoustic parameters used in JCA model is determined via finite element analysis for the hexagonal micro-structure. Moreover, a mathematical model is constructed to obtain the optimized micro-structure design, with fiber radius and gap as design parameters and average absorption performance of the porous fibrous material under set frequency band as target. Utilizing the constructed optimization model, the microstructure parameters are derived with optimal sound absorption under low frequency ($20 \leqslant f < 500$ Hz), medium frequency ($500 \leqslant f < 2000$ Hz) and high frequency ($2000 \leqslant f < 15{,}000$ Hz), respectively. On top of that, for a given thickness of porous fibrous material layer, the analytical relationship between fiber radius and optimal porosity under set frequency bands is constructed.

1. Introduction

Most of the porous sound-absorbing materials commercially available are fibrous. Porous fibrous material has been found to be one of the most effective ways for the control of noise [1–3]. Because the sound absorbing effects of porous materials are sensitive to the pore geometry, the optimization design of the pore geometry has been widely studied of late.

For many porous fibrous metal and non-metal materials, the frame is motionless in wide ranges of acoustical frequencies in many cases, thus allowing the use of models worked out for rigid framed materials. A rigid-framed porous material has high sound absorption ability because of the thermo-elastic damping and viscous loss generated while sound propagates through a large number of small air passages in the material [4]. While studying sound propagation and loss, a layer of rigid-framed porous material can be considered as a layer of equivalent fluid with the frequency-dependent effective density ρ_{eq} and compressibility K_{eq} [5–8]. The thermo-elastic damping and viscosity of porous materials are heavily dependent on their microstructural, such as porosity, shape and size of pores, size and distribution of fibers etc. [9–12]. For this reason, many researchers have focused their attention on setting up the theoretical relationship between the microscopic pore structure and sound absorption ability [4,10,13–19], most aiming to find a way to better predict sound absorption properties of porous materials. Of those researches, the most representative acoustical model is proposed by Bazley and Delany [13]. However, this empirical model studies the influence on sound absorption properties of one single macroscopic parameter, i.e. state air-flow resistivity, and is therefore irrelevant when studying microscopic structure of porous material. Moreover, the accuracy of the empirical model is limited to the vicinity of certain frequency points, and is especially inaccurate under low frequencies. After that, Johnson et al. [14], Allard and Champoux [15] developed a series of semi-phenomenological models, which included two extra macroscopic acoustic parameters, one to describe micropore structure, another to describe the viscosity and thermal conductivity between fluid and frame. The Johnson–Champoux–Allard model ("JCA model") is accurate in both high and low frequencies, and by including the two extra parameters, can be used to establish the relationship between the micro-structure and sound absorption properties of the material. On top of the JCA model, many scholars have developed other widely used semi-phenomenological models, including Biot [4], Attenborough [16], Zwikker and Kosten [17], Stinson [18], Wilson [19] and Lafarge et al. [10]. These models have improved accuracy by introducing extra macroscopic acoustic parameters, which are usually attained through solving viscous boundary value problems at the micro-structural scale. These analyses are usually highly complicated, even if simplified to assume a periodic micro-

* Corresponding author. Tel./fax: +86 0411 84706149.
E-mail address: yczhang@dlut.edu.cn (Y. Zhang).

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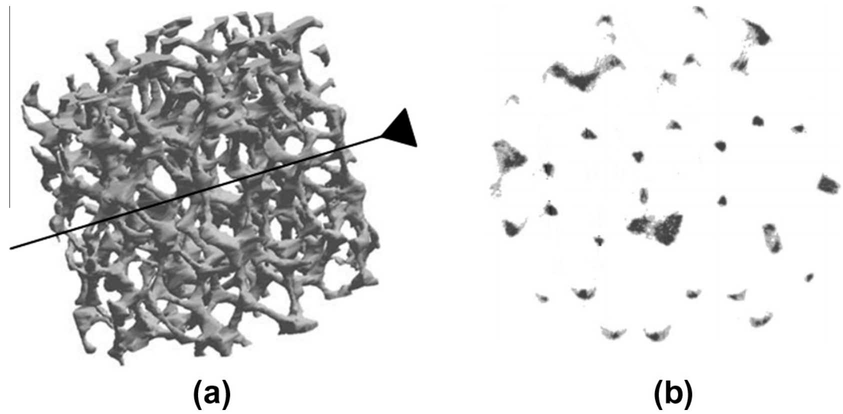

Fig. 1. (a) Porous fibrous metal and (b) its profile.

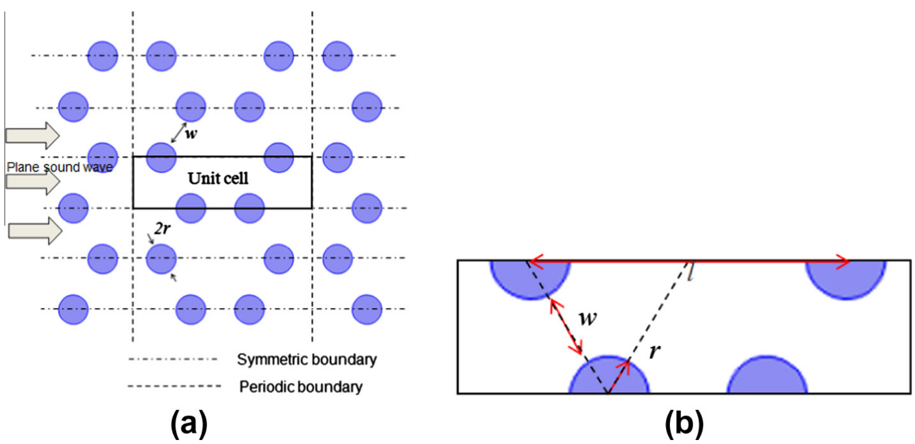

Fig. 2. (a) Cross-sections of parallel fibers array; (b) periodic micro-structure.

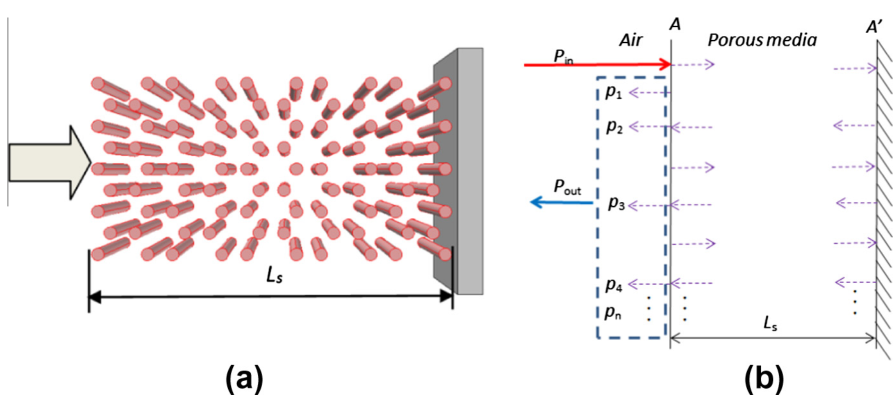

Fig. 3. (a) An absorbing porous metal layer of thickness L_s backed by a rigid wall, under normal incidence acoustic plane wave; (b) the sketch of multiple scattering.

structure, and as a result, analytical formulation is only achievable for porous materials with simple structures (e.g. cylindrical pores) [20]. For more complicated porous structures (e.g. porous fibrous), finite-element method is usually adopted, as illustrated in various publications including Zhou and Sheng [21]; Lee and Leamy [22,23]; Perrot et al. [24–26]; Felixet et al. [27,28].

The acoustic properties of porous materials can be significantly improved with the optimal micro-structural design, and as a result, a comprehensive methodology to develop optimal micro-structural design is of great importance. Of previous researches, Belov et al. [29] obtained materials with high sound absorption ability under relatively large frequency band, by altering thickness of the porous media and size of pores; Wang and Lu [30] analyzed the sound absorption of Al alloy foams and honeycombs using the point-matching method. They concluded that the optimal pore size in terms of sound absorption is of the order of 0.1 mm; Cheng et al. [31] set the optimal pore porosity for under-water sound absorbing porous materials; moreover, Camille Perrot et al. [24–25] achieved highly satisfactory results via analyzing the equivalent 2-d periodic structures of 3-d porous materials.

The majority of current work has been focusing on optimizing micro-structure or macro-parameters of porous materials for the