Composites Science and Technology 107 (2015) 10–17

Contents lists available at ScienceDirect

Composites Science and Technology

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

Anisotropic acoustical properties of sintered fibrous metals

H. Meng [a,b], Q.B. Ao [c], S.W. Ren [a,b], F.X. Xin [a,b,*], H.P. Tang [c], T.J. Lu [a,b]

[a] *Multidisplinary Research Center for Lightweight Structures and Materials, Xi'an Jiaotong University, Xi'an 710049, China*
[b] *State Key Laboratory for Mechanical Structure Strength and Vibration, School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, China*
[c] *State Key Laboratory of Porous Metal Materials, Northwest Institute for Nonferrous Metal Research, Xi'an 710016, China*

ARTICLE INFO

Article history:
Received 27 September 2014
Received in revised form 27 November 2014
Accepted 29 November 2014
Available online 5 December 2014

Keywords:
A. Fibers
B. Mechanical properties
C. Anisotropy
D. Acoustic emission

ABSTRACT

A combined theoretical and experimental study is carried out to investigate the anisotropic acoustic properties of sintered fibrous metals. In the theoretical model, based on the transversal and longitudinal dynamic mass densities and effective bulk modulus of randomly placed parallel fibers, the dynamic mass densities and effective dynamic bulk modulus of a sintered fibrous metal in the direction normal and parallel to its surface are obtained. Sound absorption coefficient, sound speed and attenuation coefficient in each of the two directions are calculated once the dynamic mass densities and effective dynamic bulk modulus are determined. For validation, experimental measurements are performed, with good agreement between theoretical prediction and measurement data achieved. Subsequent numerical investigations focus on the influence of fiber diameter and porosity on the anisotropic acoustical properties of the sintered fibrous metal. The sintered fibrous metal exhibits better sound absorption/attenuation performance in the parallel direction than in the normal direction. The anisotropy in acoustical properties increases with decreasing fiber diameter and porosity due mainly to increasing interactions between adjacent fibers.

1. Introduction

Fibrous materials are widely applied in the noise control area, either isolated or composited with other structures, for their good sound insulation and absorption ability [1–5]. In particular, fibrous materials made of metal fibers (e.g., stainless steel) through sintering process have promising potential for high-temperature noise control. The present paper aims to investigate theoretically the sound absorption performance of this kind of fibrous materials, with particular focus placed upon its anisotropic acoustic properties.

A multitude of theoretical models have been proposed to estimate the acoustical properties of fibrous materials. Due to the complex morphology of fibrous materials, one common approach is developing theoretical models based on empirical modeling. For typical instance, Delany and Bazley [6] presented a simple power-law function between the measured characteristic impedance and sound absorption coefficient as well as flow resistivity. Subsequently, Miki [7] and Komatsu [8] modified the Delany–Bazley model for more accurate predictions. Allard and Champoux [9] proposed a new empirical model by taking into account the physical properties of fibrous materials, and found that this model was valid at low frequencies in contrast with the Delany–Bazley model. Other empirical models were also proposed, such as those by Garai and Pompoli [10] and Narang [2] for polyester fibrous materials. In addition to empirical modeling, attempts have also been made to develop theoretical models based on idealized geometry of fibrous materials. For example, Tarnow [11,12] calculated the compressibility and dynamic resistivity by treating the fibrous material as array of periodically arranged parallel fibers, while Dupere et al. [13,14] modeled sound propagation both normal and parallel to array of parallel fibers and rigid spheres. Sun et al. [15] established that the model of Dupere et al. was suitable for sintered fibrous metal materials for high temperature applications. A theoretical model was proposed by Attenborough [16] for rigid fibrous soils and sands, which however needs five physical parameters. Kirby and Cumming [17] presented an improved model based on parallel fiber microstructure, targeting in particular sound absorbing properties at low frequencies.

Although numerous studies have been carried out to explore the acoustical properties of rigid fibrous materials, none concerned the acoustic anisotropy of fibrous materials. In the present study, a combined theoretical and experimental approach is employed to reveal the anisotropic acoustical properties of sintered fibrous metals. First, the dynamic mass density (i.e. the ratio of the pressure

* Corresponding author at: State Key Laboratory for Mechanical Structure Strength and Vibration, School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, China. Tel./fax: +86 29 82663223.
E-mail address: fengxian.xin@gmail.com (F.X. Xin).

http://dx.doi.org/10.1016/j.compscitech.2014.11.020
0266-3538/

gradient to the averaged fluid acceleration) and effective bulk modulus (i.e. the ratio of the pressure increase to the decrease of relative volume) for sound propagating normal and parallel to randomly placed parallel fibers are calculated theoretically to estimate the dynamic mass density and effective bulk modulus of a sintered fibrous metal along both parallel and normal directions. Next, the validity of the model predictions is checked against experimental measurements, with good agreement achieved. The model is subsequently used to analyze the acoustic anisotropy of the material in terms of sound absorption coefficient, sound speed and attenuation coefficient. The influence of fiber diameter and porosity on the acoustic anisotropy is quantified.

2. Theoretical model

Consider a sintered fibrous metal as shown in Fig. 1. As the metal fibers having equal diameter (∼50 μm) randomly lie in parallel planes, the fibrous metal may be regarded as a transversely isotropic material. In the present study, for convenience, the plane parallel to all the fibers is referred to as the "fiber plane". With reference to Fig. 1(a) and (b), the acoustical properties of the sintered fibrous metal in the direction normal to the fiber plane are expected to be different from those in the direction parallel to it. Since the stiffness and density of the metal fibers are much larger than that of the fluid (air in the current study) saturated in the fibrous metal, the fibers are regarded as rigid bodies.

The dynamic mass densities of the sintered fibrous metal in different directions are calculated based on the array of randomly placed parallel fibers as shown in Fig. 2(a). The dash lines marked around the fibers are called Voronoi polygons, which represent the interaction of adjacent fibers in the parallel fiber array. For simplicity, each Voronoi polygon is approximated by a circle having the same area; see Fig. 2(b). The porosity of the parallel fiber array is identical to that of the considered sintered fibrous metal.

Consider first sound propagating parallel to the parallel fiber array, namely, parallel to the z-direction of Fig. 2. Since the void space among these fibers is small, the viscosity of the saturated fluid is significant and should be taken into account in acoustic modeling. The fluid motion is governed by the viscous Navier–Stokes equation, as:

$$\nabla^2 u_z - \frac{i\omega\rho_0}{\eta} u_z = \frac{1}{\eta}\frac{\partial p}{\partial z} \tag{1}$$

where u_z is the fluid velocity in the z-direction, ω is the angular frequency, η denotes the dynamic viscosity, p is the fluid pressure and ρ_0 is the fluid density. By approximating the Voronoi polygons by circles having the same area [12], the general solution for Eq. (1) can be written in the form [18]:

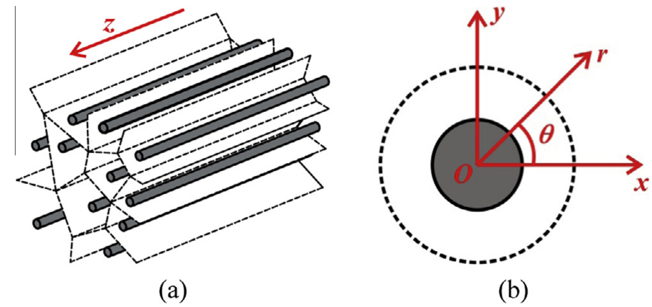

Fig. 2. (a) Schematic illustration of parallel fiber array with Voronoi outer boundaries; (b) cross section of one cell with approximated circular outer boundary.

$$u_z(r) = A_0 Ke_0\left(\sqrt{\frac{\omega}{\nu}}r\right) + B_0 Be_0\left(\sqrt{\frac{\omega}{\nu}}r\right) - \frac{1}{i\rho\omega}\frac{\partial p}{\partial z} \tag{2}$$

where $Ke_m(x) = \mathrm{ker}_m(x) + i\mathrm{kei}_m(x)$, $Be_m(x) = \mathrm{ber}_m(x) + i\mathrm{bei}_m(x)$, ker_m, kei_m, ber_m, bei_m are the Kelvin functions, (r, θ) are the polar coordinates (Fig. 2), and A_0 and B_0 are unknown coefficients to be determined by applying relevant boundary conditions.

Due to the viscosity of the fluid, the velocity at the interface between the fluid and the fiber is zero:

$$u_z(r,\theta)|_{r=a} = 0 \tag{3}$$

where a is the fiber radius. Besides, no shear stresses exist on the outer boundaries of the fibers, therefore, for a circle with radius r_{out}, the boundary condition is [13]:

$$\left.\frac{\partial u_z}{\partial r}\right|_{r=r_{out}} = 0 \tag{4}$$

Upon substitution of Eqs. (2) into (3) and (4), the coefficients A_0 and B_0 are obtained as:

$$A_0 = \frac{1}{Ke_0(R_0) - \frac{Ke_1(R_1)}{Be_1(R_1)}Be_0(R_0)}\frac{1}{\rho i\omega}\frac{\partial p}{\partial z} \tag{5}$$

$$B_0 = \frac{-1}{Ke_0(R_0) - \frac{Ke_1(R_1)}{Be_1(R_1)}Be_0(R_0)}\frac{Ke_1(R_1)}{Be_1(R_1)}\frac{1}{\rho i\omega}\frac{\partial p}{\partial z} \tag{6}$$

The velocity u_z is determined by substituting Eqs. (5) and (6) into (2), from which the mean velocity $\bar{u}_z$ is calculated as:

$$\bar{u}_z(r_{out},\omega) = \frac{1}{S}\int\int_S u_z(r)dS = \frac{1}{\pi r_{out}^2 - \pi a^2}\int_a^{r_{out}} u_z(r)2\pi r dr \tag{7}$$

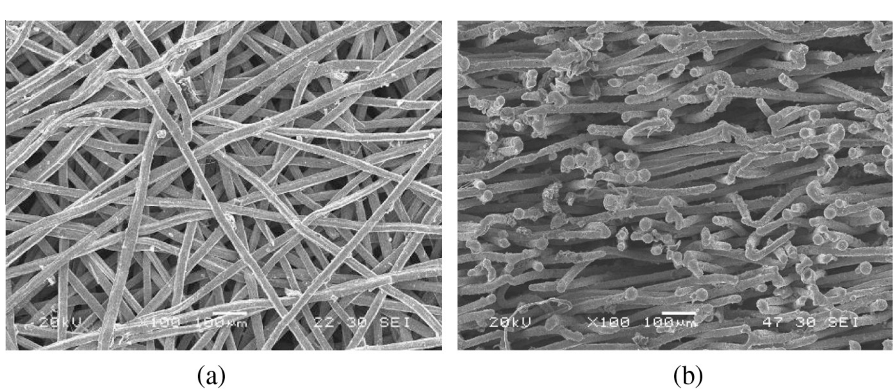

Fig. 1. Photographs of sintered fibrous metal: (a) surface parallel to fiber plane; (b) surface normal to fiber plane.