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Predicting the sound absorption of natural materials: Best-fit inverse laws for the acoustic impedance and the propagation constant

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ABSTRACT

Natural materials are becoming a valid option for sound absorption treatments. In particular, among them, natural fibers have received increasing attention given their good thermal insulation properties, lack of harmful effects on health, and availability in large quantities. This paper discusses an inverse method to predict the acoustical properties of nine natural fibers. Six vegetative fibers: kenaf, wood, hemp, coconut, straw, and cane; one animal fiber, sheep wool; recycled cardboard; and granular cork are investigated. The absorption coefficient and the flow resistance for samples of different thickness have been measured. Moving from the Delany-Bazley model, this study compares the impedance tube results with the theoretically predicted ones. Then, using a least-square fit procedure based on the Nelder-Mead method, the coefficients that best predict both the acoustic impedance and the propagation constant laws are calculated. The inverse approach used in this paper allows to determine different physical parameters and to obtain formulas to include the investigated natural fibers in software modelling for room acoustics applications.

1. Introduction

Sound absorption in room acoustics is generally obtained with porous synthetic materials, such as rock wool, glass wool or polyester, which are expensive to produce and have several environmental implications. These issues have increased the attention towards natural materials [1–3]. These are generally defined according to the natural or renewable sources for their constituent materials, the low level of environmental pollution emitted during their production, or the low embodied energy [4,5]. In particular, natural fibers have received increasing attention for acoustic uses [6–8]. They are competitive materials thanks to their low density, good mechanical properties, easy processing, high stability, minimal health impacts, high quantity availability, low price, and reduced environmental impacts for their production [4].

Based on their microscopic configurations, porous absorbing materials have been classified as cellular, fibrous, and granular [5]. In particular, fibrous materials consist of a series of tunnel-like openings that are formed by interstices in material fibers. Fiber materials are generally classified as natural or artificial. Natural fibers can be vegetable (e.g. kenaf, hemp, and wood), animal (e.g. wool and fur felt) or mineral (asbestos); whereas synthetic fibers can be mineral (e.g. fiberglass, mineral wool, and glass wool) or polymer (polyester). Moreover, vegetable fibers are categorized into: stalk or wood fiber (e.g. straw of wheat, rice, softwood or hardwood); bast fiber or skin fiber (e.g. flax, jute, kenaf, industrial hemp, ramie, rattan, and soybean); leaf fiber (e.g. sisal, palm, and agave); seed fiber (e.g. cotton and kapok); and fruit fiber (e.g. coconut). Microscopic analysis of natural fibers reveals that natural fibers present irregular shape and are aggregated in structures much less regular than synthetic porous materials [6]. The irregular structure is the main limit of theoretical models to predict the sound absorption behavior of natural materials.

The materials studied in this paper are mainly vegetable fibers, which were compressed in order to create sound absorbing samples. Although natural fibers are often commercialized in panels or blocks created through the use of a binder, in this paper unprocessed natural raw fibers are considered. Material stability was obtained only by compression, without the use of any binder.

This paper follows some recent studies of the authors about measurements of the sound absorption of natural fibers [6]. In particular, this paper elaborates the laboratory measurements to the ability to model the acoustic behavior of the fibers. The scope is to obtain formulas that could be used as predictive tools for the acoustic behavior of natural fibers. In this way, the paper will provide a way to overcome the empirical approach generally required while assessing inhomogeneous natural fibers.

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The paper is structured in the following way: Section 2 presents a review of the models for the sound absorption of porous materials; Section 3 presents the laboratory measurements; Section 4 briefly presents the natural fibers object of the investigation; Section 5 reports the results of the best-fit approach used to fit theoretical models to laboratory results; and Section 6 reports some concluding remarks.

2. Sound absorption modelling of porous materials

Useful parameters to compare the sound-absorbing characteristics of fibers are their diameter, their length, and the regularity of their shape. Electronic microscopy techniques have shown that the diameter of natural fibers tends to be larger than in synthetic fibers and much more irregular [6]. Arenas and Crocker reported the average diameter for some natural fibers: 8–33 μm for cotton, 21 mm for kenaf, 16–38 mm for wood, and 22 μm for hemp [5]. Animal fibers may be even thicker, as the fiber diameter of the wool equals to 37 mm when used as a raw material and 63 mm when used as a wool batt[6]. Given the not constant diameter of natural fiber, theoretical sound absorbing models fail from being accurate when they are applied to natural fibers.

A porous material exposed to incidental sound waves allows the air molecules within the pores to vibrate and, by doing it, to transform some sound energy into thermal and viscous heat. At low frequencies, these energy losses are isothermal and limited (resulting in low sound absorption at low frequencies), while at high frequencies, they are adiabatic and are generally more important. In fibrous materials, most of the sound energy is absorbed by its scattering among the fibers and by their vibration.

Several models for predicting the sound absorption mechanisms of porous (synthetic) materials exist, and the one to use in each case is generally selected based on the distinctive absorption mechanism and the type of porosity of the analyzed material.

Existing sound absorbing models aim to describe the characteristic wave impedance and the characteristic sound propagation constant using some basic physical properties of the materials, such as the porosity, the tortuosity, and the airflow resistance. Models requiring more than five material properties have been proposed over the years [6,9,10]. However, since the direct measure of material properties (such as the porosity or the tortuosity) is often difficult to perform and inaccurate in the results, indirect or inverse methods, where these parameters are derived from the analysis of some material behaviors, are often preferred.

Delany and Bazley proposed a simple model for fibrous absorbent materials only employing the non-acoustical parameter of the airflow resistivity for predicting the acoustical characteristics and many other parameters [9]. This model considers a porous layer as a bulk material with the rigid frame media of the material, so that the flow resistivity is sufficient to determine the characteristic wave impedance z_c and the characteristic propagation constant (or complex wave number) k_c, according to the following equations:

$$z_c = \rho_0 c\left(1 + c_1\left(\frac{\rho_0 f}{\sigma}\right)^{-c_2} - jc_3\left(\frac{\rho_0 f}{\sigma}\right)^{-c_4}\right) \quad (1)$$

$$k_c = \omega/c\left(c_5\left(\frac{\rho_0 f}{\sigma}\right)^{-c_6} - jc_7\left(\frac{\rho_0 f}{\sigma}\right)^{-c_8}\right) \quad (2)$$

where $\rho_0 c$ is the characteristic impedance (Pa s/m), ω the angular frequency ($\omega = 2\pi f$), c the sound speed (m/s), σ the flow resistivity (Rayl/m), f the frequency (Hz), and c_i (with $i = 1\ldots8$) are eight numerical coefficients. Using a best-fitting approach to a large amount of experimental data of mineral fibrous porous absorbers, Delany and Bazley defined the eight c_i coefficients necessary to define both the characteristic impedance and the propagation constant. The final relationships proposed by Delany and Bazley are [9]:

$$z_c = \rho_0 c\left(1 + 0.078\left(\frac{\rho_0 f}{\sigma}\right)^{-0.623} - j0.074\left(\frac{\rho_0 f}{\sigma}\right)^{-0.66}\right) \quad (3)$$

$$k_c = \omega/c\left(0.0987\left(\frac{\rho_0 f}{\sigma}\right)^{-0.7} - j0.189\left(\frac{\rho_0 f}{\sigma}\right)^{-0.595}\right) \quad (4)$$

Known the formulas (3) and (4), it is then possible to obtain several acoustic and non-acoustic properties. For example, the normal-incidence sound absorption coefficient is easily obtained once the thickness and the flow resistivity of the material are known.

Delany and Bazley formulas (3) and (4) were obtained over a well-defined frequency range ($10 < f/\sigma < 1000$) and with a porosity of the material close to 1. In fact, at both lower and higher values of f/σ, Delany–Bazley clarified that other power-law relations should be expected. Moreover, the Delany–Bazley c_i coefficients reported in formulas (3) and (4) were obtained from sound absorption measurements of mineral fibers with a diameter between 1 and 10 μm. Given these limits, it is not surprising that, although the simplicity of the Delany–Bazley model which is also incorporated in some standards, this model has shown several limits when applied to thicker fibers such as the natural ones [6,7,10].

Many authors, including Qunli, Miki, Mechel, Wang et al., have provided other c_i coefficients for the formulas (1) and (2) by directly measuring the characteristics wave impedance and propagation constants and subsequently applying curve-fitting procedures [10–12]. In 1990, Miki provided modified coefficients to those proposed by Delany and Bazley for porous materials [13]. Dunn and Davern modified these coefficients for a foam material, and similarly, Garai and Pompoli by experimenting polyester fibers with diameter ranging from 20 to 50 μm, proposed other coefficients that fit better for textile fibers than the coefficients originally proposed by Delany–Bazley [10]. However, since measuring the propagation constants is a difficult and inaccurate process, an alternative common way is to measure the normal–incidence sound absorption coefficient in the frequency domain for a known flow resistivity material and then to determine the eight coefficients c_i using best-fit approaches [11].

A best-fit approach to fit experimental results to formulas (1) and (2) requires to adopt an iterative numerical method to obtain the eight coefficients that best describe the measured acoustic behavior of the samples [14]. In this paper, the minimization of a quadratic error function is performed. The error function is the squared difference between the sound absorption coefficient measured for a material sample at the i-th frequency ($\alpha_{n,i}$), and the corresponding estimated value ($\widehat{\alpha}_{n,i}$) using Eqs. (1) and (2). The minimization of the error function required to set to zero the following error expression, so to obtain the values which best approximate the c_i coefficients:

$$\frac{\partial \varepsilon}{\partial A_i} = 2\sum_{i=1}^{N}(\alpha_{n,j} - \widehat{\alpha}_{n,j})\frac{\partial \widehat{\alpha}_{n,j}}{\partial A_i} = 0 \quad i = 1,\ldots 0.8 \quad (5)$$

A Matlab computer code was implemented to minimize the nonlinear Eq. (5) and to obtain the corresponding values of the eight coefficients c_i. The optimization process was performed using the Nelder-Mead simplex method [14]. The optimization method whose result will be reported in Section 4 showed to be accurate and quick, giving small errors of the prediction in just a few seconds. Moreover, although different values were set as initial input values of Eqs. (1) and (2), the optimization always converged to the same c_i coefficients values. Once the characteristic impedance was found, and the formula (1) and (2) for each material