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On the sound absorption performance of a felt sound absorber

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ABSTRACT

In this work, we have developed an analytical model of a multilayer porous material based on the transfer matrix method to predict the absorption behavior at plane wave incidence. The aim of this study is to modify/tune the sound absorption coefficient of a felt to obtain an improved absorbing performance in the mid frequency range without increasing its weight. To achieve this target, the developed model has been used to find the best combination of each layer type and thickness. The analytical results were validated by test results.

1. Introduction

Many types of sound absorbing materials are used in noise-control applications. These materials include glass fiber, polymeric fibrous materials, and various types of foams [1]. Acoustical material plays a number of roles that are important in acoustic engineering, such as the control of room acoustics, industrial noise control, studio acoustics and automotive acoustics [2]. Low weight with higher or equal acoustic performance is the main goal of the automotive industry in recent years.

Materials that reduce the acoustic energy of a sound wave as the wave passes through it by the phenomenon of absorption are called sound absorptive materials [2]. They are commonly used to soften the acoustic environment of a closed volume by reducing the amplitude of the reflected waves [2]. Felt type materials generally have a sound absorption coefficient that increases quasi-linearly from lower to higher frequencies. There may be cases where one may want to increase the mid-frequency absorption performance of a felt. In the near future, by the presence of electric vehicles, tonal noises will become more important than today because of the lack of a broadband background noise generated by today's internal combustion engines. In these cases, tunable sound absorbing materials, with similar weights of today's acoustic packs, may have more importance. Designing a multilayer absorber needs some pre-work to forecast its acoustic properties, such as the absorption coefficient and transmission loss. There are various studies in the literature that develop analytical models to predict the acoustic performances. Bai et al. [3] investigated the sound insulation performance of a multiple-layer structure, which consists of elastic solid, fluid and porous material. They calculated the sound insulation performance of composite materials based on the transfer matrix method. They showed using simulation and experimental results that the sound insulation performance is greatly improved after the air layer is used. Abid and Abbes et al. [4] developed a method to predict the acoustic parameters of viscoelastic materials to improve the acoustic insulation of multilayer panels, and different layer arrangements were also tested to find the best configuration of a multilayer panel in terms of the acoustic insulation.

This paper consists of three parts. First, we describe the analytical model based on the transfer matrix method of a multilayer porous material to predict the sound absorption coefficient subjected to plane waves with a rigid backing boundary condition. Second, the sound absorption coefficient calculation result of the model for a multilayer material has been presented to obtain more absorbing performance in the mid frequency range without increasing its weight which is the main objective of this study. Finally, the model results have been validated with the experimental results.

2. Theoretical background

Two main categories can be found in the literature for modeling the sound propagation in porous materials. The first one considers the porous media as an equivalent fluid with an effective density and bulk modulus, and this class of modeling applies to materials having either a rigid skeleton or a limp skeleton. In these materials, wave propagation can be described by a unique compression wave. The second category considers the elasticity of the frame. Biot

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theory is based on this consideration. The porous medium is modeled as two superimposed phases that are fluid and solid and describes wave propagation in terms of three waves propagating simultaneously in the solid and fluid phases, two compression waves and one shear wave [5].

Two approaches are found to be the most useful in modeling the propagation of sound within a porous absorbent. The first is a completely empirical approach as exemplified by Delany and Bazley [6]. A second approach to modeling porous absorbent is to formulate the problem using a semi-analytical approach. For instance, the propagation within the pores can be modeled semi-analytically by working on a microscopic scale [6].

One widely used model from the first category is the Johnson-Champoux-Allard model. This model considers the rigid foam frame as solid and the air saturated in the porous medium as fluid, having an effective density (ρ) and an effective bulk modulus (K). The values of these two quantities are found from Eqs. (1) and (2) by five macroscopic quantities, the open porosity (ϕ), the static airflow resistivity (σ), the tortuosity (α_∞), the viscous characteristic length (Λ) and the thermal characteristic length (Λ') [5–7].

$$\rho = \alpha_\infty \rho_0 \left[1 + \frac{\sigma \varnothing}{j\omega\rho_0\alpha_\infty} G_J(\omega)\right] \tag{1}$$

$$K = \gamma P_0 / \left[\gamma - (\gamma - 1)\left[1 + \frac{\sigma' \varnothing}{jB^2\omega\rho_0\alpha_\infty} G'_J(B^2\omega)\right]\right] \tag{2}$$

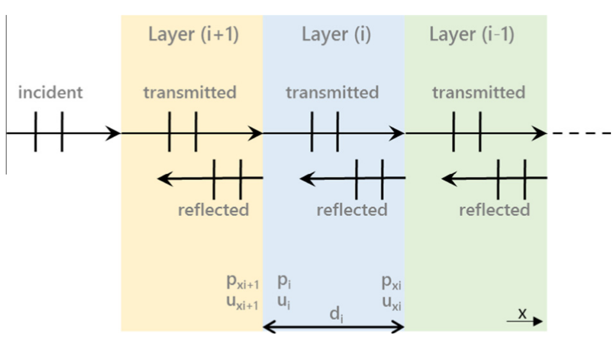

Fig. 1. Representation of the multilayer porous material structure.

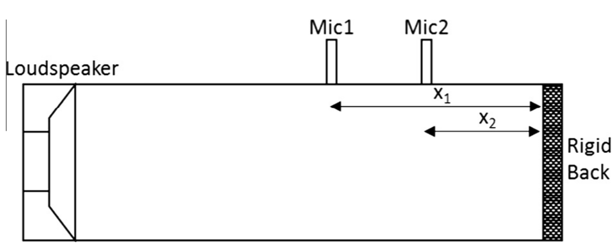

Fig. 2. Schematic of the impedance tube.

where P_0 is the atmospheric pressure, ρ_0 is the density of air, ω is the angular frequency, γ is the adiabatic constant, B is the Prandtl number, and $\sigma' \approx c'\sigma$, where c' is a coefficient. $G_J(\omega)$ and $G'_J(\omega)$ are the functions of the angular frequency and defined by Eqs. (3) and (4) [5–7].

$$G_J(\omega) = \left(1 + \frac{4j\alpha_\infty^2 \eta\rho_0\omega}{\sigma^2\Lambda^2\phi^2}\right)^{1/2} \tag{3}$$

$$G'_J(B^2\omega) = \left(1 + \frac{4j\alpha_\infty^2 \eta\rho_0\omega B^2}{\sigma'^2\Lambda'^2\phi^2}\right)^{1/2} \tag{4}$$

The values of Λ and Λ' are given by Eqs. (5) and (6) [5–7].

$$\Lambda' = \sqrt{\frac{8\alpha_\infty\eta}{\phi\sigma'}} \tag{5}$$

$$\Lambda = \frac{1}{c}\sqrt{\frac{8\alpha_\infty\eta}{\phi\sigma}} \tag{6}$$

where c is a constant that defines the cell structure shape and η is the dynamic viscosity of air. The viscous characteristic length (Λ) corresponds to the dimension of the narrow sections (small pores) in the pore network, where viscous loss is dominant because of the boundary layer effect. The thermal characteristic length (Λ') indicates the dimension of the sections with larger surface areas within the pore network, where thermal loss is dominant. As per this definition, Λ' will be larger than or equal to Λ depending upon the value of the constant c, which depends on the geometry of the pore structure [5–7].

Once the characteristic impedance (Z_C) and wavenumber (k) for the material are known, it is necessary to convert these to the surface impedance and absorption coefficient for a particular thickness of the porous material with known boundary conditions. In this case, the most flexible way of predicting the surface properties of the porous material is to use the transfer matrix method [6].

$$Z_S = -j.\frac{Z_C}{\phi} \cdot cotg(K.d) \tag{7}$$

where $Z_C = \sqrt{k.\rho}$, $k = \omega.\sqrt{\frac{\rho}{K}}$ and d is thickness of the porous material.

The reflection coefficient (R) and the absorption coefficient (α) of the material can be estimated by Eqs. (8) and (9), respectively [5–7].

$$R = \frac{Z_S - \rho_0 c_0}{Z_S + \rho_0 c_0} \tag{8}$$

$$\alpha = 1 - |R|^2 \tag{9}$$

For a multilayer porous material, at each interface between the layers, the continuity of the pressure and particle velocity is assumed. This allows a relationship between the pressure and the particle velocity at the top and bottom of a layer to be produced, which is compactly given in matrix format [8].

Table 1
Material acoustical parameters.

	Material	Density (g/m^2)	Thickness (mm)	Porosity (–)	AFR (N.s.m-4)	Tortuosity (–)	Viscous length (m)	Thermal length (m)	Shape factor (–)
1. Felt	Felt-0	1600	24	0.985	24,000	1.1	0.000055	0.000142	1.4
2. Felt + Air + Felt	Felt-1	800	11	0.945	42,000	1.3	0.000041	0.000137	1.7
	Air		8						
	Felt-2	500	7	0.96	20,000	1.2	0.000080	0.000134	1.2