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Optimizing Absorption Coefficients: A Study on Acoustic Characteristics of Saturated Fluid in Porous Media

Mustapha SADOUKI
Acoustics and Civil Engineering Laboratory, Khemis-Miliana University, Algeria
mustapha.sadouki@univ-dbkm.dz

INTRODUCTION & AIM

Noise pollution significantly impacts quality of life and health, originating from sources such as traffic, conversations, and equipment. Effective sound insulation is crucial, often achieved using porous materials that dampen noise and vibrations. The acoustic absorption and mechanical energy dissipation of these materials are essential for their performance, linked to their microscopic structure. While some properties can be directly measured, comprehensive acoustic characterization remains challenging.

To predict acoustic behavior across frequencies, semi-phenomenological models[1-2] are widely used. These models relate macroscopic properties of porous materials to their internal structure. Acoustic characterization methods are divided into direct and indirect techniques. Direct methods measure properties physically, requiring specific setups for each property, making comprehensive characterization complex. Indirect methods[3,4], often involving impedance tubes, derive properties like effective density and mass modulus through mathematical modeling and optimization processes.

This work introduces an alternative inverse method using impedance tube measurements to assess acoustic properties of rigid porous media. The method focuses on four parameters: viscous and thermal permeability, inertial factor, and thermal tortuosity. By minimizing discrepancies between simulated and experimental absorption coefficients, the approach is validated with tests on polyurethane foams, widely used for noise and vibration control.

METHOD

Porous materials are bi-phase systems with a solid structure saturated by fluid. Acoustic wave propagation in these materials is effectively described by Biot theory, predicting three wave types: two compressional waves (one in the solid phase and one in the fluid phase) and one shear wave in the solid. When the solid's rigidity or density exceeds that of air and the wavelength is larger than the pore size, sound propagation resembles an equivalent fluid with effective density and bulk modulus[1,2]:

$$\tilde{\rho}(\omega) = \alpha(\omega)\rho_0, \qquad \tilde{K}_a(\omega) = k_a/\beta(\omega) \tag{1}$$

where and account for viscous and thermal losses, respectively.
At low frequencies ($\omega \to 0$), viscous effects relax, and the permeability approaches the Darcy permeability , with tortuosity given by[1-4]

$$\alpha(\omega) \to \frac{\omega_c}{\omega} j + \alpha_0, \quad \omega_c = \frac{\eta\phi}{k_0\rho_0} \tag{2}$$

Similarly, thermal effects lead to thermal permeability and thermal tortuosity :

$$\alpha'(\omega) = \frac{\omega_c'}{\omega} j + \alpha_0', \quad \omega_c' = \frac{\eta\phi}{P_r\rho_0 k_0'} \tag{3}$$

The propagation of acoustic waves generates pressure p and velocity v fields, governed by Euler's equation and the constitutive relation:

$$\tilde{\rho} j\omega v = \nabla p, \quad \frac{1}{\tilde{K}_a} j\omega p = \nabla . v \tag{4}$$

These combine into the Helmholtz equation:

$$\nabla^2 p + \tilde{k}^2 p = 0, \quad \tilde{k} = \omega\sqrt{\frac{\tilde{\rho}(\omega)}{\tilde{K}_a(\omega)}} \tag{5}$$

In impedance tube experiments, the reflection coefficient R and absorption coefficient α are derived from the specific impedance Z[3]

$$R = \frac{Z-1}{z+1}, \quad \alpha = 1 - |R|^2 \tag{6}$$

These equations enable the characterization of porous materials, particularly their viscous and thermal parameters , which will be determined for specific foam samples.

Figure 1. Three cylindrical polyurethane foam samples

RESULTS & DISCUSSION

The estimation of key acoustic parameters for porous materials, such as static permeability (k_0), thermal permeability (k_0'), viscous tortuosity (α_0), and thermal tortuosity (α_0'), is performed using an inverse optimization process. The optimization minimizes the cost function U, defined as:

$$U(k_0, k_0'/k_0, \alpha_0, \alpha_0') = \Sigma\left(\alpha_{sim}\left(k^0, \frac{k^{0\prime}}{k^0}, \alpha^0, \alpha^{0\prime}, \omega_i\right) - \alpha_{exp}(\omega_i)\right)^2 \tag{7}$$

where α_sim is the simulated absorption coefficient, and α_exp is the experimentally measured absorption coefficient.
The process adheres to the following constraints to ensure physically meaningful results:

$$\begin{cases} k_0 \geq 6 \times 10^{-10} m^2 \\ k_0'/k_0 \geq 1 \\ \alpha_0 \geq 1 \\ \alpha_0' \geq 1 \end{cases} \tag{8}$$

The optimization was applied to three cylindrical polyurethane foam samples (S1–S3). (fig.1) The inverted parameter values are summarized below:

Samples	Thickness (cm)	σ(kNm^{-4}s)	$k_0(10^{-10}\ m^2)$	k_0'/k_0	α_0	α_0'
(S1)	24.27	20187	8.9167	2.67	3.75	1.33
(S2)	25.80	13171	13.667	3.67	1.50	1.67
(S3)	25.67	22154	8.1250	2.50	4.50	1.17

Table 1 . Inverted parameters

Figure2 comparing the simulated and experimental absorption coefficients show excellent agreement, demonstrating the effectiveness of the inverse methodology. The optimized parameters are consistent with values reported in the literature, further validating the approach.
This study highlights a robust method for simultaneously estimating all four acoustic parameters through experimental absorption data. The proposed methodology is faster, less expensive, and avoids destructive testing. The identified parameters are crucial for characterizing porous materials in applications such as soundproofing and vibration damping. Future extensions of this work may include fibrous and granular materials.

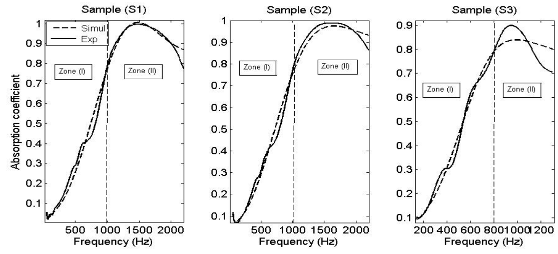

Figure 2 . Comparison between the experimental curves (black continue lines) and the simulated curves (red dashed lines) of the absorption coefficient for the three samples (S1)-(S3)

CONCLUSION

This study proposes an alternative experimental method to acoustically characterize air-saturated porous media at low frequencies, based on equivalent fluids theory. Using impedance tube measurements, the inverse problem is numerically solved to evaluate four key parameters—viscous and thermal permeability, inertial factor, and thermal tortuosity—for polyurethane foam samples. The optimized parameters align well with literature values, and the simulated absorption coefficients closely match experimental results. Notably, this method enables the simultaneous determination of viscous and thermal permeability (k_0, k_0') and tortuosity (α_0, α_0') solely from experimental absorption coefficients. This approach offers a promising, efficient tool for porous material characterization.

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