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Characterization of Sound Absorbing Materials for Noise Control

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ABSTRACT

In recent years, sound absorbing materials are finding many applications in noise control abatement schemes. Sound absorbing materials are also used to improve the acoustics in indoor and outdoor situations. Poroelastic materials consist of continuous solid elastic material interconnecting pores generally referred as frame with interstitial fluid (i.e. air) inside them. Most porous material theoretical models are formulated in terms of macroscopically measurable physical properties of the frame and the fluid. Porous material characterization starts with classification of poroelastic materials according to their nature, then measurement of macroscopic physical parameters like porosity, flow resistivity, pore tortuosity, viscous length and thermal length as well as mechanical parameters like Young's Modulus, Poisson ratio and loss factor that determine the acoustical performance of the materials. The acoustical performance of the porous materials can be predicted with available porous models using these physical parameters. The paper presents a detailed review of characterization methods for sound absorbing materials. It also presents a discussion on advanced methods like inverse characterization methods used for getting physical parameters.

1. INTRODUCTION

Poro-elastic materials are formed from a continuous solid elastic material with open spaces or pores. The pores are saturated with a fluid. The most well known examples are probably sound absorbing foams. Sound absorbing foams are very soft materials that are characterized with a very high porosity. Viscous and thermal interactions between fluid and frame occur due to the acoustic wave propagation through the porous material. These interactions are the basis of the sound absorbing properties of the porous material. Most porous material theoretical models are formulated in terms of macroscopically measurable physical properties of the frame and the fluid (which may themselves be considered as separate components). The advantage of such an approach is that it enables the investigation of the influence of the various directly measurable physical properties of the porous material, so that a particular set of physical parameters can be identified that will result in a porous material having a specified performance. It should be noted, of course, that there is a direct link between the microscopic structure of a porous material and its macroscopic properties. To-date, however, there is little information linking the microscopic properties of a porous material to its macroscopic properties. The most important macroscopic physical properties of a porous material are: flow resistivity, porosity, pore tortuosity (these first three together constituting the fluid-acoustical properties), bulk density, in vacuo bulk density, shear modulus and loss factor (the latter four properties being the elastic properties of a porous material).

2. JOHNSON-CHAMPOUX-ALLARD MODEL

Open cell Poroelastic materials are very well described by Biot theory [1]. At the same time, in many situations when a material sample is excited by acoustical waves, the frame of this material behaves approximately as acoustically rigid (motionless) over a wide range of frequencies. In this case, the porous material can be replaced on a macroscopic scale by an equivalent fluid of effective density $\rho(\omega)$ and effective bulk modulus $K(\omega)$. The motionless frame condition can occur either because of high density or elasticity modulus, or because of particular boundary conditions imposed during the test. The dynamic density $\rho(\omega)$ and complex compressibility $K(\omega)$ for Johnson Model [2] are given by following equations.

$$\rho(\omega) = \rho_0 \alpha_\infty \left[1 + \frac{\sigma\phi}{j\omega\rho_0\alpha_\infty} \sqrt{\frac{4j\alpha_\infty^2 \eta\omega}{\sigma^2\Lambda^2\phi^2}} \right] \tag{1}$$

$$K(\omega) = \gamma p_0 \left[\gamma - (\gamma - 1) / 1 + \frac{8\eta}{j\Lambda' N_{pr}\omega\rho_0} \sqrt{1 + j\rho_0 \frac{\omega N_{pr}\Lambda'}{16\eta}} \right]^{-1}$$

where ρ_0 is density of fluid, ρ_0 is atmospheric pressure, γ is specific heat ratio N_{pr} is Prandtl number, η is coefficient of viscosity of air and is circular frequency. For a porous sample of thickness , backed by rigid wall specific acoustic surface impedance is given as

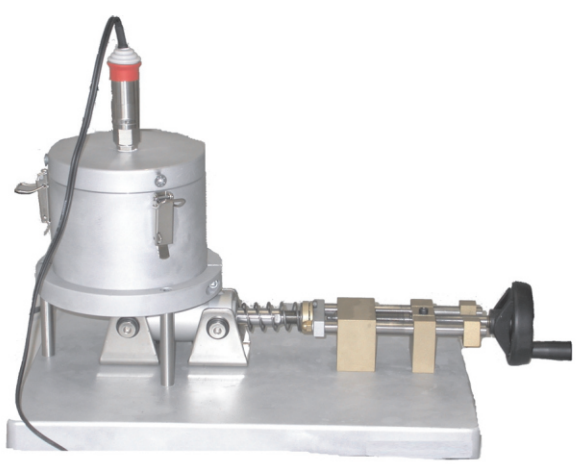
$$Z_s = -j \frac{Z_c}{\rho_0 . c_0} cot(kcd) / \phi \tag{3}$$

where Z_c and k_c are the characteristic impedance and the complex wave number of the porous specimen respectively. They are related to the effective properties of the porous medium by Eq. (4) and Eq. (5).

$$Z_c = (\rho(\omega) K(\omega))^{1/2} \tag{4}$$

and

$$k_c = j\omega . [\rho(\omega) / K(\omega)]^{1/2} \tag{5}$$



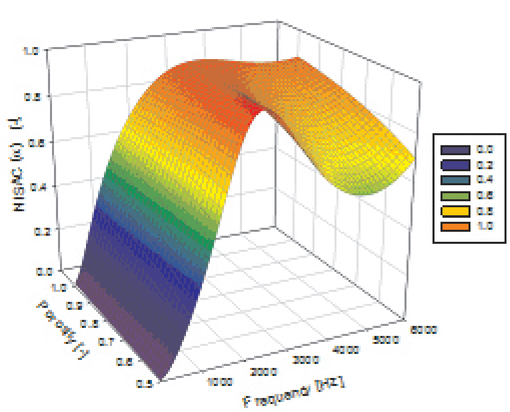


Fig. 1. Test rig for porosity measurement (ENDIF, Italy) and Effect of porosity on Sound Absorption

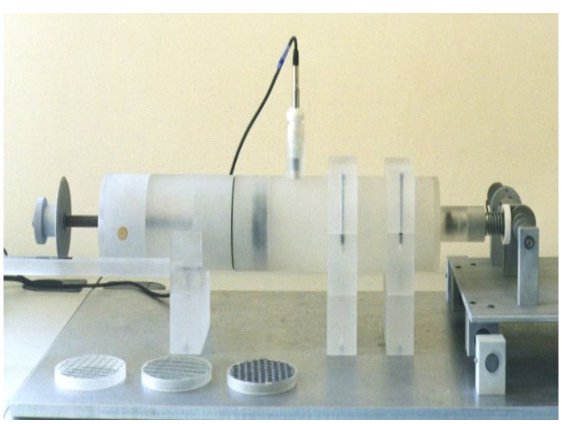
2.1 Porosity

It is the ratio of the fluid volume within the porous material to the total volume of material, on a unit-volume basis. Since the porosity quantifies the relative volume occupied is a key parameter in theories of sound propagation in porous materials [3, 4]. However, the porosity of typical acoustic materials such as foams and glass fibers is normally very high, i.e., greater than 0.90, and often greater than 0.98. Since the porosity is so large in most noise control materials, and because the variations in porosity tend to fall into a very narrow range, variations in porosity tend not to be very important when distinguishing between noise control materials. However, it should be remembered that much of the relative motion of the solid frame and the interstitial fluid, and that for this process to work, there must be continuous paths through the material. The most direct way of determining the porosity of a porous material is to measure the volume of air contained within the material. This method may be achieved using the apparatus developed by Champoux [5] shown in the figure 1. When the temperature of a rigid chamber containing a test sample is held very constant, a measurement of the change in air pressure that accompanies a known change in volume allows the volume of fluid within the sample to be determined if the change in air pressure accompanying the same volume change in a rigid, empty chamber of the same total volume is known. The figure below shows a porosity rig and effect of porosity on sound absorption coefficient.

2.2 Flow Resistivity

The specific flow resistance of any layer of porous material is defined as the ratio of the air pressure differential measured between the two sides of the layer to the steady state air velocity through and perpendicular to the two faces of the layer [6]. The flow resistivity is then the specific flow resistance per unit material thickness with SI units of MKS rayls/m. The flow resistivities of useful noise control materials vary widely, but typically fall in the range 103 rayls/m to 107 rayls/m.

The flow resistivity depends on the porosity of a material as well as its tortuosity, but for high porosity, low tortuosity fibrous materials, the flow resistivity is approximately inversely proportional to fiber radius squared at a constant bulk density: i.e., a large number of small fiber diameters results in a higher flow resistance than does a small number of larger fibers. At microscopic level, the flow resistance results from the formation of a viscous boundary layer as fluid flows over each fiber, and the amount of shearing in that boundary layer increases as the fiber radius decreases. The flow resistivity is thus usually taken to be a measure of the viscous coupling between the fluid and solid phases of the porous material, and so is a measure of the potential for viscous dissipation of sound. [7]



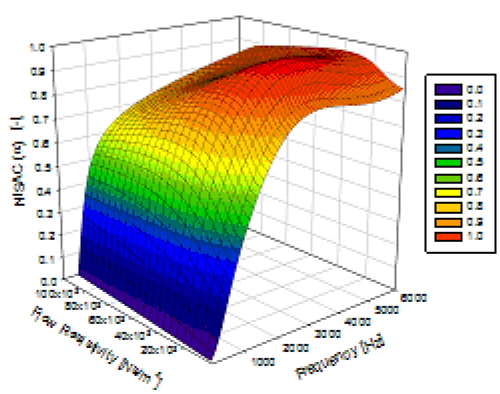
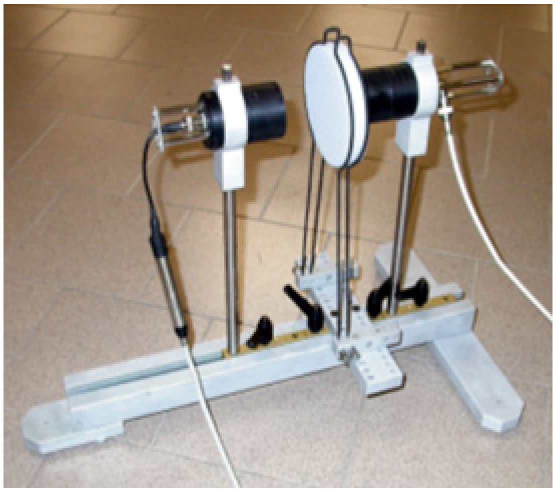


Fig. 2. Test rig for Flow resistivity measurement (ENDIF, Italy) and Effect of flow resistivity on Sound Absorption



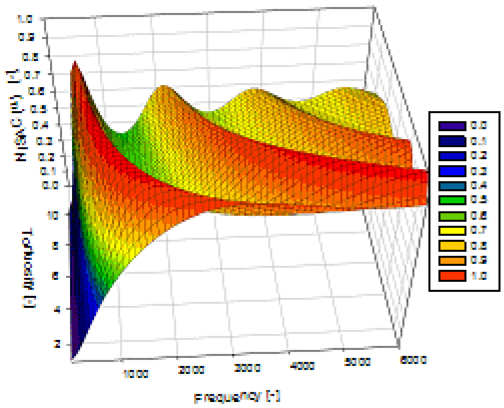
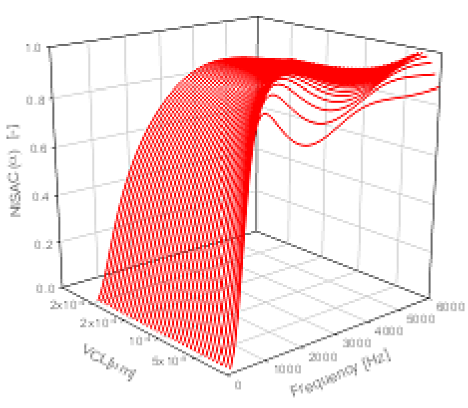


Fig. 3. Test rig for Tortuosity measurement (ENDIF, Italy) and Effect of tortuosity on Sound Absorption

2.3 Pore tortuosity

It is sometimes referred as structure factor and defined as defined as the ratio of actual path length through the material to the linear path length. It is a measure of deviation between the actual fluid flow path through the material and straight- line flow through the material. It results from inertial coupling between solid and fluid phases. The range of tortuosity is from 1 (low density fibrous material) to values of 10 (partially reticulated foams with any closed cells). Champoux and Stinson have developed an electrical conductivity technique to measure pore tortuosity. The voltage difference arising from passing a high voltage through a fluid-saturated (electrically conductive) sample is measured. With knowledge of the electrical transmitted waves. This method is based on measurement of reflected wave by the first interface of a slab of rigid porous material. This method is obtained from a temporal conductivity of fluid and fluid filled samples, a simple relation may be established to calculate the tortuosity when porosity is known. This method can not be used when material frame is conducting [8]. Recently Ultrasonic reflectivity method is proposed for measuring tortuosity of porous materials having a rigid frame. Tortuosity is a geometrical parameter which intervenes in the description of the inertial effects between the fluid filled the porous material and its structure at high frequency range. It is generally easy to evaluate the tortuosity from model of the direct and inverse scattering problems for the propagation of transient ultrasonic waves in a homogeneous isotropic slab of porous material having a rigid frame [9].



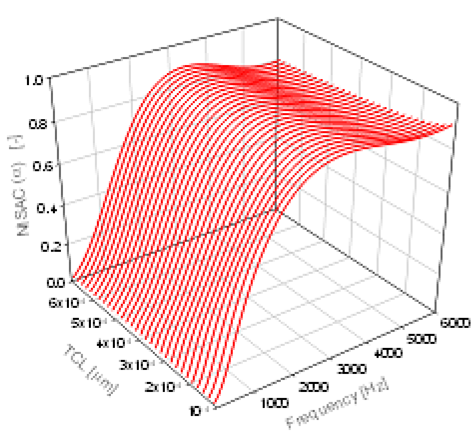


Fig. 4. Effect of characteristic lengths on Sound Absorption

2.4 Characteristic Lengths

The concept of viscous characteristic length is used to describe the acoustical behavior of fluid-saturated porous media in the high-frequency regime. A method to determine this parameter consists of measuring the wave attenuation in the high-frequency limit. This method has already been used for porous materials saturated by super fluid He. It is tested in the case of air-filled absorbent materials in a frequency range of 50-600 kHz. The thermal characteristic length is assumed to be known or measured independently [10]. Recently inverse characterization is becoming popular for predicting physical parameters using optimization techniques. In this paper characteristic lengths are predicted using genetic algorithm optimization. The effect of characteristics lengths on sound absorption is shown in Fig. 4.

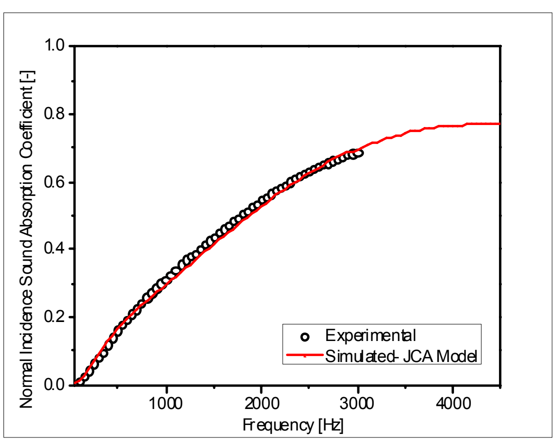
3. RESULTS AND DISCUSSION

Porous materials of different typologies are tested and physical parameters are measured using specialized test rigs as discussed above. The physical parameters depicted in table 1. These measured parameters are fed to JCA model and sound absorption coefficient is simulated with compared with measured sound absorption coefficient using two microphone impedance tube.

Table 1. Physical Parameters

	Physical Parameters PET Felt 25 mm 24 Kg/m^3	Polyurethane foam-B 25 mm 40 Kg/m^3
Porosity	0.98	0.986
Flow Resistivity	6634	23367
Tortuosity	1.06	1.7
VCL	147	43
TCL	203	258

The comparison is shown in Fig. 5 for PET felt and in figure 6 for Polyurethane foam-B. From these figures it is clear that there is good correlation between measured sound absorption coefficient and simulated sound absorption using physical parameters of porous materials.



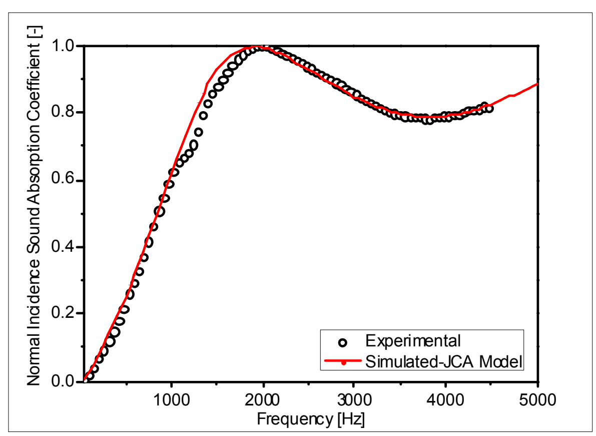


Fig. 5. Comparison of Sound Absorption coefficients with predicted sound absorption (5a): PET felt, (5b): Polyurethane foam

4. CONCLUSIONS

This paper presents a discussion on speclized test rigs for the measurement of physical geometrical parameters of porous materials. It also gives a comparison of measured sound absorption coefficient and simulated sound absorption coefficient using experimentally measured physical parameters of porous materials.

5. ACKNOWLEDGEMENT

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