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EXPERIMENTAL CHARACTERIZATION OF MATERIALS FOR ACOUSTIC PERFORMANCE WITH APPLICATIONS

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ABSTRACT

The acoustic performance of a porous material are determined by its bulk density, airflow resistivity, porosity, tortuosity, viscous and thermal characteristic lengths, elastic modulii and loss factor. A set of measuring techniques and equipment for characterizing such a material was implemented and is described in this paper. The procedure of conducting a material characterization is demonstrated by examples and the accuracy of these techniques is validated by comparing the prediction of the normal absorption coefficient of a material based its measured parameters to its measured absorption coefficient. Excellent agreement was observed over a broad frequency range and results of the test samples are presented. In addition, examples of applying these techniques in conjunction with analytical tools to design mulit-layered liners in noise control applications are also presented in this paper.

1 - INTRODUCTION

Porous materials are widely employed in noise control solutions due to their good sound absorption properties; fiberglass, foams, ceiling tiles, acoustic blankets, just to name a few, are example of such materials. In order to apply these materials more effectively in the design of a noise control treatment, theoretical porous material models [1] based on the Biot Theory [2] can be used to assist in selecting materials, estimating performance and designing layered configurations [3], [4], [5] and [6]. Several material parameters (e.g., airflow resistivity, porosity, tortuosity, etc.) required in the porous material models are usually unavailable from material suppliers. Therefore, it is necessary to have materials characterized before applying analytical models to design noise control treatments. A set of experimental techniques for measuring material acoustical parameters has been implemented at United Technologies Research Center (UTRC). This paper describes this complete experimental rig set. In addition, test cases are prescribed to illustrate how to use the measured parameters in modeling material acoustical properties and its application to predict the performance of layered noise control treatments.

2 - MATERIAL MICROSTRUCTURE PARAMETERS AND MEASURING TECHNIQUE

Based on the poroelastic acoustic model [1], [2], the parameters determining the acoustic performance of a porous material include flow resistivity, porosity, tortuosity, viscous and thermal characteristic lengths, elastic modulii and loss factor. These parameters and the rigs used for measuring these parameters are briefly described in what follows.

2.1 - Flow resistivity

The flow resistivity (Rayls/m or Ns/m^4) is defined as the pressure decrease of airflow crossing a porous medium with unit area and unit thickness. To measure flow resistivity [7], [8], a vacuum pump was used to create airflow passing a sample placed within a sample holder through an orifice, which gives a fixed airflow rate that was obtained based on its pre-calibrated Discharge Coefficient [9]. Different orifices having different diameters are used sequentially for various flow rates; pressure transducers are installed on both sides of the sample to measure the pressure gradient across the sample at each flow rate. On a pressure vs. flow rate plot, the flow resistivity of the sample can then be calculated from the slope of the measured data. A picture of this flow resistivity rig is shown in Figure 1.

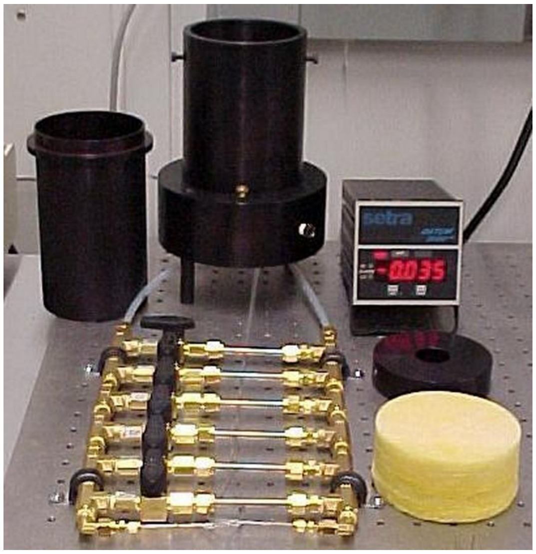

Figure 1: Flow resistivity and porosity experimental rigs.

2.2 - Porosity

Porosity is the fraction of the fluid phase volume in a porous material. If a porous material is fully reticulated (e.g., fibrous materials), its porosity can be calculated directly from its bulk density and raw material density. However, if the material is partially reticulated, the volume of the fluid trapped within the pores is considered, along with the raw material, as the ”solid part” in modelling acoustic waves propagating within the medium and the porosity of the material needs to be measured more carefully [10]. A commercial gas displacement pycnometer, AccuPyc 1330 pycnometer, is used to measure the material porosity. A sample with a known bulk volume is placed within a sealed chamber, which is filled with inert gas, and the pressure within the chamber is measured before and after the gas chamber expanded. Based on the ideal gas law, the porosity of the sample can then be obtained. The picture of the device is shown in Figure 2.

Figure 2: Flow resistivity and porosity experimental rigs.

2.3 - Tortuosity

The tortuosity is a parameter defined to measure the dispersion of the microscopic molecular velocity of an inviscid fluid that flows through the frame, and its measurement can be done through different methods [11], [12], [13]. One method, referred as the non-acoustical method, is to saturate the sample in an electrical conductive fluid and to measure its tortuosity from the change of the electrical resistance. Another method, referred as the acoustical method, measures the tortuosity from the time delay and phase change of an ultrasonic wave passing through the sample. The acoustical method was selected and implemented due to its non-destructive characteristic and ease of operation. A pair of identical ultrasonic transducers is used to send and receive an acoustic pulse passing through the test sample, and the time delay of the pulse signal caused by the existence of the sample is then used to calculate the tortuosity of the sample. The experimental set-up based on the ultrasonic technique is shown in Figure 3.

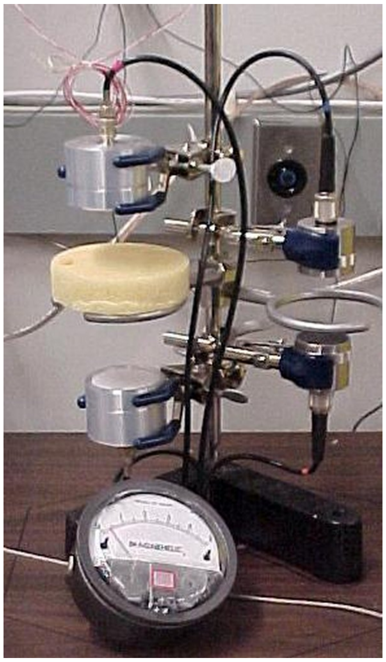

Figure 3: Experimental rig for measuring tortuosity, viscous and thermal characteristic lengths and elastic modulii (polyimide foam).

2.4 - Viscous and thermal characteristic lengths

Viscosity and thermal conductivity are another two mechanisms that can dissipate the acoustic energy in a porous medium. The viscous characteristic length Λ is defined as the ratio of the velocity field in the bulk of a given pore to the velocity field at the surface of the material for an inviscid fluid under steady flow, and the thermal characteristic length Λ' is defined as the ratio of twice the pore volume to the surface area in contact with the fluid [14]. The viscous and thermal characteristic lengths of a material can be determined from the attenuation of the phase velocity of high frequency waves propagating within the sample. After the tortuosity is measured in the air, the same procedure is repeated but with a different gas, such as helium, and the two measurements can be combined to solve for both the viscous and the thermal characteristic lengths simultaneously. The experimental set-up is the same as the tortuosity rig, except the rig is now placed in a chamber that can be filled with different gases: see Figure 4.

2.5 - Elastic modulii and loss factor

When acoustical waves propagate within a poroelastic medium, the motion of the material solid phase is coupled with the fluid phase and, therefore, the bulk material Young's modulus, E, and shear modulus, G, have significant effects on its acoustical behaviour. The Young's modulus of the elastic frame can be determined by measuring the resonance frequency of a standing wave in a cylindrical sample under longitudinal excitation. The shear modulus can be determined by a similar procedure but with a rotational excitation. The width of the resonance peak is a measure of the attenuation and is employed to calculate the loss factor. A picture of the elastic modulii rig is shown in Figure 5.

3 - EXAMPLE OF MATERIAL CHARACTERIZATION

In the task of conducting a material characterization, the order of conducting each test described above can affect the test results. For example, measurement of the flow resistivity and porosity may break the membranes of some closed cells and, therefore, change the material microstructures during the tests. If the material sample is fragile, the tests that may cause damage to the sample pore structures should be

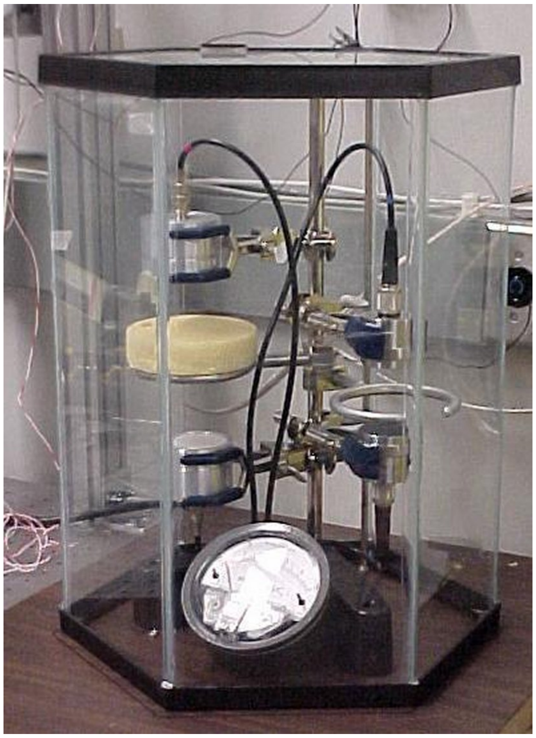

Figure 4: Experimental rig for measuring tortuosity, viscous and thermal characteristic lengths and elastic modulii (polyimide foam).

performed last. In addition, it would be desirable to use the same sample for all characterization tests as well as the impedance tube test to eliminate the uncertainty caused by the material heterogeneity. Therefore, the sample holders of most test rigs at UTRC were designed to have the same dimensions with an exception of the elastic modulii rig. Examples of conducting material characterization are given for two elastic porous foams, melamine foam and polyurethane foam, and the characterized material parameters of these test samples are summarized in Table 1.

Foam Property	Melamine foam	Polyurethane foam
Thickness, d	0.051 m	0.025 m
Density, ρ	8.30 kg/m^3	30.0 kg/m^3
Flow Resistivity, σ	14000 Rayls/m	45000 Rayls/m
Tortuosity, τ	1.02	2.01
Porosity, ϕ	0.99	0.98
Viscous Characteristic Length, Λ	100 μm	15 μm
Thermal Characteristic Length, Λ'	300 μm	50 μm
Youngs' Modulus, E	6.7 $\times 10^5$(1+0.14i) Pa	8.0 $\times 10^5$(1+0.25i) Pa
Shear Modulus, G	1.5 $\times 10^5$(1+0.09i) Pa	4.0 $\times 10^5$(1+0.25i) Pa

Table 1: Measured material properties of the melamine foam and polyurethane foam.

The measured parameters for the melamine foam material in question were incorporated in the poroelastic model to yield the theoretical prediction of the normal absorption coefficient. The comparison between the measured normal absorption coefficient and the analytical prediction is sown in Figure 6 (a). The polyurethane sample was bonded onto a 1/8" aluminum panel, and the random sound transmission loss was measured with the intensity technique in a reverberation room. The measured parameters of the polyurethane foam were then input to the poroelastic model in conjunction with a transfer matrix approach [16] to predict the random incidence sound transmission loss of the two-layered configuration. The comparison between the measurement and the prediction is shown in Figure 6 (b). The agreements between measurements and predictions of two cases are found to be very good. These examples illustrate the potential of applying the described acoustic material characterization technique to understand the

Figure 5: Experimental rig for measuring tortuosity, viscous and thermal characteristic lengths and elastic modulii (cylindrical sample is melamine foam).

microstructures of acoustical materials and the potential to change the material manufacturing process to optimize material acoustic performance for noise control applications.

4 - APPLICATIONS

Acoustical liners used in UTC products (for example, noise treatments of helicopter cabin interiors, wrappings or liners of HVAC systems) are normally designed with multiple layered configurations to simultaneously account for various requirements including sound absorption and transmission loss. With several material options available in a multiple layered configuration, the design of an acoustical liner can be complicated and time consuming. However, if each type of material that will be used in the liner are characterized in advance, then analytical tools can be applied to simulate the acoustical performance of different liner designs without building many sample coupons for testing. Not only can this analytical design procedure reduce the development time and cost, but also can enable the optimization of multi-layered liners [3].

In this work, results obtained on two noise control blankets are used as examples herein: Sample 1 is a three-layered composite structure and Sample 2 is an eight-layered construction, which comprises the sample 1 plus five layers of vinyl and foam materials. The foam acoustical parameters were characterized by using the techniques described above whereas the simulation was performed using an infinitely extended representation based on the transfer matrix approach. The sound transmission loss measurements of the two samples were done with the intensity technique in a reverberant room. The comparison between prediction and measurement of sound transmission loss of two samples are shown in Figure 7. The discrepancy between measurement and prediction of Sample 2 is speculated due to the fact that the panel-mounting boundary conditions in the reverberation room are different from the theoretical case. However, reasonably good agreement is observed over a wide frequency range.

Once the material characterization procedure and the multi-layered acoustic model are validated, the analytical acoustical material model can then be combined with system level noise prediction tools like Statistical Energy Analysis (SEA) or Finite Element Method (FEM). An example of such application can be found in a previous work [17] in modeling the vibroacoustic response of a helicopter sidewall structure composed of airframe, structural frame, trim panels and windows with acoustic treatments like noise blankets (made of five layers) and batting (foam blocks employed for acoustic absorption). The

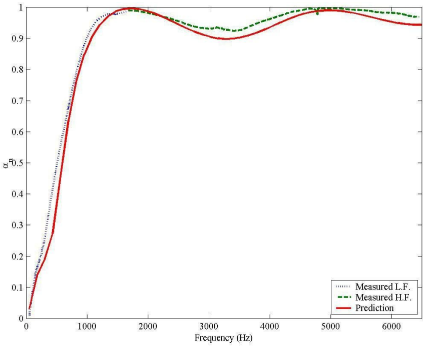

Figure 6(a): Normal sound absorption coefficient of melamine foam; dashed lines are measurements done by using the low and high frequency impedance tube; the solid line is the theoretical prediction.

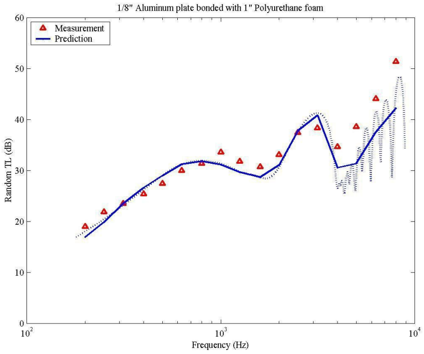

Figure 6(b): Comparisons between measurements and predictions of random incidence sound transmission loss of polyurethane foam bonded on an aluminum plate; marks are measured data, the solid line is the prediction in 1/3-octave band and the dotted line is the prediction in narrow band frequency.

overall system response to acoustic and structural excitation is represented through a detailed AutoSEA 1.5 model. Good agreement between measured and predicted response of the complete sidewall section was reported.

These example applications illustrate the importance of correctly characterizing the acoustical material parameters to enable the numerical simulation of sound absorption and sound transmission loss characteristics of simple and complex noise control treatments and their impact on large vibroacoustic system level models. These simulation tools will enable the development of enhanced noise control treatments.

5 - SUMMARY

A modern material model can accurately predict the acoustic properties (i.e., surface impedance, absorption coefficient and transmission coefficient) of a porous material if the required parameters are available. The acoustical porous material can be characterized by the following parameters: density, flow resistivity, porosity, tortuosity, viscous and thermal characteristic lengths, elastic modulii and loss factor. A number of advanced measurement techniques have been implemented and described herein to perform such a task. The final illustration of the merit of porous material characterization is illustrated by comparing the experimental and analytical absorption coefficients of a test sample. In addition, an example was presented to demonstrate the ability of present theoretical models to represent the sound transmission loss of complex multilayer constructions and comparison to measured data. Good agreement was observed over a broadband frequency range. With these advanced measurement techniques and equipment, it is now possible to further investigate the fundamental mechanisms of how a porous material attenuates acoustical energy and use this knowledge to seek solutions for improving its acoustical performance and designing more effective noise control treatments.

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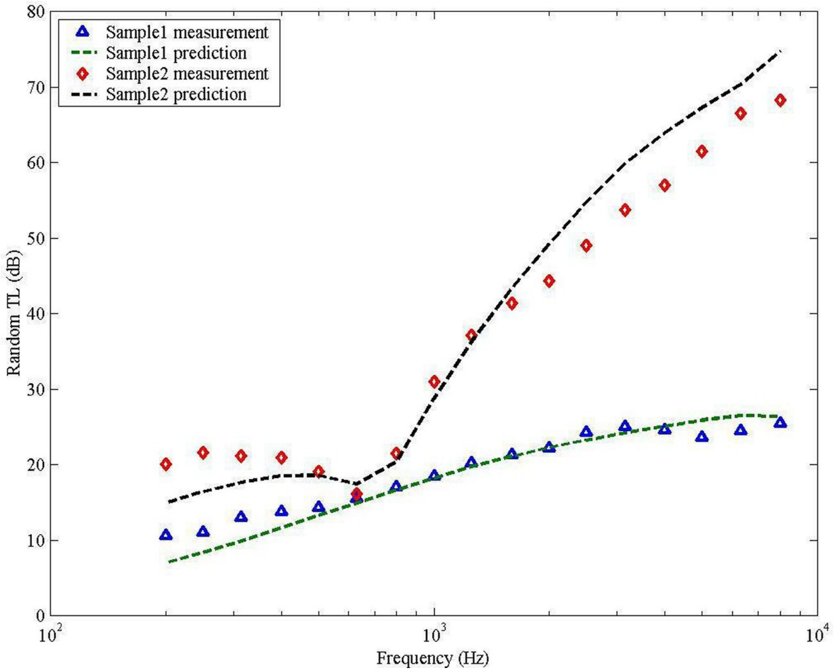

Figure 7: Comparisons between measurements and predictions of random incidence sound transmission loss of two noise control treatments used in interior noise control; dotted lines are predictions, and marks are measurements.

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