

Review of Test Methods for Material Properties of Elastic Porous Materials

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ABSTRACT

Biot's model of elastic porous materials is widely used to predict the acoustical performance of noise control materials in the automotive industry. Material properties of acoustical materials, often referred to as Biot parameters, such as porosity, airflow resistivity, tortuosity, viscous characteristic length and thermal characteristic length are required inputs in the Biot model. Various test methods have been developed to measure Biot parameters. This paper conducts a comprehensive review of the existing test methods, discusses accuracy and applicability of each test method, and provides recommendations to the SAE Acoustical Materials Committee regarding the need for the development of SAE test methods for Biot parameters.

INTRODUCTION

Porous materials such as polymer foams, polyester and cotton fibers are widely used as noise control materials in the automotive industry. Elastic porous materials consist of two phases: a solid phase known as skeleton and a fluid phase that is normally air. Porous materials absorb acoustic energy via viscous and thermal exchange between the air that oscillates inside the pores and the skeleton. The most comprehensive model to describe sound propagation in these materials is the Biot theory [1]. According to the Biot theory, there are three types of waves propagating within the material: a compression wave related to the fluid phase, a second compression wave related to the solid phase, and a shear wave in the solid phase. Johnson et al [2] and

Champoux and Allard *et al* [3, 4] developed a simple model that can accurately predict the acoustical behavior of elastic porous materials over a wide range of frequencies with the assumption that the skeleton is acoustically rigid and the fluid is incompressible on the scale of the pore size. Consequently, only one compression wave propagates in the fluid medium. The Johnson-Champoux-Allard model uses five geometric parameters, commonly referred to as Biot parameters, to describe the coupling between solid and fluid phases of elastic porous materials at the macroscopic scale. The five parameters are: porosity ϕ , static airflow resistivity σ , tortuosity α_{∞} , viscous characteristic length Λ and thermal characteristic length Λ' .

Various techniques have been developed to characterize the five Biot parameters. The first approach, known as the Direct Methods [5], measures the parameters directly based on physical definitions. Direct measurements typically use non-acoustical techniques, and require dedicated equipment for each parameter.

In the second approach, material parameters are determined based on acoustical measurements of phase speed, attenuation and transmission of the propagating compression wave in the high frequency limit using ultrasonic techniques. Test methods using this approach are referred to as the Ultrasonic Methods in this paper.

The third approach is based on measurements of acoustical quantities such as dynamic density and bulk modulus that are related to material parameters through acoustical models. Material parameters are derived

through analytical inversion of the acoustical models. Test methods using this approach are referred to as the Indirect Methods in this paper.

Finally, the fourth approach is based on parameter identification techniques where material parameters are derived from impedance tube measurements and optimization algorithms. This approach is referred to as the Identification Methods in this paper.

Despite numerous test methods existing in the literature, there are no standard test methods for tortuosity α_{∞} , viscous characteristic length Λ and thermal characteristic length Λ' at this time. This paper begins with the definition of each of the Biot parameters, followed by a comprehensive review of the existing test methods of all four approaches to determine Biot parameters. Applicability and measurement accuracy of the test methods are discussed. Recommendations are provided to the SAE Acoustical Materials Committee regarding the need for the development of SAE test methods for Biot parameters.

DIRECT METHODS

POROSITY TEST METHODS - Fiber and foam absorbers contain open pores saturated with air. Porosity ϕ is defined as the ratio of the volume of air space V_a in a material to the total volume of the material V_t : $\phi = V_a / V_t$. Note that only open pores are considered in the air volume. Closed pores pertain to the volume of the elastic structure or skeleton. The value of porosity ranges between 0 and 1.

In 1942, Beranek [6] published a test method to directly measure porosity based on the equation of state for ideal gases at constant temperature (i.e., Boyle's law). In the Beranek method, the acoustical material with known total volume is placed in a rigid chamber of a given volume. The change of air pressure in the rigid chamber as a result of a known change in volume in the chamber is measured. The porosity of the porous material is then calculated using Boyle's law. Changes in pressure and volume are measured by an U-shaped fluid-filled manometer and a graduated scale. Measurement accuracy is limited using the original Beranek Apparatus. Champoux *et al.* [7] developed a much improved measurement system, called the porosimeter, based on the same principle proposed by Beranek. The air-based porosimeter measurement system uses an airtight cylindrical chamber with a high precision electronic pressure transducer and a micrometer piston device with a precision-ground shaft to accurately measure pressure and volume changes. Two tests are performed to measure porosity. The first test is performed with the chamber empty at ambient pressure. The piston is slowly driven into the chamber and increase in pressure is recorded. The test is then repeated with porous material in the chamber. The displacements of the piston are kept the same in both tests. Assuming the process is

isothermal, porosity of the porous material is calculated from Boyle's law. The porosimeter works well, and can provide high accuracy of better than 1% in measurements. However, care must be taken to maintain temperature equilibrium during measurement. Residual temperature effects before and after piston movement do exist and have a negative impact on measurement accuracy. Sample volume also affects measurement accuracy. For most automotive acoustical materials, the authors determine that sample volumes between 50 cm³ and 300 cm³ will have less than 1% to 2% measurement error based on the relationship between measurement error, porosity and sample volume given by Champoux *et al.* [7].

Following the same principle, porosity can be measured directly using the gas pycnometer apparatus as described in the ASTM D6226-05 test standard [8]. The apparatus consists of a calibrated sample chamber and a calibrated expansion chamber connected by a valve. The volumes of both chambers are known. The calibrated sample chamber is connected to a source of high purity (at least 99.99 %) dry gas such as nitrogen or helium. Initially both chambers are at the ambient pressure and temperature. After placing the porous sample in the calibrated sample chamber, the pressure is increased in the sample chamber to a predetermined pressure P_1 . The valve between the two chambers is then opened and the second lower pressure P_2 is recorded. The ratio of the pressure change P_1/P_2 is directly related to the volume of the sample chamber displaced by the porous sample following Boyle's law. The difference between this volume and the geometric volume of the specimen is a measure of the open pore volume. For acoustical materials with 96% porosity, the repeatability standard deviation is 1.6%, and the reproducibility standard deviation is 3.4% [8].

Salissou and Panneton [9] developed a simple experimental setup to directly measure porosity based on experimental determination of the volume of the solid phase of the porous sample using the perfect gas law. In this method, four tests are conducted to measure four masses with and without porous sample at low and high pressure respectively. The isothermal condition holds when the process between and during tests is very slow and room conditions are constant. The open porosity and true mass density can then be determined using the ideal gas equations and the Boyle's law under isothermal conditions. The method needs only simple apparatus such as vacuum pump, airtight sample chambers, high precision balance and manometer, etc. Measurement accuracy can be improved by using heavier gas and/or higher saturating pressure. Increasing test-sample-bulk-volume-to-test-chamber-volume-ratio also improves measurement accuracy. For most automotive acoustical materials, the authors calculate that sample volumes greater than 350 cm³ will have less than 2% measurement error based on error analysis by Salissou and Panneton [9].



Panneton and Gros [10] proposed a “missing mass” method to determine the open porosity ϕ through experimental determination of the volume of the skeleton in a porous test sample. The method is based on the measurement of the apparent (in-air) mass M_1' and true (in vacuum) mass M_1 of a porous material, where an in-air “missing mass” ($M_1 - M_1'$) is found and related to the volume of the solid phase through the Archimedes' principle. The open porosity is related to the missing mass by the following equation [9]:

$$\phi = 1 - \frac{M_1 - M_1'}{\rho_f V_t} \quad (1)$$

Where ρ_f is the density of air with moisture and can be estimated by the ideal gas law, and V_t is the total bulk volume of the porous sample.

The method uses a simple setup to measure M_1 , M_1' and V_t . It does not require the assumption of an isothermal process, and its accuracy is predictable from the knowledge of the total bulk volume of the porous sample and the precision of the balance used. Measurement accuracy improves as the ratio of sample volume to balance readability increases. Increasing the porous sample volume and using a more precise balance reduce the measurement error. For typical automotive acoustical materials, the authors determine that sample volumes greater than 250 cm³ will have accurate results using a 1 mg readability balance based on experimental results reported by Panneton and Gros [10].

Alternative methods based on ultrasonic technique [11] have been developed and are reviewed in later sections.

AIRFLOW RESISTIVITY TEST METHODS - The airflow resistance is the ratio of static air pressure drop ΔP across a porous material to the volume velocity Q of airflow through the material. The specific airflow resistance is defined as the product of the airflow resistance of a porous material and its cross section area A . The units for specific airflow resistance are mks rayl or Pa·s/m. Airflow resistivity σ of a homogeneous porous material is simply the quotient of its specific airflow resistance divided by its thickness t . Airflow resistivity is derived from Darcy's law:

$$\sigma = \frac{\Delta P A}{Q t} \quad (2)$$

The measuring units for airflow resistivity are mks rayl/m, Pa·s/m² or Ns/m⁴. Airflow resistivity is one of the most important design parameters for automotive acoustical materials.

Airflow resistivity can be measured directly based on its definitions by measuring volume velocity of airflow through a porous material specimen and the air pressure

drop across the specimen. Various measurement devices have been developed to measure flow resistivity. One of the best-known measurement systems was developed by Brown and Bolt [12] in 1942. In this method, a steady flow of air is maintained through the porous test sample by siphoning water from a large bottle through a stopcock into a graduated cylinder. For steady flow, the volume of air flowing through the sample in a given time equals to the volume of water flowing into the graduated cylinder. The pressure difference across the sample is measured by a manometer connected to the sample holder. Airflow resistivity can be calculated from measured pressure difference, sample cross section area, sample thickness, and the volume of air passing through the sample in a given amount of time. In order to obtain accurate measurement results, considerable care must be taken to ensure that:

1. Sample edges are sealed to the sample holder to prevent air leakage between test sample and sample holder.
2. A steady flow of air is drawn at a very low speed to maintain laminar airflow through the sample.

For most elastic porous materials, flow resistance increases as the air velocity flowing through the sample increases. The flow resistance levels off to a constant minimal value at low air velocities for most porous materials. Efforts should be made in the measurement to maintain low air velocity such that the minimal value of flow resistance is measured. It is the minimal value of flow resistance that is significant for acoustical properties of the porous material. Brown and Bolt reported that flow resistance measurements using this method can vary widely (+/- 25%) for different samples of the same material, but can be measured accurately (+/- 2%) on the same sample. The original measurement system proposed by Brown and Bolt can be made as precise as desired. However, measurement using the device is time consuming.

A simplified flow resistance measurement device was developed by Leonard [13] based on the method developed by Brown and Bolt. In the Leonard apparatus, the pressure drop through the sample is established by means of an analytical balance. The analytical balance is able to measure small pressure difference with considerably improved resolution. The Leonard apparatus can measure flow resistance as low as about 200 rayl for test samples of 50 mm diameter with accuracy of +/- 40 rayl. The main disadvantage of the Leonard apparatus is the length of time required in setting up and performing measurements.

The measurement system developed by Brown and Bolt has been standardized in ASTM C522-03 [14] using modern instruments such as vacuum pump, high accuracy flow meters, pressure transducers, etc. The