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Characterization of porous acoustic materials. State of the art.

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More than 60 years ago, Zwikker and Kosten published their book 'Sound Absorbing Materials'[1]. In this book, they present models to predict the behaviour of acoustic materials, based on their microstructure. The work of Zwikker and Kosten can be considered as an extension of earlier work of Rayleigh and Kirchhoff. The strong point of this book is that apart from theoretical models, experimental devices are described to measure the input parameters of the models. Since then, a lot of work has been done by Biot [2], Attenborough [3], Allard [4] and others and the models have been optimised to take more physical effects into account and to provide a physical unambiguous definition of the material parameters. Parallel to the improvement of the models, experimental techniques were designed to measure the material parameters independently. In this paper, we give an overview of the experimental techniques that have been developed over the last fifteen years.

1 Introduction

Porous acoustic materials are widely used in buildings, cars and airplanes to reduce unwanted noise. They are used both for their sound absorption properties and their possibility to improve sound insulation. It has become increasingly important to predict the behaviour of an acoustic material in advance in order to optimise its performance or to minimise cost and/or weight. During the last decade, it has become possible to predict the acoustic absorption and insulation of a multilayered structure, taking an increasing number of effects into account like finite size effects and anisotropy [4,5,6]. The 'quality' of such a prediction thus depends strongly on the precision of the input parameters.

2 A short description of the model

The theoretical model that is currently being used is based on the equations developed by M.A.Biot in 1956. The original Biot model was designed to sound propagation in water saturated porous rocks, but has later been adapted to include the physical effects that occur in sound absorbing materials. The model predicts two longitudinal waves and one shear wave. The phase velocities and amplitudes of these waves can be calculated as a function of the material parameters and the way the material is excited. In a crude approximation, one longitudinal wave will propagate in the frame of the material, its phase velocity being largely determined by the elastic coefficients of the frame and its apparent density. This wave is excited efficiently if the frame of the material is in direct contact with a vibrating plate for instance. The second longitudinal wave propagates mainly in the air in the pores. Its phase velocity depends on the compressibility of the air in the pores (which may differ from the adiabatic value due to thermal effects in the pores) and the apparent density of the air in the pores (which may differ from the density of free air due to viscous and inertial effects in the pores). This wave is generally excited efficiently by a sound wave impinging on the free surface of the material. At low frequencies, or for materials with a low permeability, it is not always possible to identify the two longitudinal waves as a 'mechanical' and an 'air' wave. The shear wave is mainly supported by the frame, the air in the pores having only a minor influence on its phase velocity [7].

3 The material parameters

In this paragraph, we will give a short description of the different material parameters, their importance and the way they can be measured. The material parameters are [4,5,7,8]:

- density of frame : $(1-\phi)\,\rho_s$
- thickness of the layer: d
- porosity : ϕ
- flow resistivity (permeability) : σ
- tortuosity : α_∞
- viscous 'pore size' (characteristic length) : Λ
- thermal characteristic length : Λ'
- shear modulus of the frame : N
- Poisson ratio of the frame : ν (or any other elastic constant)

The measurement of the frame density and layer thickness is straightforward, although they can cause some difficulties for some materials like low density mineral wool.

3.1 Porosity

The porosity is the volume amount of air in the material, divided by the total volume of the material. The acoustic porosity is the 'open' porosity. This means that only those pores that can be accessed from the outside contribute to the porosity. Closed cells should not be taken into account, they have only an effect on the apparent density and elasticity of the frame. 'Dead-end' porosity, pores that are open on one side, but do not allow percolation because they are closed on one side constitute a special problem. Figure 1 shows a SEM picture of the cell structure of two different plastic foams.

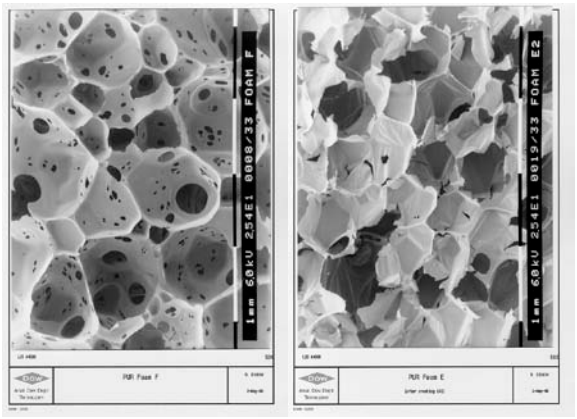

Figure 1. Microstructure of two different plastic foams.
The foam on the left does not show any closed cell porosity.
The foam on the rigth has been mechanically crushed.

In case the material does not contain closed cells and the density of the material is known, the porosity can simply be determined from the apparent weigth of the sample. Often, the density of the frame material is not accurately known (as for instance for a mineral wool when a binder is used to glue to fibres together). In this case, the porosity can be determined with a method based on the ideal gas law: the material is enclosed in a small container. Small volume variations are introduced with a moveable piston and the resulting pressure changes are measured using a manometer. If the temperature is unchanged, the total amount of material that cannot be accessed by air can be deduced [9]. Recently, an elegant method to extract the porosity, based on the measurement of the reflection coefficient of a high frequency wave has been developed by Fellah [10,11].

3.2 The flow resistivity

The flow resistivity is one of the most important parameters for acoustic materials. Its evaluation has been described accurately in ISO 9053:1991 and is a standard equipment that is available in most acoustics laboratories nowadays. Alternatively, the flow resistivity can be extracted from the low frequency behaviour of the material, since at low frequencies, viscous effects dominate all other effects [12].

3.3 Tortuosity

For a long time, tortuosity was measured by measuring the electrical conductivity of the sample, saturated with an electrically conductive liquid. Sound absorbing materials are often difficult to saturate and the method is not always convenient. In 1996, Allard [13] proposed a method based on the high frequency asymptotic limit of the phase velocity of the air wave in the material. At high frequencies, the inertia of the frame being very large, only the air wave is excited. At high frequencies, the viscous skin depth (the distance from the pore wall at which viscous effects are still noticeable) becomes very small and the effect of viscosity becomes negligible. The compressibility being adiabatic, the phase velocity depends only on the effective density of the air in the pores, which depends only on tortuosity. Figure 2 shows the experimental setup and the extracted dispersion curve (phase velocity as a function of frequency). The tortuosity can be extracted from the asymptotic value.

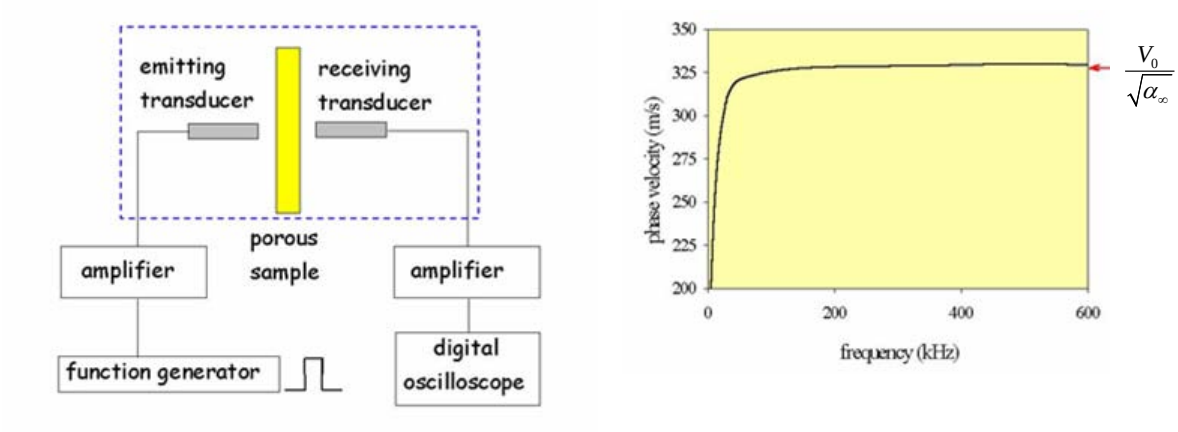

Figure 2. Experimental setup and measured dispersion curve of the ‘air’ wave
in a porous material. The high frequency value of the phase velocity gives the tortuosity.

3.4 Viscous and Thermal characteristic lengths

In the original paper by Biot, the viscous effects were calculated for pores with a cylindrical geometry. The radius of the pores relative to the viscous skin depth determine whether the velocity profile of the oscillating fluid in the pores is low frequency Poiseuille-like or high frequency piston-like. If the pores are not cylindrical, some kind of average pore size can be imagined. In a similar way is the transition between the low frequency isothermal compressibility and the high frequency adiabatic compressibility determined by the ratio of the thermal wavelength (the distance at which thermal changes are noticeable) and the pore radius. It is thus easy to understand that the pore radius (or an averaged pore radius) intervenes in the model. However, in case the radius of the pores is not constant, a different kind of averaging is needed for the viscous and the thermal effects. If we try to imagine a pore with a variable cross section, velocity gradients will be highest at those places where the pore is the narrowest: these sections will contribute most to the viscous effects. The thermal exchange between the air and the pore wall however is not very much influenced by the existence of narrow parts. Therefore, two different ‘characteristic’ lengths are needed, the viscous characteristic length being smaller or equal to the thermal characteristic length. Figure 3 shows the physical interpretation of these two characteristic lengths graphically. It can also be seen from Figure 1 that thermal and viscous characteristic lengths can be different.

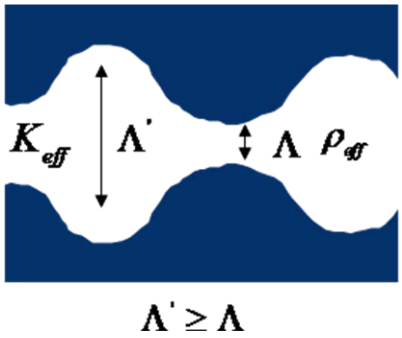

Figure 3. Graphical representation of the concept of viscous and thermal characteristic length.

The characteristic lengths can thus be determined from the viscous and thermal effects in the material [14]. The propagation constant of the air wave at high frequencies is:

$$k = \frac{\omega}{c_0}\sqrt{\alpha_\infty\left[1+\sqrt{\frac{2\eta}{\omega\rho_0}}\frac{(1-i)}{2}\left(\frac{1}{\Lambda}+\frac{\gamma-1}{B\Lambda'}\right)\right]}$$

With c_0 the phase velocity in free air, ω the circular frequency, η the viscosity, ρ_0 the density of free air, γ the ratio of the specific heats, B the square root of the Prandtl number and Λ and Λ' the viscous and thermal characteristic lengths. Λ and Λ' can be evaluated from the real part of k (refractive index) or the imaginary part of k (damping or Q-factor) if two different measurements are performed with different gases saturating the pores. In practices helium and air are used, since they differ significantly in thermal and viscous properties. The experimental configuration is the same as in Figure 2, the transducers and the samples now being enclosed in a container (dotted line) that can be filled with different gases. Figure 4 shows the refractive index and Q-factor for a foam in different gases.

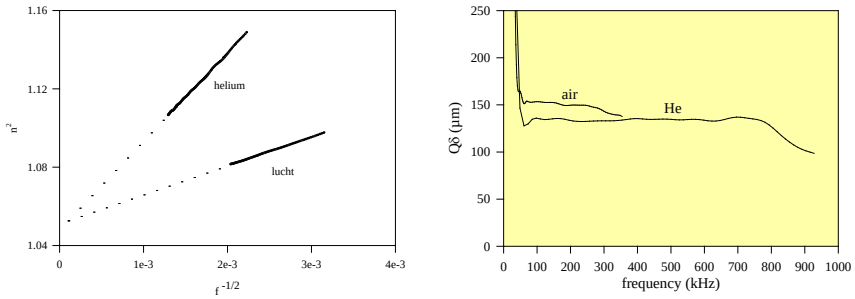

Figure 4. Square of the refractive index of the air wave in the porous material for two different gasses filling the pores. The intersection gives the tortuosity (see par. 3.3), the slopes give Λ and Λ'. Alternatively, Λ and Λ' can be determined from the Q factor (rigth) in two different gases.

3.5 Elastic coefficients

The knowledge of the elastic coefficients of the frame is crucial if the material is in direct contact with a vibration plate or when the flow resistivity of the material is high. Traditionally, the elastic moduli are evaluated with quasi static experiments like the one shown in Figure 5. A shaker can generate longitudinal (or shear) waves in a bar-like sample of the material. The reflection at the free end of the sample will generate standing waves that can be measured with small accelerometers on both sides of the sample. From the resonance frequency, the Young (or shear) modulus can be determined. Various variants of this method exist [15, 16]. These experiments are not very difficult, but some problems occur:

- The range of elastic moduli of absorbing materials may vary from 10^5 to 10^8 pascal. It is difficult to cover this range with one setup.
- The resonance frequency is usually very low (below a few hundred hertz). These materials being viscoelastic, the elastic coefficients depend on frequency.
- Due to the manufacturing process, the materials are anisotropic (often orthotropic) and measurements in different directions may be necessary.

- The air in the pores may influence the resonance frequency (especially for a compression test) and the measurement needs to be done in vacuum or the inversion procedure should take the presence of air into account.

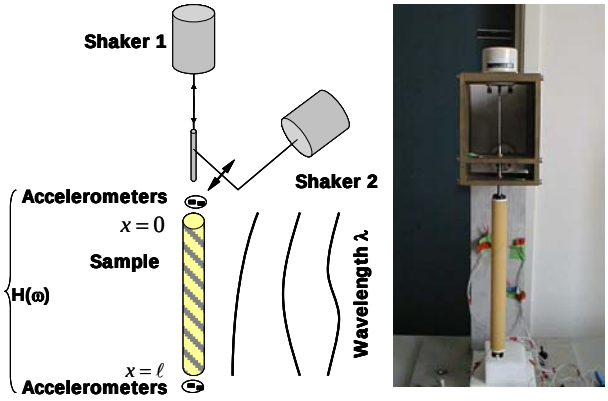

Figure 4. Experimental setup for measuring the Young modulus (using shaker 1) and the shear modulus (using shaker 2) of a bar-like sample.

In order to increase the frequency interval at which data can be obtained, methods based on the study of propagating mechanical waves have been developed during the last years [18, 19, 20]. A shaker generates propagating surface waves (Rayleigh-type or Lamb-type) on a thick slab of the material (typical size a few square meters and a few tens of centimeters thick). The displacement can be measured at different distances from the shaker in different directions (See Figure 5)

Figure 5. Typical setup for the measurement of the elastic moduli using surface waves.

This way, elastic moduli for up to a few kilohertz can be obtained and information about the elastic modulus in different directions can be extracted. Figure 6 shows typical dispersion curves for different modes that are excited in the layer and the shear modulus as a function of frequency that has been extracted from the data.

4 Summary

During the last fifteen years, considerable effort has been made to design measuring techniques to evaluate the material parameters of poro-elastic sound absorbing and insulating materials. Together with a correct modeling of the sound propagation in these materials, this can be used to predict and optimize their performance.

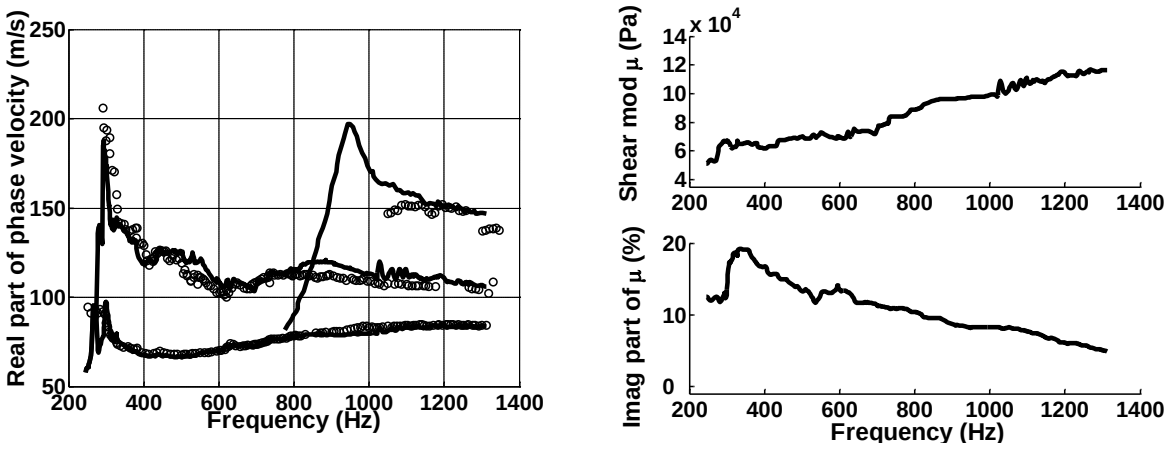

Figure 6. Typical dispersion curves (left) and shear modulus as a function of frequency (right)

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