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Characterisation of sound absorbing materials

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During the last 10 years, different techniques have been developed to measure the material parameters of poro-elastic materials. Measuring tortuosity and characteristic lengths using the ultrasonic technique have become a procedure that is available in several laboratories now. Until recently, data of the elastic properties of poro-elastic materials were obtained using quasi-static techniques that only provide data at low frequencies. Since a lot of damping and sound absorbing materials are visco-elastic, the elastic coefficients may depend strongly on frequency and temperature. In this talk, we will give an overview of the different techniques available for the characterisation of sound absorbing materials.

1 Introduction

Advances in numerical methods have made it possible to calculate the absorption and transmission of multilayered structures, taking an increasing number of physical effects into account like finite size effects, the presence of inhomogeneities or inclusions or the effect of anisotropy of the material properties [1,2]. However, accurate predictions depend on the availability of material data. During the last fifteen years, considerable work has been done on developing measuring techniques to evaluate the relevant parameters of poro-elastic materials [3]. We will give an overview of the techniques that are currently available.

2 Propagation of sound in poro-elastic materials

Materials used for sound absorbing and dampening applications are often much softer than solid materials and have of porosity higher than 90%. As already predicted by Zwikker and Kosten [4], two longitudinal waves can propagate in such a medium (apart from a shear wave when the material is insonified at oblique incidence). Due to the high difference in density between the frame and the air in the pores, the properties of one wave (the mechanical wave) is mainly determined by the apparent elastic moduli and the apparent density of the material, the air in the pores having only a minor effect of the wave properties. The second wave (the air wave) mainly propagates in the air in the pores, but its properties are strongly determined by the pore geometry due to inertial, viscous and thermal effects in the pores. The material parameters can thus be divided in 'mechanical parameters' and 'acoustic parameters'. Which wave carries the most energy depends on the method of excitation: if the frame is directly excited, for instance through contact with a vibrating plate, almost all energy is carried by the mechanical wave. If the material is insonified from air, the air wave is the most intense and the acoustic parameters determine the behaviour. One should realise that the above described simplification is not always valid for every material or for every frequency interval. For instance at low frequencies or for materials with low permeability, movement of the air in the pores may generate a vibration in the frame and vice versa and the full physics of sound propagation in poro-elastic materials should be taken into account [5].

3 Materials parameters

3.1 Acoustic parameters

The 'acoustic' parameters of the material are:

- Porosity φ
- Flow resistivity σ
- Tortuosity α_∞
- Viscous characteristic length Λ
- Thermal characteristic length Λ'

Porosity can be evaluated with commercial equipment (picnometer), based on the measurement of pressure variations as a result of small volume variations in a small cavity or methods derived from this [6]. A few years ago, an elegant method has been proposed to extract the porosity from the high frequency reflection coefficient of the sample. In the asymptotic limit of high frequencies, the reflection coefficient of a thick sample depends only on tortuosity and porosity [7,8].

The measurement of the flow resistivity is well described in ISO 9053:1991. An (low frequency) AC and a DC method are described. Since the acoustic behaviour of the material at low frequencies is dominated by the viscous effects, the flow resistivity can also be extracted from the transmission coefficient of the sample at very low frequencies [9].

For a long time, the tortuosity was evaluated by measuring the electrical resistivity of a sample saturated with an electrical conducting liquid. The more 'tortuous' the pores, the higher the electrical resistivity. The method was developed for geological samples (see for instance the references on this subject in [1]) and was not always easy to apply this method to plastic foams. Fifteen years ago, Allard [10] proposed a simple method to evaluate the tortuosity from the high frequency asymptotic behaviour of the phase velocity of the acoustic slow wave in the material. At high frequencies, the inertia of the frame is too large and the frame remains immobile, as if the materials was rigid. The only wave that can propagate is the air wave. At high frequencies, the viscous skin depth is very small and viscosity does not influence the velocity very much. The compressibility is basically adiabatic and the only parameter influencing the phase velocity at these frequencies is the inertia and thus the tortuosity. The experimental setup is shown in Figure 1. Special air-coupled (piezoelectric or capacitive) transducers are used to emit and detect high frequency sound waves in air. The phase velocity is determined as a function of frequency by unwrapping the phase of the Fourier Transform of the received pulse.

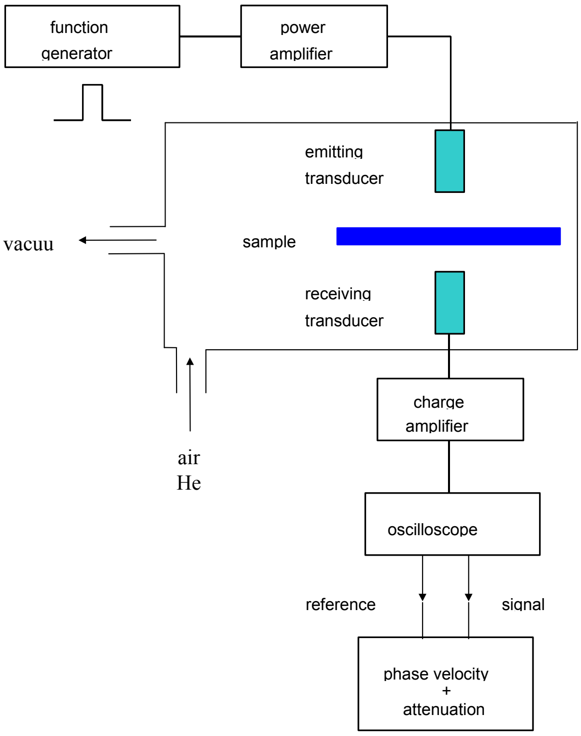

Figure 1 : Experimental set-up for the ultrasonic measurement of the tortuosity (from ref [3])

The method is fast and accurate. The main disadvantage is that it requires equipment that is not always available in a standard acoustics laboratory. However, the method is widely used nowadays and is commercially available [13].

The viscous and the thermal characteristic lengths are without any doubt the most difficult to measure among the acoustic parameters. They determine the transition between low and high frequency velocity profile in the pores and between isothermal and adiabatic compression of the air in the pores respectively. Since viscous effects are dominant in small constrictions in the pores and thermal effects are more dependent on the average distance the heat has to travel to reach the pore walls, two different characteristic pore sizes are needed, the 'viscous' pore size being always smaller or equal to the 'thermal' pore size. These characteristic pore sizes can be estimated (at least in order of magnitude) from the attenuation of an ultrasonic wave that passes through the material. If discrimination between viscous and thermal characteristic length is needed, the attenuation should be measured with different gases (having different viscous and thermal properties) saturating the pores [11]. This is schematically shown in Figure 1, where the setup is build in a transparent container, that can be filled with helium or air. For details on the measurement of Λ and Λ', see the references [1] and [2].

3.2 Mechanical parameters

If the flow resistivity of the material is not too high and if the material is not in contact with a vibrating plate, the acoustic parameters suffice to describe the acoustic behaviour of the material. In all other cases, the mechanical parameters are also needed. Techniques to measure the elastic coefficients of soft materials exist (Oberst type experiments) but regarding poro-elastic materials, some supplementary complications occur:

- The coupling between air and frame introduces some extra attenuation, that is not a result of the frame's damping. The experiments should be performed in vacuum or the inversion should take the coupling with the air into account.
- Since the materials are often designed to have a maximum damping in the audio frequency range, the principle of causality shows that this results in a frequency dependent elastic modulus.
- Due to the manufacturing process (foam rising or fibrous material build-up), the mechanical parameters (and often to a lesser extend also the acoustic parameters) become anisotropic. In most cases, an orthotropic symmetry describes the material accurately, but it requires the introduction of supplementary elastic coefficients.
- The elastic coefficients of materials used in acoustic applications may vary from 10^5 Pa to 10^9 Pa. This enormous range makes it difficult to design one single experiment that can measure this entire range.

A typical setup for the measurement of the shear modulus is shown in Figure 2. A shear wave is generated in two slabs of the porous material (using a shaker attached to a plate). From the position and the width of the resonance peak, the shear storage and loss modulus can be determined.

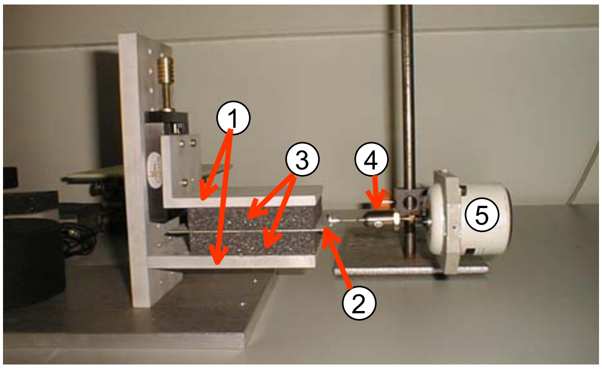

Figure 2. Setup to measure the shear modulus of the frame. 1) rigid plate; 2) moveable plate; 3) sample 4) B&K 8001 impedance head; 5) shaker (from ref [3]).

Since the air in the pores does not support any shear wave, the shear velocity and damping is only slightly influence by the air saturating the pores. The main disadvantage is that this measurement typically results in a shear modulus at a few hundred hertz, whereas for a lot of applications, the elastic coefficient is needed at much higher frequencies.

One way of overcoming this frequency limitation is to extract the elastic modulus from the phase velocity of propagating waves [12]. This way, the only frequency limitation that remains is a result of the increasing attenuation as a function of frequency: at a certain frequency the signal to noise ratio is not good enough.

A typical setup consists of a relatively large slab of the material, a mechanical shaker to generate waves in the structure and a detector, preferentially a laser Doppler vibrometer that can scan the sample as a function of position. Figure 3 shows a setup from ref [13].

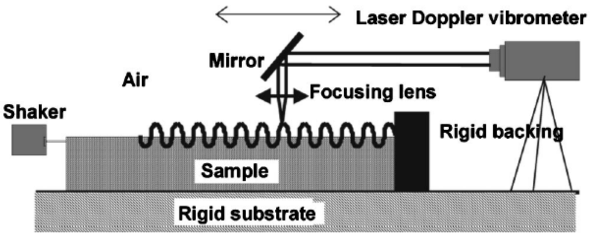

Figure 3. Typical setup for the measurement of propagating mechanical waves. From ref [14]

A shaker generates harmonic plane waves at one end of a porous slab (typically a few square meters in size). These waves propagate at the surface of the sample and reflect at a rigid termination, forming a standing wave. The wavenumber can be determined with a scanning laser Doppler vibrometer. If the frequency is high enough so that the thickness of the sample is more than a few wavelengths, only a Rayleigh-type wave can propagate and the extraction of the shear modulus from the phase velocity is relatively easy. Any dispersion that is observed as a function of frequency is the result of the frequency dependence of the elastic coefficients of the material. When the wavelength is too large, the porous slab acts as a waveguide and multiple dispersive modes can propagate. The phase velocities of the different modes can be extracted by performing a (space → wavenumber) Fourier transform of the displacement as a function of position of the standing wave in front of the rigid termination. Figure 4 shows the typical dispersion curves that can be obtained in this configuration.

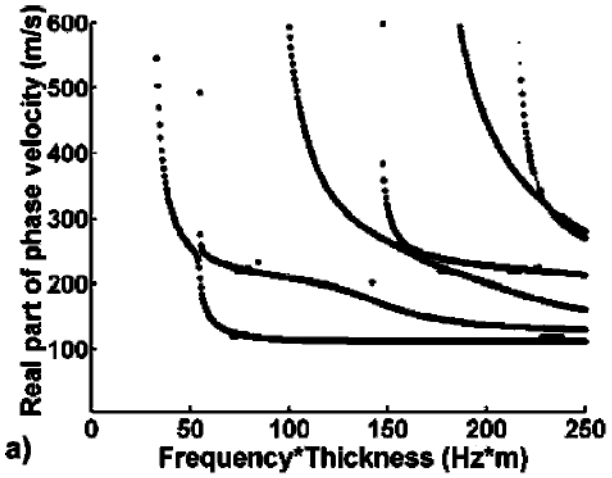

Figure 4. Typical dispersion curves for the configuration of figure 3.

This configuration is easy to establish, but since the data need to be windowed before the FFT calculation, there is a slight sensitivity of the result on the type and position of the window. On top of this, the shaker does not couple a lot of energy to the foam which can be detrimental to the signal to noise ratio. Different variations of this method have been tried, including extracting the dispersion curves from a 2D FFT (space, time) → (wavenumber, frequency) when the source generates broadband bursts or using Time-Frequency analysis [15, 16].

To overcome these problems, a symmetrical setup is preferential. This is shown in figure 5.

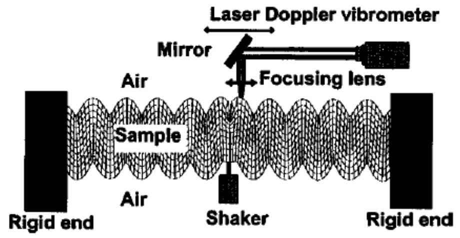

Figure 5. Symmetrical setup for the generation of guided modes in a porous slab.

The configuration is now in a 'Lamb' condition (free surfaces on top and on bottom). The shaker couples much more energy to the foam and due to the symmetric clamping conditions left and right, no spacial windowing in necessary. Figure 6 shows some typical standing wave patterns and the corresponding Fourier transform. Each 'peak' in the Fourier transform corresponds to the wavenumber of a mode excited in the layer.

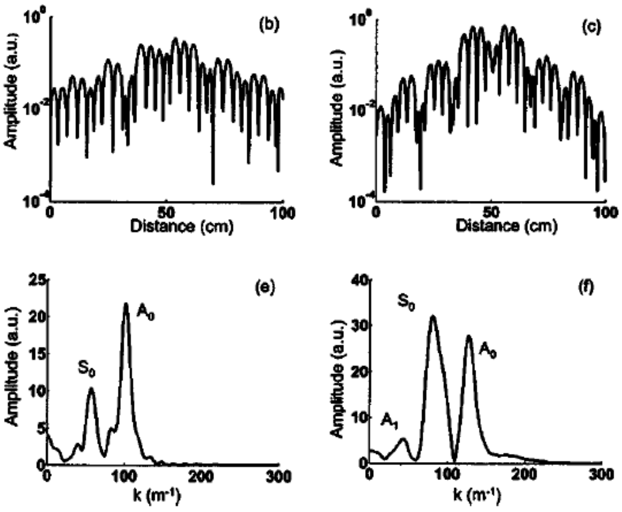

Figure 6. Standing wave pattern and spacial Fourier transform for the configuration of figure 5. Frequency 600 Hz (left) and 800 Hz (right).

By fitting the theoretical dispersion curves to the measured ones, the shear modulus as a function of frequency can be extracted. Figure 7 shows a typical result of a shear modulus of a foam as a function of frequency.

At present, work is continuing on different configurations that are more easy to realise and on the temperature dependence of the elastic constants.

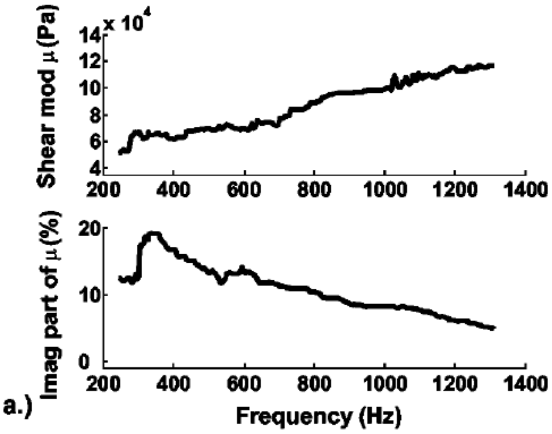

Figure 7. Typical result of a shear modulus as a function of frequency.

A ‘simplified‘ version of this technique has been proposed by Geebelen [17]. Using an acoustic point source made of a compression driver and a tube, a shear wave can be generated in a layer of the sample. The quarter wavelength resonance of this shear wave can be detected with a laser Doppler vibrometer pointing at an angle towards the surface. This method does not require a complicated setup.

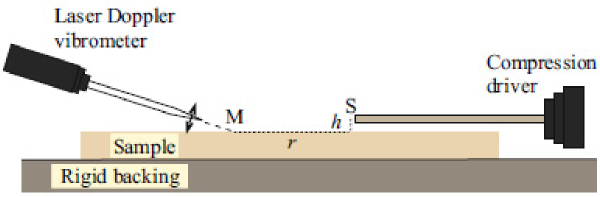

Figure 8. Experimental setup for measuring the shear modulus from the quarter wavelength resonance in a layer. (from ref [16])

4 Conclusion

An overview has been presented of the different methods that can be used to determine the material parameters that govern the acoustic behaviour of a poro-elastic materials. It is now possible to obtain the frequency dependent shear modulus for viscoelastic foams.

Remerciements

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