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Ultrasonic transmission experiments on porous materials

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ABSTRACT

The experiments are based on the detection of air-borne slow compressional waves after transmission through absorbent porous materials. The measurement of the attenuation and the velocity of the slow wave at ultrasonic frequencies enables us to determine some important material parameters which are needed for the prediction of the acoustic performance (in the audible range) of the samples.
In addition, an XY positioning system is useful for probing the samples at different positions. The difference in velocity and attenuation as a function of the measuring point on the sample gives information on the homogeneity of the material. This leads to non-destructive testing and to a study of the difference in material properties within one sample.

INTRODUCTION

In general two longitudinal waves can propagate in a fluid saturated porous material as predicted by Biot [1] : the fast and the slow wave. All the experiments which will be presented here use the detection of the slow wave after traveling through the porous material.

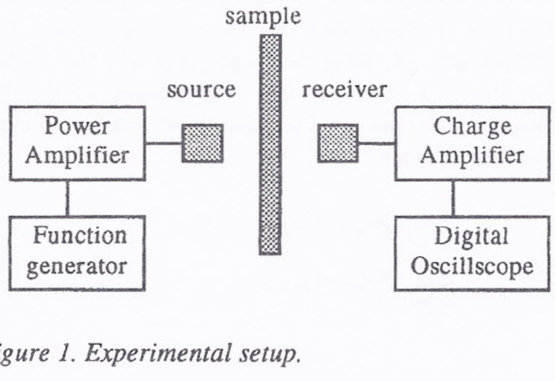

Figure 1. Experimental setup.

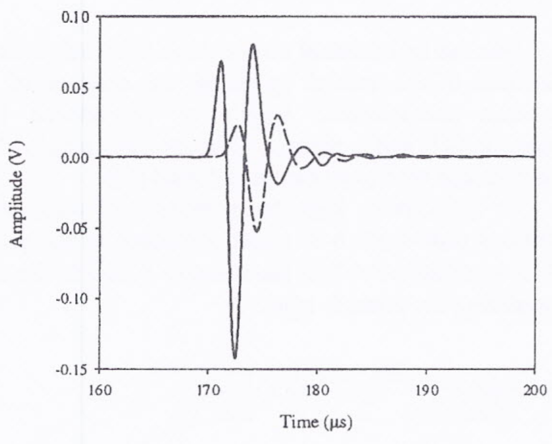

Figure 2. Signal in air (solid line) and signal after introduction of a foam between source and receiver (dashed line).

All the measurements are performed on air-saturated polyurethane foams. A schematic representation of the experimental setup is given in figure 1. For the generation of the ultrasonic wave in air we used both piezoelectric and capacitive transducers. In order to obtain a sufficiently large signal, the transducers were fed by a 300 V pulse. For the detection the capacitive transducers turned out to be the most sensitive ones. They consist of an aluminum coated Mylar film on a backplate. When using a film of 6μm thickness, ultrasonic pulses with frequency components from 80 to 700 kHz can be generated and detected. The thickness of the sample used depends on the attenuation which can be very high at ultrasonic frequencies.

MATERIAL PARAMETERS

Sound propagation in fluid saturated porous materials can be described by a number of parameters: porosity, flow resistivity, density, elastic constants, tortuosity, viscous and thermal characteristic lengths. A review of the complete theory and the definition of all these parameters can be found elsewhere [2].

The classical determination of the tortuosity α_∞ by electrical resistivity measurements has a few drawbacks. The most important ones are the difficulties encountered when saturating the porous foam by a conducting fluid. Therefore an ultrasonic measurement of the tortuosity in air has been proposed by Allard et al. [3]. The method is based on the increase of the time of flight of an ultrasonic pulse when the sample is introduced between the two transducers (see figure 2). When plotting the phase velocity versus frequency, the tortuosity can immediately be calculated from the high-frequency asymptotic value of the phase velocity.

Viscous and thermal effects have been taken into account in the model by using the concept of a viscous characteristic length Λ (introduced by Johnson [4]) and a thermal characteristic length Λ' (introduced by Champoux and Allard [5]).

At sufficiently high frequencies, i.e. when the viscous skin depth δ is small compared to the pore size, one can prove that the speed of sound in the air saturating the pores is equal to

$$c = \frac{c_0}{\sqrt{\alpha_\infty}}\left[1 - \frac{\delta(1-i)}{2}\left(\frac{1}{\Lambda} + \frac{\gamma - 1}{B\Lambda'}\right)\right] \qquad (1)$$

with c_0 the speed of sound in free air, B the square root of the Prandtl number, γ the specific heat ratio of air and $\delta = \sqrt{2\eta / \rho_0 \omega}$, η being the viscosity and ρ_0 the density of air.

It is useful to define a quality factor Q which is a function of the phase velocity V_φ and the attenuation α :

$$Q = \frac{1}{2}\frac{\omega}{\alpha V_\varphi} \qquad (2)$$

In the high frequency limit we obtain

$$\lim_{\omega \to \infty} \frac{1}{Q\delta} = \frac{1}{\Lambda} + \frac{\gamma - 1}{\Lambda'} = L \qquad (3)$$

Figure 3 gives an example of $Q\delta$ as a function of frequency, calculated from the phase velocity and attenuation measured on a reticulated foam.

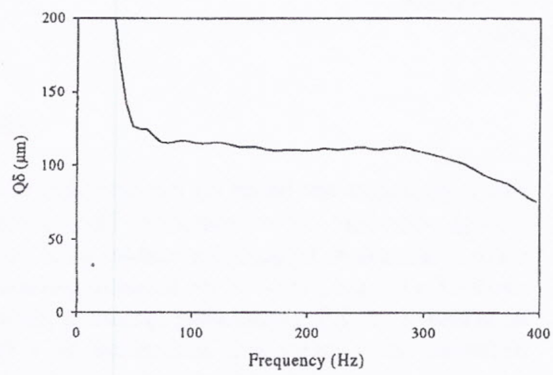

Figure 3. $Q\delta$ *as a function of frequency.*

As expected, $Q\delta$ goes towards a constant value at higher frequencies, i.e. between 100 and 280 kHz. The deviation of this constant value at frequencies higher than 300 kHz will be discussed further.
Starting from this value it is possible to calculate a value for the expression on the right hand side of equation (3). If Λ or Λ' is known, one can determine the other quantity in this way [6].

However it is possible to determine both the viscous and thermal characteristic length by doing the same measurement in two different gases (e.g. helium and air) saturating the pores [7] (see figure 4). Since Λ and Λ' are independent of the gas saturating the pores, it is possible to determine them from the system

$$\lim_{\omega \to \infty} Q\delta_{air} = L_{air}$$
$$\lim_{\omega \to \infty} Q\delta_{He} = L_{He}$$

For the above example we end up with a value of 132 µm for Λ and of 292 µm for Λ' .

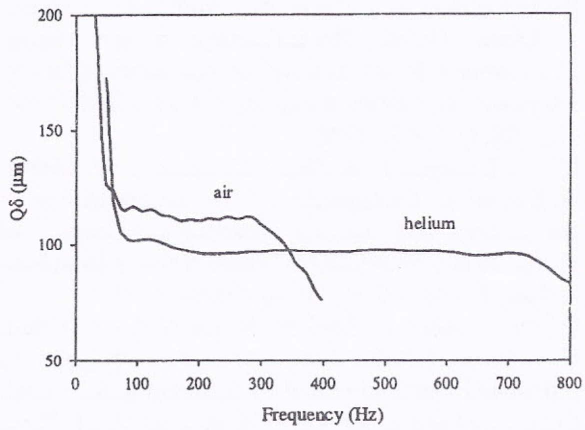

Figure 4. Qδ in different gases as a function of frequency.

An additional attenuation is the reason for the deviation of Qδ form the constant value at high frequencies.

Figure 5 shows a measurement on another foam in three different gases. One can clearly notice that the "cutoff" frequency depends on the gas that is saturating the pores : approximately 130 kHz in the CFC, 260 kHz in air and 763 kHz in helium. Note that the ratio of these frequencies corresponds to the ratio of the sound speeds in the free gases.

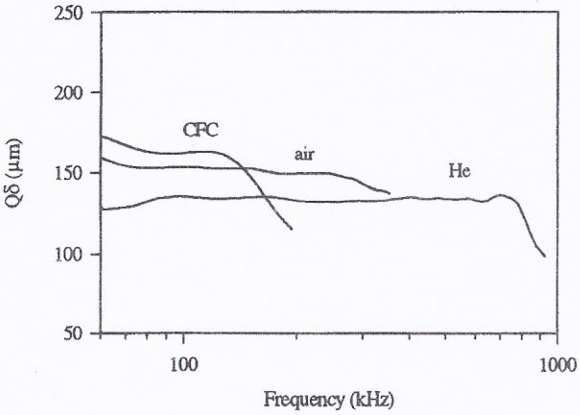

Figure 5. Qδ as a function of frequency in three different gases.

This leads us to the conclusion that the extra attenuation is caused by a scattering effect. The scattering amplitude depends on the ratio of the size of the scatterer (being the frame of the porous material) and the wavelength. Of course, the critical wavelength from which this scattering effect becomes important does not change in the three cases. However, the velocity being different, the cutoff frequency will change following the ratio of the sound speeds. If the decrease of Qδ was due to a viscous effect for instance, the ratio of cutoff frequencies would be different. Using a simple scattering theory, the curves in the above measurement can be predicted as described in reference [8].

A small additional remark can be made concerning the measurements in the CFC. The gas used was CH_2F-CF_3. Because the specific heat ratio γ is almost equal to 1 ($\gamma = 1.12$), the thermal characteristic length has almost no influence on our measurement as can be seen in formula (3). So in this case the measurement of Qδ leads to a good estimation of the viscous characteristic length Λ by making only one measurement.

NON-DESTRUCTIVE TESTING

It can be interesting to use this ultrasonic transmission experiment as a tool for testing an entire slab of material. Indeed, by using a computer controlled XY-positioning system, it is possible to create an image of the changes in attenuation and velocity of the slow wave as a function of the position they have been measured on.

The image in figure 6 is an example of a 14 by 14 cm scan on a highly attenuating polyurethane foam.

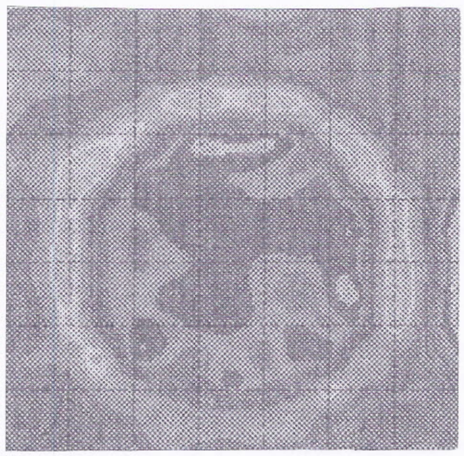

Figure 6. Example of a XY-scan on a polyurethane foam.

The light circular region in figure 6 corresponds to a local lower attenuation. In fact, the material has been damaged slightly in that region (invisible for the eye) by placing a tube on the sample.

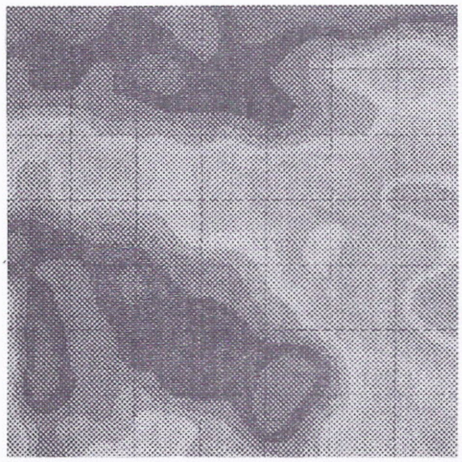

Figure 7.

Figure 7 shows density variations in the foam due to the production process.

Compared to traditional C-scans, the advantage of this technique lies in the fact that the measurement can be performed in air.

CONCLUSIONS

In this paper we have tried to give an overview of some applications of transmission experiments on porous materials at ultrasonic frequencies.

We have showed that this technique provides us with an effective tool for determining tortuosity and viscous and thermal characteristic lengths. Moreover, this type of measurements can be useful for non-destructive testing of reticulated foams in air.

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