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Temperature and frequency dependence of the visco-elasticity of a poro-elastic layer

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ABSTRACT

Besides their structural complexity, the acoustic behavior of polymer-based poro-elastic layers is complicated also due to their frequency dependent elasticity. In this work, we address the frequency and temperature dependence of the elastic behavior in general, and the shear modulus in particular, of poro-visco-elastic materials. The analysis is based on the monitoring of mechanically excited guided acoustic wave propagation by means of a laser Doppler vibrometer scanning technique. The concept and practical implementation of the experimental method are presented, as well as the signal processing procedure and data analysis. Experimental data are presented for a polyurethane foam. The observed visco-elastic behavior, complemented with dielectric spectroscopy data, is interpreted in the framework of two underlying relaxation processes.

1. Introduction

The elasticity of porous materials plays a key role in their acoustic and mechanical behavior, which are crucial for many applications, such as acoustic absorption and vibration damping. Even in the linear regime of elasticity, the relation between the bulk elasticity of the polymer of which the frame of cellular materials consists, and the effective, macroscopic frame elasticity is quite complicated. With respect to the macroscopic shear modulus, for not too high frequencies, the situation gets simplified, since the (non-viscous) fluid filling the pores does not have to be taken into account in the analysis. Quite some work has been performed on the development of theoretical models connecting the elastic moduli of the frame material in bulk form, the microscopic cell wall dimensions and the microscopic morphology on one hand, to the macroscopic elasticity on the other hand [1]. In a model proposed by Gibson and Ashby [2], the relation between the macroscopic frame's Young's (E) and shear (G) modulus on one hand, and the Young's modulus of the bulk material (E_s) on the other hand, is given by:

$$E, G \sim E_s \left(\frac{\rho}{\rho_s}\right)^2, \qquad (1)$$

where the ratio between the volume density of the bulk material, ρ_s, and the frame density, ρ, make an important part of the proportionality, expressing that the material softens with increasing porosity.

An additional challenge that is encountered in this matter is how to predict the macroscopic frame damping. Indeed, besides the contribution to the acoustic wave attenuation for the airborne wave of the porous morphology (imaginary parts of Biot parameters [3] and attenuation due to scattering), which is mainly important towards higher frequencies, also the contribution due to non-zero imaginary parts of the elastic moduli of the frame is of high importance for the global attenuation behavior. The latter contribution relates to the visco-elastic nature of many frame materials, in particular for polymer foams. Besides the technological interest to understand and predict the effective acoustic attenuation and effective elastic damping by the frame, starting from the visco-elastic behavior of the bulk frame material and from the geometrical frame parameters, the relation between the bulk behavior and porous behavior is also quite intriguing from the physics point of view. The phenomenology of the glass transition in bulk visco-elastic materials is better and better understood, but much less

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research has been done on the link between the bulk level and the porous level. One could expect that the imaginary parts of the elastic moduli follow the same trend as Eq. (1), but with some mixing between the different moduli, due to the mixed motion on the microscopic level.

In the following, we contribute to clarifying the behavior by reporting on results for the temperature (245–301 K) and frequency (1200–4400 Hz) dependence of the shear modulus of a Urecom® (trademark of Recticel) poro-elastic layer of 5 cm thickness.

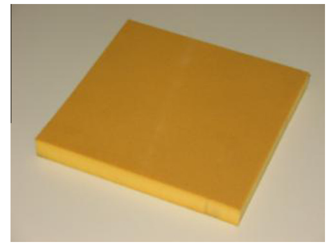
2. Determination of the shear modulus of a poro-elastic frame by guided wave propagation analysis

For the elastic characterization of the materials under study, we have made use of guided acoustic waves, whose propagation characteristics are closely connected with the material parameters via known theoretical models [4]. In principle the acoustic waves guided in our slabs of finite thickness are of the Lamb type. However, in the accessible frequency range between 1.2 and 4.4 kHz, the longitudinal and shear acoustic wavelengths, and thus the penetration depth of the guided waves, are significantly shorter (less than 3 cm) than the layer thickness of 5 cm, so that the waves are of the Rayleigh type, confined at the excitation side. Since Rayleigh waves are not subject to geometry-related dispersion, any measured dispersion or damping can be considered to be resulting from the intrinsic dispersion of the material. This feature makes Rayleigh waves more suitable than Lamb waves to study viscoelastic material dispersion and damping, in spite of the disadvantage that, contrary to Lamb wave dispersion analysis, they do not allow to simultaneously determine the two moduli (longitudinal/shear).

In earlier work we have shown that in the frequency range 1.2–4.4 kHz) the propagation of guided acoustic waves, excited and detected via the frame, is dominated by the frame properties, with negligible influence of the Biot parameters or of the fluid [5]. It turns out that for surface waves of the Rayleigh type, the wave propagation velocity is mainly determined by the shear modulus, and to a good approximation it can be considered independent of the longitudinal modulus. The shear modulus is proportional with the square of the shear wave velocity, with whom the Rayleigh velocity is roughly proportional.

In our experimental setup quasi-monochromatic Rayleigh wave burst packets were generated by means of a shaker. Their velocity and damping were determined by analyzing the time of arrival Δt and (average burst) amplitude A of free-running wave signals, measured by means of laser-Doppler vibrometry, at different distances Δx from the source, over a range between 5 and 30 cm, depending on the damping distance. The quality of the signal was enhanced by placing (acoustically thin) retro-reflective stickers along the path of interest. The time of arrival of a wave signal was determined by cross-correlating it with the burst of 5–20 cycles. The burst signal was generated by an Agilent 33120A function generator which was amplified by a Bruel and Kjaer type 2706 amplifier and send to an LMS Qsources shaker. The velocity of the waves was then determined from the slope of the linear curve of Δx versus Δt. The damping was determined by fitting an exponential decay function to A(x). The analysis was done in the temperature range between 245 and 301 K and for frequency between 1200 Hz and 4400 Hz. As a result of the increasing wavelength with decreasing frequency, the burst length below 1 kHz became too long with respect to the maximum distance range between the generation and detection site. Above 4.4 kHz, due to increased damping, the signal-to-noise ratio was too weak for adequate analysis.

Table 1
Material properties of the investigated Urecom® material.



Porosity ϕ	$\geqslant$0.95
Density ρ	(96 ± 4) kg m^{-3}
Tortuosity	1.5 ± 0.1
Flow resistivity σ	(400 ± 3) kN s m^{-4}
Viscous characteristic length Λ	(60 ± 7) μm
Thermal characteristic length Λ'	(119 ± 12) μm

The temperature of the sample was controlled by placing it in a temperature controlled atmosphere, in which the sample surface was optically accessible for the vibrometer via a window.

The material properties of the investigated Urecom® (trademark from Recticel) material are listed in Table 1.

3. Temperature and frequency dependence of the phase velocity of the real and imaginary part of the Rayleigh wave propagation velocity

Fig. 1 shows the experimental results for the frequency dependence of the phase velocity (a) and the attenuation coefficient (b) of the Rayleigh wave along the 5 cm acoustically thick Urecom® sample under investigation at different temperatures. The phase velocity c (m/s) and the attenuation coefficient α (Np/m) are calculated from the measured (complex) wavenumber k as follows (e.g. see [6]):

$$c = \mathrm{Re}\{\frac{\omega}{k}\} \quad \alpha = \mathrm{Im}\{k\} \tag{2}$$

where c is the phase constant in radians per metre (rad/m) and α is the attenuation constant in Nepers per metre (Np/m).

Fig. 2 depicts the same data, but in the form of the temperature dependence at different frequencies. Given that Poisson's ratio for this kind of material typically only varies between 0.20 and 0.25, the Rayleigh velocity is roughly proportional with the shear

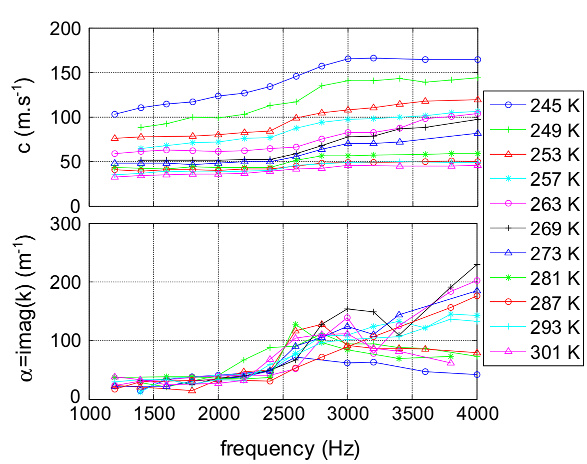


Fig. 1. Frequency dependence of the real part of the propagation velocity (top) and the imaginary part of the wavenumber (bottom) of Rayleigh waves in Urecom® polyurethane as function of frequency, for different temperatures.