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MEASURING THE DYNAMIC SHEAR MODULUS OF POROELASTIC FOAMS IN THE AUDIBLE FREQUENCY RANGE.

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Abstract

The prediction of acoustical properties of multilayered systems including poroelastic layers using the full Biot theory is in principle possible but in practice limited by the absence of material data. One of the parameters that is difficult to measure is the dynamic rigidity of the porous frame. Current experimental methods are limited to the lower part of the audible frequency range¹ (typically below 400 Hz) and require special shapes of the sample (cube, cylindrical rod or very thin samples). Since most sound absorbing plastic foams are viscoelastic, the elastic moduli may vary strongly with frequency, a measuring technique in the full audible frequency range is needed. Recently² a new method for the measurement of the dynamic shear modulus of the frame of poroelastic foams in the medium and high audible frequency range (1 to 4 kHz) has been presented. This method is based on the measurement of the velocity and the damping of a Rayleigh-type surface wave on sample with thickness larger than the Rayleigh wave penetration depth. The Rayleigh wave was excited through direct mechanical excitation of the frame or the porous material and detected using a laser-doppler vibrometer. The velocity of this wave is closely related to the shear velocity, which is directly linked to the shear modulus. The damping of the Rayleigh wave can be used to determine the imaginary part of the shear modulus.

In this work a first attempt is made to measure the dynamic shear modulus on a layer of finite thickness. In this way there is no requirement whatsoever concerning the shape of the sample under investigation.

1. Rayleigh-like surface waves on a semi infinite substrate

On the surface of a semi-infinite elastic substrate in vacuum, only one surface wave (the Rayleigh wave) can propagate. This wave is non-dispersive and its phase velocity is close to the shear wave velocity in the substrate. Since a poro-elastic medium can support two longitudinal waves and a shear wave, surface waves on a poro-elastic half space are more complicated^{2,3}. In this paper, we consider air filled porous media used for sound absorbing applications in automobile and building acoustics. The porosity of these materials is very high. Since the density of the frame is much higher than the density of the air saturating the pores, the shear wave and one of the compressional waves are very similar to the shear wave and the compressional wave that propagate in an effective elastic material with the same density and the same elasticity. The other compressional wave propagates mainly in the air saturating the pores. Its phase velocity depends on frequency and is mainly determined by the flow resistivity, tortuosity and the characteristic lengths. Surface waves on thin porous rigid layers saturated by air have been studied in the past⁵⁻⁷. The present paper focuses on the frame-borne surface wave.

Frame-borne waves can easily be excited using mechanical excitation. The air in the pores moves almost in solidarity with the frame but is too light to modify the velocity noticeably. A possible visco-elastic nature of the frame, viscous friction between air and frame and thermal exchanges between air and frame can cause the wave to be attenuated. A previous study² of surface waves on an air filled poro-elastic half space confirm that a Rayleigh-like surface wave can be generated, whose properties are very close to the properties of a Rayleigh wave on an equivalent elastic half space. The phase velocity of this surface wave can thus be used to estimate the shear modulus of the frame. The attenuation of the Rayleigh wave is mainly

related to the non-zero imaginary part of the shear modulus

2. Experimental procedure

The experimental procedure for exciting and detecting frame-born surface waves in porous materials has been described in detail elsewhere². Basically, a LDS shaker excites the surface of a large thick block of foam with a narrow-band sine burst. The vertical velocity component of the surface is measured at incrementing distances from the source, using a Polytec vibrometer. A cross-correlation provides the correct phase velocity.

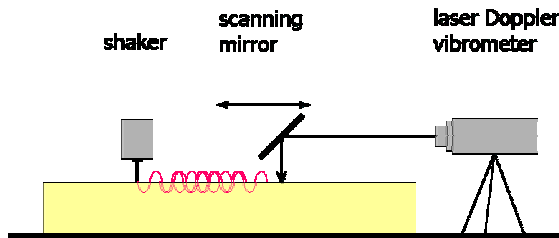


Figure 1. Experimental setup.

Results have been obtained in the frequency range 2-3 kHz on a block of foam with surface area 1.5x1.5 square meters and a thickness of 10 centimetres.

3. Rayleigh-like waves in a porous material.

Figure 2 shows the vertical velocity component (calculation based on the Biot model⁴) as a function of time for different positions from a point source generating a short pulse. Each time signal was recorded at different distances from the source, in increments of 25 mm. The time signals are shifted vertically for convenience. The Rayleigh wave velocity is as low as 50 m/s, due to the large density (25 kg/m^3) and low elastic modulus. For these data, the shear modulus of the foam was taken to be $75 \times 10^3 + 15 \times 10^3 i \text{ N/m}^2$, flow resistivity 50000 Ns/m^4 , tortuosity 1.4, porosity 0.98, viscous length $50 \text{ } \mu\text{m}$, thermal length $150 \text{ } \mu\text{m}$ and Poisson ratio 0.3.

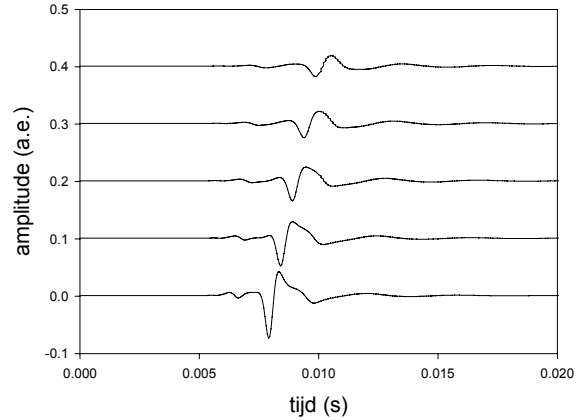


Figure 2. Calculated data for the vertical displacement component of a Rayleigh wave as a function of time for different distances from the source. Each time signal is shifted vertically for clarity. Vertical axis in arbitrary units.

At the frequencies of the measurement, the wavelength of the Rayleigh wave was 2.5 centimetres or smaller. Thus the block can safely be considered as semi infinitely thick: the amplitude of a Rayleigh wave is usually negligible at a depth of 2 to 3 wavelengths. At higher frequencies, the Rayleigh wave becomes strongly attenuated and its phase velocity difficult to measure, due to geometrical spreading present in point source excitation. It is an interesting challenge to decrease the measuring frequency of this method. In that way, shear modulus information would be obtained between the high range covered by the Rayleigh wave method, and the low range that is accessible by traditional low frequency methods.

4. Lamb-like waves on a slab of poroelastic foam with finite thickness.

Once the wavelength λ becomes larger than about one third of the thickness d of the foam layer, surface waves become Lamb wave like. They become dispersive and other modes may appear. For our modelling, we treat the elastic layer as an effective medium, which has the same density and elastic constants as the poro-elastic frame. The elastic layer is bonded to a perfectly rigid substrate. We approximate the elastic coefficients as frequency-independent. Fig. 3 shows measured data for the configuration, which is used for our experiment. We consider waves propagating on a slab of porous material of 0.05 m thickness. The shear modulus of the material is $35 \times 10^3 + 6 \times 10^3 i \text{ N/m}^2$, the Young's modulus is $86 \times 10^3 + 8 \times 10^3 i \text{ N/m}^2$ and the density is 30 kg/m^3 . For the calculation we neglected the imaginary parts of the elastic moduli. Under these circumstances the material

has a Rayleigh velocity of about 31m/s. At low frequencies, i.e. for small values of d/λ , the modes are analogous to odd Lamb modes in an elastic plate of thickness $2d$, since these modes have approximately a horizontal and vertical displacement equal to zero at the symmetry plane half-way the plate. At high frequencies, the mode velocities tend to the Rayleigh wave velocity or to the bulk wave velocities. Each mode has a cut-off frequency below which it cannot propagate. Below the first cut-off frequency no sound mode can propagate at all. In a free plate with thickness $2d$, only the A0 and the S0 mode could propagate at low frequencies. However, these modes do not exist in our case due to the bonded edge condition between the layer and the substrate. For the experiment, in the lower frequency range, a burst with a Gaussian envelope was used to excite the Lamb-like waves. Measured waveforms are depicted in Fig. 3. The amplitudes were normalized, because the source strength was changed regularly depending the the experimental circumstances. With increasing centre frequency of the Gaussian burst, multiple Lamb-like wavepackets with different velocities appear. A summary of the used frequencies and corresponding measured phase velocities of the multiple waveforms is given in Table 1. The different phase velocities were calculated by first removing possible edge-reflected waves using a 2D Fourier transform. Then the velocities were determined using a cross correlation between wavepackets at different probe positions. Also time differences between extrema in subsequent wavepackets were used. Lower frequencies were measured at distances closer to the source to prevent diffraction effects, which occur when the source-detection distance largely exceeds the length (25 cm) of the used line source.

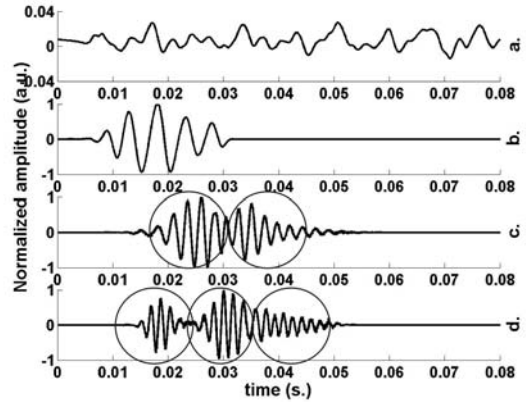


Figure 3 Measured Lamb-like waveforms on a slab of porous material.

- a) 120Hz: below first cut-off frequency.,
 - b) 200Hz: first mode appears,
 - c). 400Hz, two modes are visible,
 - d). 600Hz, the third mode appears.
- (mind the different scale for fig 3a)

Figure 4 compares the measured phase velocities with calculated dispersion curves. Discrepancies between measurement and simulation are probably related to neglecting the imaginary parts and the frequency dependence of the elastic moduli in the simulation.

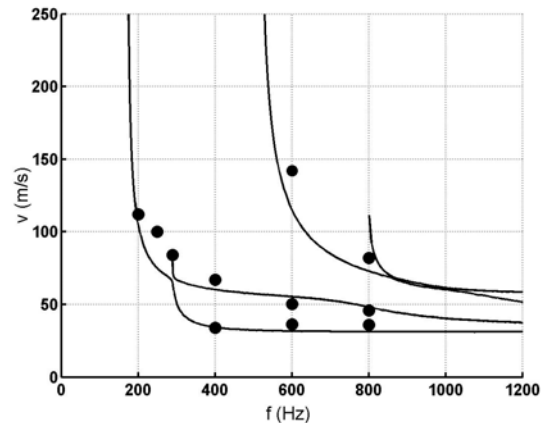


Figure 4. Measured phase velocities (circles) and calculated dispersion curves (solid line) for equivalent elastic material.

Caution is advised when interpreting the curves around 290 Hz. The first two modes do not cross, but converge to each other, as it is the case around 900 Hz. Because of the absence of the A0 and S0 mode, the lowest cut-off frequency can be unambiguously determined from the simulated curves. The value of 170 Hz corresponds

well with experimental observations. Below 190 Hz we observed a drastic decrease in signal amplitude and change of shape of the waveform. Note also that at higher frequencies the modes approach the Rayleigh velocity.

Freq (Hz)	$v_{\text{mode 1}}$ (m/s)	$v_{\text{mode 2}}$ (m/s)	$v_{\text{mode 3}}$ (m/s)
120	No propagating modes were observed		
200	112		
250	100		
290	84		
400	34	67	
600	36.2	46	82
800	36	50.3	142

Table 1. Phase velocities of Lamb-like modes at different frequencies.

5.

6. Conclusions and future research

For the first time, propagating Lamb-like modes in a slab of porous material with finite thickness were observed and analyzed in the audible frequency range. The phase velocities of the waves were determined and compared with simulated velocity dispersion curves for an equivalent material. The proposed method offers a new possibility to characterize poroelastic foams. We are currently attempts to improve the measurement resolution and increase the amount of time-position combinations in order to accurately obtain spectral amplitude data in the frequency-wavevector domain.

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