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Experimental evaluation of phase velocities and tortuosity in fluid saturated highly porous media

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In the current contribution, we present a novel method for the determination of the high frequency tortuosity parameter, α_∞ in high porous media. Therefore, time-domain measurements of ultrasonic signals are performed with a transmission technique. Aluminium foams with different pore fluids will be under the scope of experimental investigation. Finally, the experimental results are compared with analytical wave propagation tests.

1 Introduction

Quantification of sound and ultrasound in highly porous media, saturated with viscous fluids, is of high importance in many research areas with applications in engineering and medical technologies. In particular, Quantitative UltraSound (QUS) became of great interest with respect to osteoporosis diagnosis. In order to improve predictive diagnosis tools, physical models are required. The accuracy of such multiphase models, like Biot's poroelasticity [1], depends on various material parameters of the bulk phases but also parameters which take into account coupling phenomena between the pore fluid and the solid skeleton. One of those important coupling parameters is the tortuosity of Biot's theory, which is a geometrical and frequency-dependent quantity, cf. [1]. It accounts for the coupling of the solid and the fluid, especially in the high frequency range where inertia coupling dominates.

2 Biot's theory

Biot's theory is often used for the prediction of wave propagation in fluid saturated porous media. It assumes the propagation of one transversal (S-wave) and two compressional waves (fast and slow P-wave) [1]. The theory distinguishes between the high- and low-frequency regimes. Both ranges are divided by a critical rollover frequency ω_r. It can be calculated from the condition $\delta = r$, where δ indicates the characterising frequency-dependent viscous boundary layer of the pore fluid and r the averaged pore radius. The applicability of the theory is limited to wavelengths much longer than the pore radius ($\lambda \gg r$). In the low-frequency regime ($\delta \gg r$) the locking of the fluid and solid of the fast P-wave arises from the fluid viscosity. However, the slow wave requires a relative motion between the fluid and solid. Hence, it cannot propagate in this frequency region. By contrast, in the high-frequency region the viscous effects decreases, so that the relative motion between the fluid and solid is not impeded by viscous drags anymore. Therefore, the slow wave can propagate. The boundary conditions of the ultrasound measurements were chosen such that the experiments had taken place in the high-frequency region. Therefore, it can be assumed that the viscous effects are negligibly small, so that the time or velocity delay between the refence and sample signal is mainly caused by the tortuosity of the pore channels. In this region the P-wave velocities are frequency-independent and can be expressed by the following equations, cf. [2]:

$$c_{P,\infty} = \left(\frac{\Delta \pm [\Delta^2 - 4\,(\rho_{11}\,\rho_{22} - \rho_{12}^2)\,(P\,R - Q^2)]^{1/2}}{2\,(\rho_{11}\,\rho_{22} - \rho_{12}^2)} \right)^{1/2} \quad \text{where} \qquad \Delta = P\,\rho_{22} + R\,\rho_{11} + 2\,Q\,\rho_{12}. \tag{1}$$

P, Q and R are elastic parameters, which can be related to measurable quantities like the bulk modulus of the fluid K^F, solid K^S and the modules of the skeletal frame K and G. The terms $\rho_{11} = (1-\phi)\,\rho^{SR} - (1-\alpha_\infty)\,\phi\,\rho^{FR}$, $\rho_{22} = \alpha_\infty\,\phi\,\rho^{FR}$ and $\rho_{12} = (1-\alpha_\infty)\,\phi\,\rho^{FR}$ describe the interaction between the solid and fluid due to the inertial coupling and can be formulated with regard to the effective densities of the solid ρ^{SR} and the fluid ρ^{FR} and the tortuosity α_∞. Furthermore, equation (2) implies that only tortuosity appears as coupling parameter.

3 Experiments

For the experimental study, we have used 20 ppi AlSi7Mg-foams of different thickness and porositiy around 94 % by m.pore GmbH [3]. The specimens had an open cell structure enabling a full saturation of the foams with air or water. Two identical

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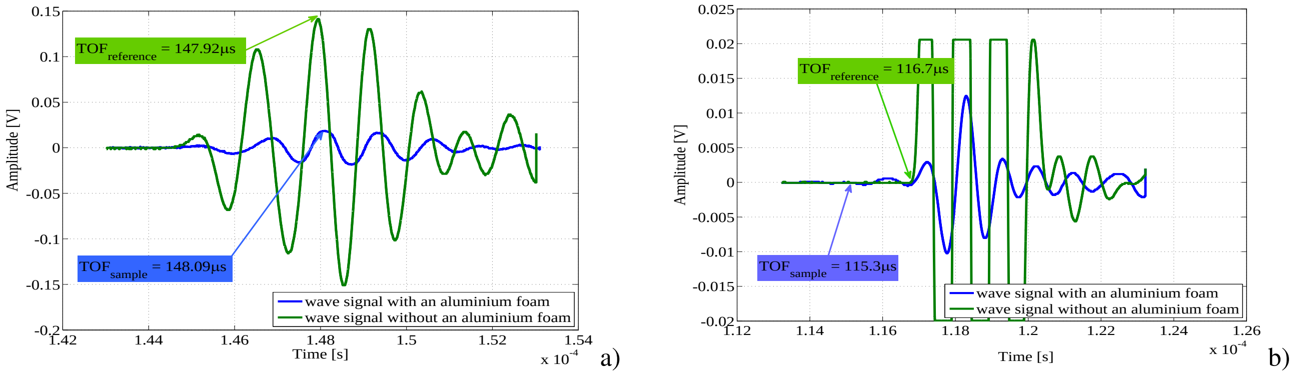

Fig. 1: Sample and reference signals of the ultrasound wave in **a)** air and **b)** water.

immersion-P-wave-transducers with central frequencies of 1 MHz were used for the ultrasound experiments. One served as a transmitter and the other as a receiver. The whole experiment was either perfomed in a water tank or under ambient air conditions. An arbitrary function generator pulsed the transmitter. The generated electrical signal was amplified up to ±400 V and in the case of air measurements the recieved signal was pre-amplified with 50 dB. The signal detected by the reciever was digitized and displayed by a digital storage oscilloscope. In order to improve the signal to noise ratio, the recorded wave signal was stored in the memory of the oscilloscope and averaged. Before each measurement the fluid temperature was determined.

4 Results and conclusion

The wave speed is measured in time domain by comparing the Time Of Flight (TOF) of the sample and reference signal. The time difference ΔTOF itself, can be expressed in frequency domain by the phase difference of both signals $\Delta\phi_\omega(\omega)$:

$$c = 1/\left(\frac{1}{c_{ref}} + \frac{\Delta TOF}{l}\right) \quad \text{with} \quad \Delta TOF = \frac{\Delta\phi_\omega(\omega)}{\omega} \tag{2}$$

l is here the thickness of porous sample and c_{ref} the sound velocity in the reference material. The time difference ΔTOF is difficult to determine in the time domain, if the ultrasound signal changes its shape after travelling through the sample. Therefore, a Fast Fourier Transformation is necessary to compute the amplitude spectras of the signals. The recorded sample waveforms (blue) and the reference signals measured in air or water are also shown (green) are pictured in Fig. 1.

In case of air-saturated aluminium foam, we could observe the slow P-wave only. Due to the high impedance contrast a total reflection of the induced ultrasound wave occurs at the interface of both constituents resulting in a wave propagation only through the pore channels. Therefore the reference signal reaches the receiver earlier than sample signal, see Fig. 1)a). Taking the amplitude maxima of the time signals as the TOFs we obtain a wave velocity of $c = 337.05$ m/s compared to a wave velocity of $c_{ref} = 338$ m/s in air.

The results achieved in water measurements clearly show that the sample signal arrives earlier at the receiver than the reference signal. Using equation (2), leads to a wave velocity of $c = 1582$ m/s ($c_{ref} = 1499$ m/s). It has not been fully investigated whether the detected sample signal is only the fast P-wave propagating through both constituents or both P-waves occuring directly one after another without a distinct time space between.

Future work will be focused on separating the possible fast and slow P-wave in time by using different pore fluids such as oils. In comparison to the air measurements the induced ultrasound wave in water causes the aluminium frame to vibrate whereas the air wave only propagates through the fluid phase. Comparing the experimental investigations with the high-frequency limit of Biot's equations, we are able to determine the tortuosity parameter of the used aluminium foam, cf. [1–3]. As we assume that the tortuosity is the only physical effect responsible for the time delay between the reference and signal, we obtain a tortuosity factor of $\alpha_\infty = 1.054$ for the aluminium foam.

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