Anelastic characterization of soft poroelastic materials by anelastography

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Abstract. This paper presents the 1D characterization of the local anelastic strain determined in soft poroelastic materials through acoustic scattering in a creep test configuration. Backscattering signals are obtained at successive times in a specimen submitted to a constant stress, applied coaxially to the acoustic beam of a 5 MHz ultrasonic transducer operated in pulse-echo mode. The local displacement is measured by determining the local shift between the RF traces by performing a running cross-correlation operation between equivalent segments extracted from two pairs of RF traces. The local strain the in the specimen is obtained as the displacement gradient.

The method has been implemented on biphasic porous materials that present poroelastic behaviors such as synthetic latex sponges impregnated with viscous liquids. The strain/time curves have been interpreted through a continuous bimodal anelastic model (CBA), composed of an infinite set of Kelvin-Voigt cells connected in series with an elastic spring. The fit of an experimental strain/time curve selected at a specific depth through the CBA model allow characterizing the local anelastic behavior through a set of 7 characteristics parameters for the specimen at this location: three short-term and three long-term anelastic parameters and one elastic constant.

1. Introduction

The elastic alterations of tissues are often associated with the apparition of pathological lesions [1] and so, palpation has long been a valuable practitioners tool for detecting such pathologies. However, the small size and depth of some lesions make the detection through hand palpation unreliable and can hinder an early diagnostic. Elastography has therefore proven highly valuable to assist the physician by offering high-resolution modulus maps of the soft tissues. Similarly to the elastic properties, it can be expected that pathological tissues would exhibit anelastic (or viscoelastic) properties alterations that can be detected by ultrasonography [2]-[4]. This work presents a characterization of soft material anelastic properties based on a creep test experiment to yield significant local viscoelastic parameters extracted from a series of successive 1-D backscattering signals.

2. Materials and Methods

Anelastography consists in generating a set of local maps of the materials viscoelastic properties through the characterization of the backscattering signal temporal evolution when submitting the specimen to a controlled mechanical stress. As the backscattering signal patterns are generated by the heterogeneities of the material, the location and movement of these heterogeneities can be monitored giving an insight to the local deformation inside the specimen.
2.1. Materials
The anelastography experiment has been implemented on synthetic latex sponges, impregnated with a liquid detergent (viscosity: 3000 mPa·s), and cut as a right rectangular prism, with a base area larger than 25 cm² and a height of at least 2 cm.

Presence of air bubbles inside the specimen would alter its poroelastic behavior and hinder the propagation of the acoustic waves. Therefore, to guarantee the total air bubbles removal, the immersed specimens are saturated in a vacuum chamber under primary vacuum for 30 minutes, allowing the air bubbles to escape from the elastic structure of the polymer matrix, and carefully returned to atmospheric pressure.

2.2. Experimental setup
The experiment consists in placing the specimen in an immersion chamber filled with the corresponding fluid, above a 5.0 MHz broadband transducer mounted on the bottom wall with its acoustical axis oriented vertically (Fig.1). The whole cell is placed in the vacuum chamber and the saturation processed performed. The assembly is then removed from the vacuum chamber and placed under the loading device, composed of a 35mm diameter acrylic disk, with mobility in the vertical direction only. The loading device is loaded with the corresponding weight and successive RF traces are acquired. The contraction of the specimen under load can be observed as a similar contraction of the RF signal, converted to distance through a constant sound velocity (1500m/s).

![Figure 1](image.png)

**Figure 1.** Experimental setup and typical backscattering signal generated by saturate synthetic sponge with a zoom of two consecutive RF traces.

2.3. Data processing
The local displacement is extracted from the RF data through a running cross–correlation between each pair of the successive traces previously normalized. Then the strain is determined by applying the gradient operator to the integrated displacement. As this process is highly noise sensitive, the displacement map is previously filtered through a moving average method.

3. Results and discussion

3.1. Homogeneous sponge
As an illustration, the anelastic behavior, produced during a 50 minutes creep test (300 gr load: \(\sigma_0 = 5.3\) kPa), is observed on a latex sponge, saturated with liquid detergent. Figure 2a presents the displacement/depth/time map. The sharp increase of the displacement during the early experiment slows down rapidly to tend toward a saturation level as expected for viscoelastic behavior. The derivative of the displacement map corresponds to the strain map (Fig.2b). The strong evolutions observed at both extremities of the depth axis are due to processing artifacts and should be disregarded. In consequence, the strain behavior shows here a fairly homogeneous strength across the specimen, with a slight hardening in the region close to the transducer.
Figure 2. Creep test in latex sponge saturated with detergent (load = 200 gr, $\sigma = 3.3 \text{kPa}$) (a) Displacement map (b) Strain Map.

Figure 3. Experimental curves (symbols) and their respective fit (continuous lines) for a creep test (load = 200 gr) of a detergent saturated latex sponge. CBA parameters: $G_{01} = 2.6 \times 10^{-7}/2.84 \times 10^{-7}/2.97 \times 10^{-7}$ for the upper/middle/lower curves resp., $\eta_{01} = 2.9 \text{kPa} \cdot \text{s}$, $\sigma_{01} = 30 \text{kPa} \cdot \text{s}$, $G_{02} = 5 \times 10^{-9}$, $\eta_{02} = 0.9 \text{MPa} \cdot \text{s}$, $\sigma_{02} = 15 \text{MPa} \cdot \text{s}$, $E_{\text{anel}} = 550 \text{ Pa}$. Insert: CBA Model with two bimodal Gaussian distribution of the viscosity coefficient.

3.2. The Anelastic Continuous Model

A continuous bimodal anelastic model (CBA) has been developed to match accurately the experimental strain/time curves. This model is based on the Standard Anelastic Rheological model and is composed of a continuous series of elemental Kelvin-Voigt (KV) cells holding a bimodal distribution of their viscosity coefficients (Fig. 3), which yields the following constitutive equation:

$$\epsilon(t) = \frac{\sigma_0}{E_{\text{elast}}} + \frac{\sigma_0}{E_{\text{anel}}} \int_0^t \left(1 - e^{-\frac{t - \tau}{\eta}}\right) G(\eta) d\eta$$

(1)
Where $\sigma_0$ is the applied tension, $E_{\text{Elast}}$ an elastic constant and 

$$G(\eta) = G_{01} e^{\frac{(\eta - \eta_{01})^2}{2\sigma_{01}}^2} + G_{02} e^{\frac{(\eta - \eta_{02})^2}{2\sigma_{02}}^2}$$

the viscosity bimodal distribution.

4. Conclusions
The anelastography method proposed here offers a reliable tool to evaluate the local anelastic behavior of soft materials under constant mechanical stress.

A continuous bimodal anelastic model has been proposed to successfully characterize the anelastic behavior of soft poroelastic materials through two main relaxation times.

It is expected that this method would be easily extended to 2D or 3D elastography and implemented to biological tissues characterization and in vivo biomedical diagnostic. In this last case, however, the duration of the experiment should be significantly reduced.

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