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Estimating the local viscoelastic properties from dispersive shear waves using time–frequency ridge analysis

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ABSTRACT

Modulated low-frequency shear waves can be non-invasively generated locally within a medium, by the oscillatory acoustic radiation force resulting from the interference of two focused quasi-CW ultrasound beams of slightly different frequencies. The propagation of such shear waves within a viscoelastic medium is known to be affected by the dispersive effects of viscosity. Specifically, a low-frequency (LF) spectral component was shown to arise with increased viscosities and higher modulation frequencies and appear as a 'slow' wave at the end of the shear waveform. In this paper, the shear dispersion characteristics are studied based on the Pseudo–Wigner–Ville distribution (PWVD) in the time–frequency domain. The ridges of the PWVD are then extracted and used to calculate the frequency-dependent shear speed, by identifying the LF dispersive component both in time and frequency. Using numerical simulations, it is shown that this way of estimating the shear dispersion is more efficient and robust than the conventional phase-delay Fourier method. Thus, more accurate estimates of the local shear modulus and viscosity of the propagating medium could be achieved. The effects of noise on the proposed method are also discussed.

1. Introduction

A wide class of elastography methods, aiming at measuring and visualizing the mechanical properties of tissue, are based on the remote generation of shear waves. In a viscoelastic medium, two focused quasi-CW ultrasound beams of slightly different frequencies can be used to non-invasively generate a localized modulated radiation force at the difference frequency [1] (see Fig. 1). In response, the excited region will give rise to low-frequency shear waves also at the modulation frequency, whose propagation characteristics can be monitored and thus, reveal quantitative information about the viscoelastic properties of the medium. Extensive research in the field of shear wave-based elastography has been dedicated in estimating the local shear speed by employing a time-of-flight approach or by tracking the shear-wave phase delay over a specific distance [2–8]. In the latter class of techniques, measurements at different frequencies can be subsequently fitted into a viscoelastic model (e.g. the Voigt model) [9,10], enabling thereby the tissue elasticity and viscosity to be extracted. However, in the majority of these works, either viscosity has been completely ignored (assumption of elastic medium) [1–3] or weak-viscosity conditions have been assumed [8], that is, the effects of dispersion have been undermined.

In [4–6], the propagation characteristics of the generated shear waves in viscoelastic media were investigated for conditions that generally conformed to FDA diagnostic safety standards. It was shown that despite their narrowband nature, these shear waves can become significantly dispersive under the effects of viscosity. Specifically, for conditions of increased viscosity, such as those reported in real biological tissues (0.5–10 Pa s) [11,12], a low-frequency (LF) spectral component arises and is pronounced for higher modulation frequencies. This LF component can be attributed to the effects of the frequency-dependent shear speed due to viscosity, which causes the lower frequencies to move much more slowly than the higher frequencies, and thus, appears as a 'slow' wave at the end of the shear waveform [Cobbold].

Methods for estimating the shear modulus and viscosity were presented in [4–7] in which, dispersion curves were estimated from the phase delay of the Fourier spectra between the received waveforms at two different locations. In [5,6], the potential of improving the corresponding estimates by using the aforementioned LF spectral component was demonstrated. Nevertheless, no indication about the temporal localization of the identified frequencies can be provided in the frequency domain, something that can result important and contribute significantly to the study of dispersive signals. Efficient methods to describe how the spectral

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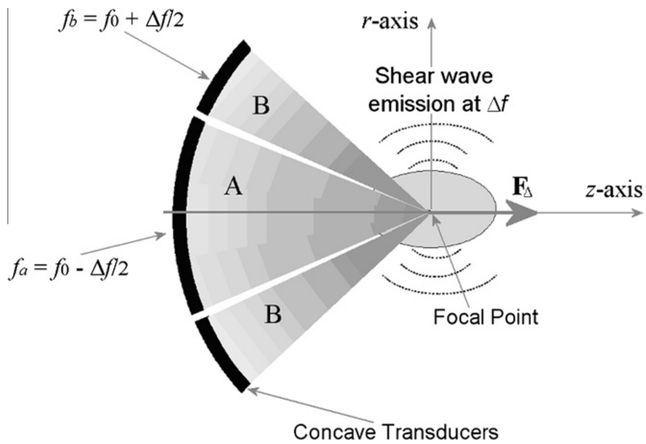

Fig. 1. Illustrating the principles of a simple confocal radiation-force imaging system used to generate modulated low-frequency shear waves.

content of a signal changes with time are by means of time–frequency (TF) representations [13], such as, the short-time Fourier transform (STFT), the Wigner–Ville distribution, the Gabor representation, the continuous wavelet transform, the Hilbert–Huang transform, etc. Such techniques have been successfully applied for the study of oceanic [14] and seismic signals [15], electrocardiogram (ECG) data [16] or ultrasonic guided waves for non-destructive-evaluation (NDE) applications [17]. To the best of our knowledge they have not been, so far, applied for the study of shear-waves in tissue-like media. However, as described previously, the dispersive and non-stationary nature of these waves makes them an appropriate candidate for such type of analysis, which from one side, will provide a better understanding of the associated frequency-dependent effects and furthermore, will provide new ways of estimating the viscoelastic properties.

In this paper, we perform a simulation study that employs a time–frequency method in order to estimate the shear dispersion and extract the local shear modulus and viscosity in viscoelastic propagating media. Specifically, the Pseudo–Wigner–Ville distribution (PWVD) will be used to study the dispersive effects of viscosity and localize both in time and frequency the appearance of the 'slow' wave, which carries most of the dispersion information. The ridges of the PWVD will be, next, detected and the frequency-dependent shear speed will be estimated by tracking the arrival times at two different locations of only those ridge points that correspond to the LF 'slow' component. The proposed PWVD ridge-based approach provides shear dispersion curves that are in better agreement with the Voigt model of viscoelasticity than by using the conventional phase-delay Fourier method. Furthermore, it is shown through numerical simulations, that it is sufficiently robust to several associated parameters (such as the location of the observation points and the presence of the coupling wave). Therefore, by studying the dispersive effects of viscosity and isolating in time and frequency the LF 'slow' wave, more accurate estimates of the local viscoelastic properties of the medium could be achieved. The effects of noise on the proposed methodology will be also discussed.

2. Theory

2.1. Generation of shear-waves by a modulated acoustic radiation force

Two intersecting CW ultrasound beams A and B are assumed, as shown in Fig. 1, with slightly different frequencies, i.e., $f_a = f_0 - \Delta f/2$ and $f_b = f_0 + \Delta f/2$. f_0 and Δf denote the center and difference (modulation) frequencies, respectively, where $\Delta f << f_0$. An infinite, isotropic, and homogeneous medium is considered with tissue-like attenuating characteristics, i.e. frequency-dependent attenuation given by $\alpha = \alpha_0 f^{\gamma}$, where α_0 is the attenuation coefficient and γ a factor that defines the power law (for real biological media $\gamma \approx 1$) [18]. In the intersection zone, a modulated acoustic radiation force at the difference frequency Δf is generated, which can be described by [4,5].

$$F_{\Delta}(0,t) = \delta(\mathbf{r}) \frac{2\alpha_0 (f_a^{\gamma} + f_b^{\gamma}) p_a(0) p_b(0)}{\rho c^2} H(t) H(D-t) \cos(2\pi \Delta f t) \quad (1)$$

where $\mathbf{r}$ denotes a point in the three-dimensional (3-D) space, c is the propagation speed, ρ is the density of the medium, $p_a(0)$, $p_b(0)$ describe the pressure amplitudes at the geometric focus of the ultrasonic beams A and B, respectively, and $H(.)$ denotes a Heaviside step function. In the above formula, the radiation force (pointing to the direction of propagation) was taken to be a spatial impulse at the origin (geometric focus) that is generated at time $t = 0$ and consists of a short cosine wave of duration D. The term *point* force hereafter, will refer to a spatial (and not a temporal) impulse. Furthermore, it has been assumed that the corresponding pressure components p_a, p_b arrive in phase at the geometric focus.

In response to the above radiation force, modulated shear waves at Δf are produced, which propagate away from the focal zone. The generated shear displacement can be described by a time convolution between the radiation force and the shear Green's function, i.e. [4,8]:

$$u_s(\mathbf{r},t) = F_{\Delta}(0,t) * G_s(\mathbf{r},t), \quad (2)$$

where $G_s(\mathbf{r},t)$ is the shear component of the viscoelastic Green's function and $\mathbf{r}$ the location of the observation point in the 3-D space. It should be also noted, that the shear term $u_s(\mathbf{r},t)$ in the above equation refers to the z-component of the corresponding displacement vector, since it is the component that contributes the most to the total displacement. Furthermore, it was shown in [5], that for conditions of high viscosity (believed to be characteristic of soft tissue [11,12]) and higher modulation frequencies, the approximate shear wave Green's function, as given in [8,19] would not accurately represent the shape and amplitude of the shear response. A more exact viscoelastic Green's function, as derived in the k-space [5], was shown to more accurately represent the low-pass and dispersive effects associated with a Voigt model of viscoelasticity, i.e.:

$$G_s(k,t) = \exp(-k^2 \eta_s t / 2\rho) \exp\left(-kt\sqrt{k^2 \eta_s^2 - 4\mu_l \rho}/2\rho\right) \quad (3)$$

where $k = 2\pi f_0 / c$ is the wave number that defines the number of wavelengths $\lambda = c/f_0$ per 2π units of distance [18] and μ_l and η_s denote the local shear modulus and viscosity, respectively. By numerically calculating the inverse spatial Fourier transform of the above equation, the required improved shear Green's function $G_s(\mathbf{r},t)$ can be obtained in the real space and subsequently, plugged into the time convolution of (2).

The propagation characteristics of the generated shear waves were investigated in [4–6], where the generation of a LF component was demonstrated under the above viscosity and frequency conditions. As will be shown in Section 3, in the time-domain, it appears as a 'slow' wave at the end of the shear waveform. Intuitively, in such dispersive signals, the associated changes of the frequency content with respect to time might be more efficiently described by an appropriate time–frequency representation, rather than the conventional Fourier transform. Such an alternative method will be explored in this paper for the study of the frequency-dependent effects caused by viscosity.