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Broadband ultrasonic spectroscopy for the characterization of viscoelastic materials

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ABSTRACT

In this study, non-destructive experimental method based on acoustic through transmission technique along with broadband spectroscopy is proposed in order to determine the linear viscoelastic material properties in 20–400 kHz range. Material properties such as phase velocity and attenuation coefficient of longitudinal and shear waves are measured. Diffraction correction developed for focused transducers is used to eliminate the spreading error due to the spherical wave generated by the hydrophone which is used as a transmitter. Method is validated on polymethyl methacrylate (PMMA). Both longitudinal wave velocity, shear wave velocity and attenuation coefficient of longitudinal wave of PMMA are in agreement with the previously reported values which are given in the literature. Attenuation coefficient of shear wave in PMMA is measured successfully and in agreement with the theoretical predictions. Longitudinal wave velocity and corresponding attenuation coefficient of gelatine gel are also measured.

1. Introduction

Determination of material properties is the most important issue of engineering science. Recent advances in material science and engineering technology requires the knowledge on frequency dependent material properties in wide range of frequencies and temperatures.

Several techniques have been developed in order to determine frequency dependent material properties of viscoelastic materials. Dynamic material analysis (DMA) is the one of the methods used in determination of temperature and frequency dependent material properties [27]. Test specimen is subjected to harmonic load of tension, compression, torsion or bending at a given frequency and temperature. Frequency and temperature dependent storage and loss modulus of the material is obtained. This methodology allows one to determine material properties up to 100 Hz. Time–temperature superposition is used in order to extend the results of DMA to a wider range of frequencies [12]. Another methodology used in determination of elastic and viscoelastic material properties is resonant ultrasound spectroscopy (RUS) [24,28]. Prism like test specimen excited between two piezoelectric transducers and frequency response of the specimen is recorded in RUS. Material parameters are determined by solving inverse problem via computer simulations. This method allows one to determine the material properties between 10 kHz and 10 MHz depending on the transducers used and specimen material. Difficulties in determination of material properties below first resonance frequency of the specimen limit RUS. Another disadvantage of RUS is experimental results are highly susceptible to user and specimen preparation. Broadband viscoelastic spectroscopy (BVS) is used to determine material properties from low frequencies to some hundreds of kHz in which specimen subjected to torsional and bending loads with frequency sweep [9]. Both DMA, RUS and BVS have been widely used for materials with relatively high stiffness. Characterization of soft matter is a challenging task due to the measurement uncertainties in these methods. Measurement uncertainties plays a critical role in characterization of soft matter [10].

Determination of material properties of soft matter is also critical due to emerging technological applications. Rheometers are used in determination of viscoelastic material properties of gels [26]. When the loss modulus of material is high, rheometers can be used up to 100 Hz. Moreover rheometers cannot be used for soft matter such as tissue or stiff materials. Atomic force microscopy is also used in characterization of soft matter [18]. Atomic force microscopy can be used up to frequencies of few hundred Hz.

There has been an interest in development of instruments or methodologies based on ultrasound due to their nondestructive nature for the characterization of tissues or soft matter in order to be used in biomedical applications or soft actuators. One common approach in determination of material properties of soft matter is to use Rayleigh wave speed [44]. In many tissues and soft matter, shear wave speeds and surface wave speeds varies

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between 1 m/s and 10 m/s [17,44] which limits the measured value of material properties to few hundred Hz. Acoustic radiation force is also used to predict the material properties of soft matter [32,33]. In this method, acoustic force is applied to an object embedded in a soft matter. From the radiated waves from the obstacle or an interface and using the theory for the interaction between two media, material properties of soft matter is predicted. In the recent years material characterization methods based on ultrasonic spectroscopy is well developed [2,10,21,23,30]. Interference of the propagating wave with the waves reflected from the environment or structural waves, which causes a loss of coherence, makes it difficult to use ultrasonic methods for material characterization at lower frequencies or in the long wavelength limit in which wave lengths are comparable with the specimen dimensions. Moreover, most of the ultrasonic transducers has central frequency of 150 kHz or higher.

Methods proposed in the literature are either for relatively rigid materials or have limited frequency range [2,10,37]. In this study, method based on acoustic through transmission technique [16,29,39] is proposed for broadband material characterization of linear viscoelastic materials with any rigidity which was first presented in [3]. Material properties are measured between 20 kHz and 400 kHz. Method is validated on PMMA. Longitudinal wave velocity and attenuation coefficient of 10% w/w gelatine gel is also measured in order to demonstrate its capability in measuring material properties of soft matter.

Paper is organized as follows. Equilibrium equation of a linear elastic material along with relations between the phase velocities, attenuation coefficients and Lamé coefficients are given in Section 2. Method used for calculating phase velocities and attenuation coefficients are drawn in Section 3. Details of experiments such as experimental setup, specimen preparation and signal processing are presented in Section 4. In Section 5, experimental results are given. Discussions on experimental results are made in Section 6 and conclusions are drawn in Section 7.

2. Theory

In this study, we assume that material is linear, homogeneous, isotropic viscoelastic material. Equilibrium equations in frequency domain can be written as:

$$\rho\omega^2\mathbf{u} + (2\mu+\lambda)\nabla\nabla\cdot\mathbf{u} - \mu\nabla\times\nabla\times\mathbf{u} = 0. \tag{1}$$

In Eq. (1), $\mathbf{u}$ is the displacement and ρ is the mass density. λ and μ are the complex Lamé coefficients. ω is the circular frequency. One can write the displacement field as $\mathbf{u} = \mathbf{u}_L + \mathbf{u}_S$ where $\mathbf{u}_L$ is the displacement induced by the longitudinal wave and $\mathbf{u}_S$ is the displacement induced by the shear wave such that $\nabla\times\mathbf{u}_L$ and $\nabla\cdot\mathbf{u}_S$ is zero. Equilibrium equations corresponding to longitudinal and shear wave can be written as:

$$\rho\omega^2\mathbf{u}_L + (2\mu+\lambda)\nabla^2\mathbf{u}_L = 0, \tag{2}$$

$$\rho\omega^2\mathbf{u}_S + \mu\nabla^2\mathbf{u}_S = 0. \tag{3}$$

From Eqs. (2) and (3), complex longitudinal wave velocity $\bar{c}_L$ can be written as:

$$\bar{c}_L = \sqrt{\frac{2\mu+\lambda}{\rho}}, \tag{4}$$

and complex shear wave velocity $\bar{c}_S$ as follows:

$$\bar{c}_S = \sqrt{\frac{\mu}{\rho}}. \tag{5}$$

In addition, one can write the complex longitudinal wave modulus and shear modulus as:

$$M = 2\mu+\lambda = \rho\left[\frac{c_L}{1+ir_L}\right]^2, \tag{6}$$

$$\mu = \rho\left[\frac{c_S}{1+ir_S}\right]^2 \tag{7}$$

where

$$r_L = \frac{\alpha_L c_L}{\omega} \tag{8}$$

and

$$r_S = \frac{\alpha_S c_S}{\omega}. \tag{9}$$

In Eqs. (8) and (9), α_L and α_S are the attenuation coefficients and c_L, c_S are the wave velocities corresponding to longitudinal and shear waves respectively and $i=\sqrt{-1}$. Following [25] and with the assumption of attenuation is due to the viscous damping, one can write following relation between wave velocities and attenuation coefficients:

$$\frac{r_s}{(1+r_S^2)^2} = \frac{r_L}{2(1+r_L^2)^2}\left(\frac{c_L}{c_S}\right)^2. \tag{10}$$

One must note that Eq. (10) is valid when $\Im m(\lambda)$ is zero [25].

3. Method

Through transmission technique is used to determine the phase velocity and attenuation coefficient [16,29,39]. This technique depends on the comparison of signals obtained with and without specimen in order to obtain the phase velocity and corresponding attenuation coefficient. Methodology of calculating attenuation coefficient and phase velocity is given below for the readers convenience. Two signals received with and without specimen are

$$A_{sp}(\omega) = A_T(\omega)A_1(\omega)T(\omega)A_s(\omega)D_s(\omega)A_2(\omega)A_R(\omega), \tag{11}$$

$$A_{wp}(\omega) = A_T(\omega)A_1(\omega)A_w(\omega)D_w(\omega)A_2(\omega)A_R(\omega). \tag{12}$$

In Eqs. (11) and (12), $A_{sp}(\omega)$ is Fourier transform of the signal in water–specimen–water path and $A_{wp}(\omega)$ is Fourier transform of the signal in water only path. $A_T(\omega)$ and $A_R(\omega)$ are the transfer functions of the transmitter and receiver respectively. $A_s(\omega)$ is the transfer function of the specimen and $A_w(\omega)$ is the transfer function of the water replaced by the specimen. $A_1(\omega)$ is the transfer function of the water between the transmitter and specimen. $A_2(\omega)$ is the transfer function of the water between the specimen and receiver. $T(\omega)$ is the transmission coefficient of the specimen. $D_s(\omega)$ and $D_w(\omega)$ are the transfer functions due to the spreading of spherical waves in path with specimen and water only path respectively. Each transfer function can be represented as $B_a(\omega) = |B_a(\omega)|e^{i\phi}$, where ϕ is the phase angle. Dividing Eq. (11) with Eq. (12), one obtains

$$A(\omega) = \frac{T(\omega)A_s(\omega)D_s(\omega)}{A_w(\omega)D_w(\omega)} = \frac{|T(\omega)||A_s(\omega)||D_s(\omega)|}{|A_w(\omega)||D_w(\omega)|}e^{i(\phi_T+\phi_s+\phi_{Ds}-\phi_w-\phi_{Dw})}. \tag{13}$$

Frequency range which is of interest of this study is 20–400 kHz. In this frequency range, wavelengths of the propagating wave in the specimen are comparable to the specimen dimensions for most of the materials. In addition, travel time of the wave package through the specimen is much larger than the travel time of the wave front through the specimen. This causes interference of the wave with itself during the transmission through the specimen.