A DUAL-MODE ULTRASONIC PROBE FOR VISCOELASTIC MATERIAL CHARACTERIZATION

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INTRODUCTION

Biological soft tissues and/or liquids could be characterized by their bulk and viscoelastic properties. Such characterization is important and useful for biomedical applications, such as pathology for instance, since tissue viscoelastic properties often change due to diseases and/or aging. An ultrasonic technique is one of the methods to determine the viscoelasticity of materials [1-4].

Several parameters such as viscosity (η), shear modulus (G), bulk modulus (K) and longitudinal modulus (M) represent material properties. These parameters can be obtained by the ultrasound reflectance method, where the reflection coefficient (R) at the boundary between a solid substrate and a sample is measured [2-4]. Ultrasonic shear wave (*SW*) and longitudinal wave (*LW*) are used to obtain the shear and the longitudinal properties, respectively.

Since a tissue is often inhomogeneous and its viscoelastic properties are temperature dependent, accurate and efficient measurement could be conducted if the shear and longitudinal properties are measured simultaneously under the same measurement conditions. Therefore, an ultrasonic probe capable of transmitting and receiving the SW and LW simultaneously designed and developed and discussed in this paper.

THEORETICAL BACKGROUND

The reflection coefficient at the substrate-sample boundary is expressed by Eq. 1, where Z and Z_{sub} are the acoustic impedances of the sample and the substrate, respectively.

$$R = \frac{Z - Z_{sub}}{Z + Z_{sub}} \,. \qquad (1)$$

Experimentally, R is determined by comparing the amplitude and phase of the ultrasound signals reflected from the solid substrate attached to the sample (V_r), as shown in Fig.1 (b), and with those exposed to air ($V_{r\text{-}ref}$), as shown in Fig.1 (a). Therefore, R is given by:

$$R = \frac{V_r}{-V_{r\_ref}} = -\frac{A_r}{A_{r\_ref}} e^{j(\phi_r - \phi_{r\_ref})} = -re^{j\Delta\phi} \qquad (2)$$

$$r = \frac{A_r}{A_{r\_ref}} \qquad (3)$$

$$\Delta\phi = \angle R = \phi_r - \phi_{r\_ref} \,, \qquad (4)$$

where A_r and ϕ_r are the amplitude and phase of V_r, respectively, the subscript *ref* represents the reference signals with air, and r and $\Delta\phi$ are the amplitude ratio and phase shift, respectively, between the sample and reference signals.

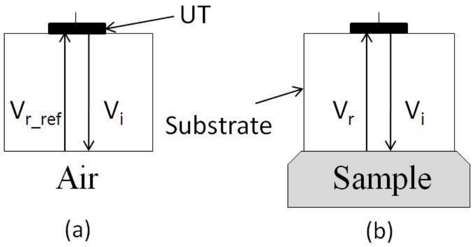

Figure 1: Ultrasound reflectance method. (a) Reference signal measured with air, and (b) signal measured with sample.

Shear property

A Voigt model is selected to represent the viscoelastic sample [5] to calculate the shear properties from the shear reflection coefficients. The complex shear modulus (G^*) and acoustic impedance ($Z_s{}^*$) of the viscoelastic material are given by Eqs. (5) and (6), respectively, where ω is the ultrasound angular frequency; G, η and ρ are the shear modulus, viscosity and density of the sample, respectively; and R_S and X_S are the real and imaginary part of Z_S*, respectively [3].

$$G^* = G + j\omega\eta \tag{5}$$

$$Z_S{}^* = \sqrt{\rho G^*} = \sqrt{\rho(G + j\omega\eta)} = R_S + jX_S \ . \tag{6}$$

From Eqs. (1) to (6), Z_S* is obtained by Eq. (7), where the subscript S represents the parameters associated with the SW.

$$Z_S{}^* = \frac{[1 - r_s e^{j(\Delta\phi_S)}]Z_{S\_sub}}{1 + r_s e^{j(\Delta\phi_S)}} \ . \tag{7}$$

Therefore, R_S and X_S can be obtained by the measurement of the amplitude (r_s) and phase ($\Delta\phi_s$) of the complex reflection coefficient with the known shear impedance ($Z_{S\text{-}sub}$) of the substrate. Finally, G and η can be calculated using Eqs. (8) and (9), respectively, with the known ω and ρ.

$$G = \frac{R_S{}^2 - X_S{}^2}{\rho} \tag{8}$$

$$\eta = \frac{2R_S X_S}{\rho\omega} \ . \tag{9}$$

Longitudinal property

Since the longitudinal acoustic impedance of the sample (Z_L) is assumed a real quantity, the longitudinal modulus is obtained by:

$$M = \frac{[(1 + r_L)Z_{L\_sub}]^2}{\rho(1 - r_L)^2} \ , \tag{10}$$

where $Z_{L\text{-}sub}$ is the longitudinal acoustic impedance of the substrate and the subscript L represents the parameters associated with the LW. There is a relationship among K, M and G, as follows:

$$M = K + \frac{4}{3}G \ . \tag{11}$$

PROBE DESIGN

Substrate selection

In terms of the measurement procedure of the ultrasound reflectance method, shown in Fig.1, the higher sensitivity could be expected in the measurements of r and $\Delta\phi$ if the amplitude and phase of V_r have a larger difference between the air and sample. From Eq. (1), R depends on the acoustic impedance of the substrate material employed. In order to select a suitable substrate material, which could achieve higher measurement sensitivity, the numerical calculations of the reflection coefficients are conducted with different substrate materials.

The sample parameters used for the calculations was silicone oil. We assume that it was a pure viscous (Newtonian) fluid, where its G equals zero. The parameters of the silicone oil are: η=1000 cSt and ρ=972 kg/m^3 [6]. The LW and SW acoustic impedances of typical substrate materials are given in Table 1, where they are assumed to be a real quantity.

Table 1: Acoustic impedances of substrate materials [6], [7].

Substrate material	**Acoustic impedance (kg/m^{2}s)**	
	LW	**SW**
Plexiglas	3.26 x 10^6	1.33 x 10^6
Polyetherether-ketone (PEEK)	3.29 x 10^6	1.45 x 10^6
Fused Silica	1.26 x 10^7	8.25 x 10^6
Aluminum	1.73 x 10^7	8.21 x 10^6
Stainless Steel	4.57 x 10^7	2.45 x 10^7

The calculated results of r_s and $\Delta\phi_s$ for the SW with respect to the ultrasound frequency are shown in Figs. 2 (a) and (b), respectively, with different substrates. It can be seen that both r_s and $\Delta\phi_s$ decrease monotonically as the frequency increases. This means that the higher measurement sensitivity could be realized at the higher frequency. In addition, among the substrates considered here, the substrates having lower acoustic impedance, such as Plexiglas and PEEK, would have better sensitivity than the metallic substrates because of the better impedance matching between the substrate and sample.

Figs. 3 (a) and (b) shows the calculated results of r_s and $\Delta\phi_s$, respectively, with respect to the sample viscosity at 2 MHz with different substrates. The figure shows that r_s and $\Delta\phi_s$ decrease monotonically as the sample viscosity increases in the range from 0 to 10,000 cSt. The substrate with lower acoustic impedance has better sensitivity because of the better impedance matching to the sample.

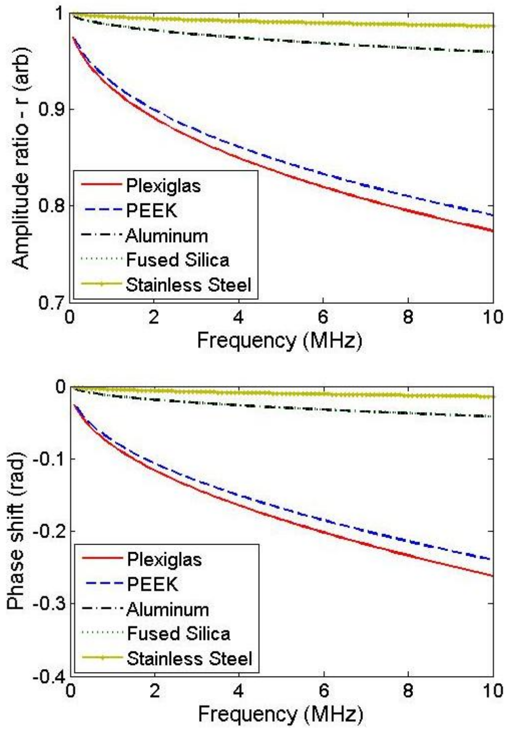

Figure 2: Calculated reflection coefficients: (a) r_S and (b) $\Delta\phi_S$ with respect to ultrasound frequency.

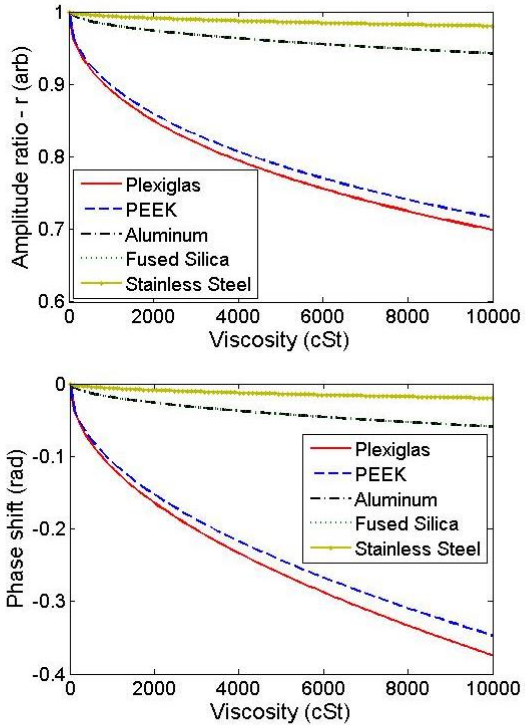

Figure 3: Calculated reflection coefficients: (a) r_S and (b) $\Delta\phi_S$ with respect to sample viscosity.

Probe configuration

Based on the substrate selection discussed above, Plexiglas was selected as the substrate material. A mode conversion technique was used to produce the SW. Fig. 4 shows a schematic view of a proposed SW and LW probe, composed of a LW ultrasonic transducer (UT) and a Plexiglas substrate having a mode conversion angle.

In Fig. 4, the UT transmitted the LW into the substrate. The transmitted LW was reflected toward the probing end at the two tilted faces. The upper part of the LW was reflected at the face with a tilting angle of 63.2° where the LW was converted into the SW, while the lower part of the LW was reflected as the LW at the 45° tilting face. The mode conversion angle of 63.2° was determined according to [8]. Furthermore, the dimensions of the substrate were determined in such a way that the LW and SW signals, reflected at the probing end and received by the UT, were not overlapped in the time domain.

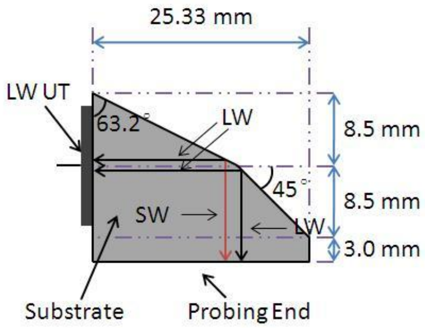

Figure 4: Design of ultrasonic probe.

PROBE FABRICATION

Plexiglas substrate was machined according to the design discussed above. A lead zirconate titanate (PZT)/PZT composite film LW UT [9] was attached onto the substrate using an epoxy resin. The fabricated probe is shown in Fig. 5. Fig. 6 shows the experimental results obtained with a pulse-echo technique. The first roundtrip signals of the LW and SW appear clearly at 20.8 μs and 28.8 μs, respectively. The second roundtrip signals are not observed because of the high attenuation of the Plexiglas substrate.

Fig. 7 presents the frequency spectra of the SW and LW signals in Fig. 6. The center frequency and bandwidth of the SW signal are

1.5 MHz and 2MHz (133%), respectively, and those of the LW signal are 2.4 MHz and 3.3 MHz (138%), respectively. The center frequency of the SW is 0.9 MHz lower than that of the LW due to the higher attenuation of the SW than LW in the Plexiglas substrate. It is verified that the probe developed has a broad bandwidth suitable for the pulse-echo measurement.

SUMMARY

The ultrasonic probe developed has a broad bandwidth applicable for the pulse-echo measurement. This probe could be used to characterize viscoelastic materials, by measuring their shear and longitudinal properties simultaneously.

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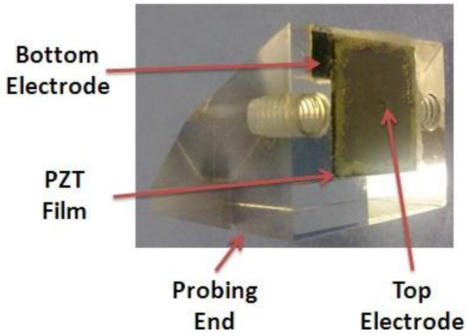

Figure 5: A photograph of the probe developed.

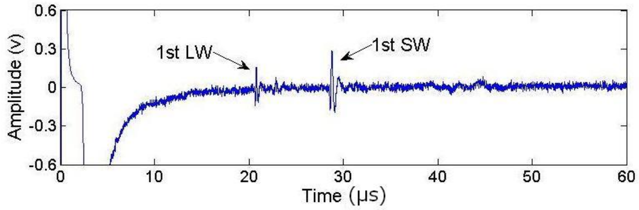

Figure 6: LW and SW signals reflected from the probing end with air.

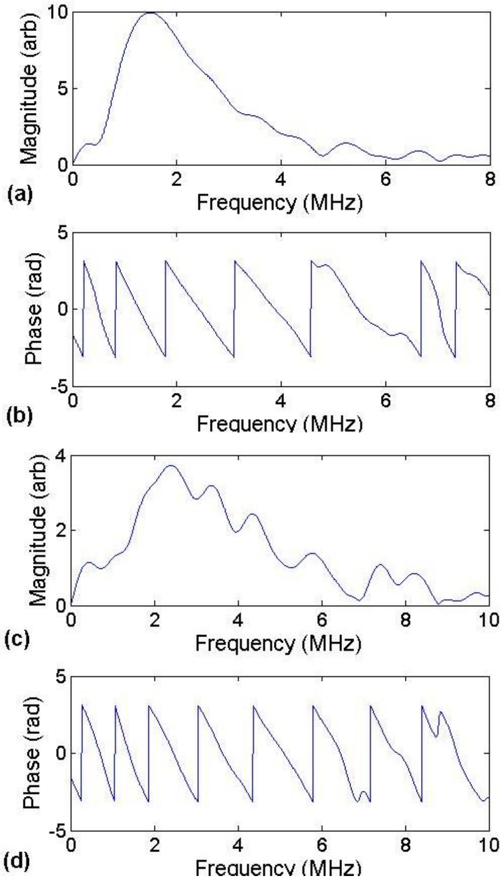

Figure 7: Frequency spectra: (a) magnitude and (b) phase of SW, (c) magnitude and (d) phase of LW.