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Fourier Transform Ultrasound Spectroscopy for the determination of wave propagation parameters

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A R T I C L E I N F O

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A B S T R A C T

The reported results for ultrasonic wave attenuation constant (α) in pure water show noticeable inconsistency in magnitude. A “Propagating-Wave” model analysis of the most popular pulse-echo technique indicates that this is a consequence of the inherent wave propagation characteristics in a bounded medium. In the present work Fourier Transform Ultrasound Spectroscopy (FTUS) is adopted to determine ultrasonic wave propagation parameters, the wave number (k) and attenuation constant (α) at 1 MHz frequency in tri-distilled water at room temperature (25 °C). Pulse-echo signals obtained under same experimental conditions regarding the exciting input signal and reflecting boundary wall of the water container for various lengths of water columns are captured. The Fast Fourier Transform (FFT) components of the echo signals are taken to compute k, α and r, the reflection constant at the boundary, using Oak Ridge and Oxford method. The results are compared with existing literature values.

1. Introduction

Pulse-echo method is the standard method widely used for measuring the velocity (v) and attenuation constant (α) of ultrasonic waves for characterizing solid and liquid samples including biological systems. In a recent work [1], it has been reported that, this method is not reliable for accurate measurement of intrinsic attenuation constant α. In fact, a common experience of experimentalists working with attenuation measurement in solid and liquid samples is that, it is very difficult to obtain reproducible results for α. An elaborative illustration in this point is the work by Martinez et al. [2] on pure water where both pulse-echo and through-transmission methods are used to measure α. It is observed that at relatively small distances from the transducer, α varies widely, while at large distances it is possible to obtain an average value of α. Moreover, the values of α obtained from pulse-echo and through transmission methods differ significantly and do not agree with any of the other values reported in the literature [3–6]. A comparison of the literature values, showing the wide variation is available in ref. [1]. The propagating-wave analysis of pulse-echo method [1] gives a satisfactory explanation for the variation. It shows that the echo amplitudes depend on α, the reflection coefficient r at the boundaries and the sample length l in a complicated way. As a consequence, the attenuation measured from the echo heights is an effective attenuation α_e, different from the intrinsic attenuation α of the propagating medium. The dependence of α_e on r was reported [7] in solid samples where the effect is more prominent due to the presence of the couplant used for bonding the transducer to the sample. We show that the intrinsic attenuation α along with r can be computed from the frequency spectrum of the pulse-echo signal using Oak Ridge and Oxford parameter fitting method [8]. This method has been used to determine α in tri-distilled water at room temperature (25 °C) at the transducer frequency 1 MHz. The experimental method is described in Section 2, Section 3 presents the results and discussion and Section 4 gives the conclusion.

2. Experimental procedure and analysis

Ultran HE900 rf burst generator is used to generate the input exciting signal. The carrier frequency (f) of the rf pulse is 1 MHz, pulse width is ~3 μs, pulse repetition time is ~100 ms, peak-to-peak height of the pulse is ~250 V. This carrier frequency pulse train may be considered as the superposition of a large number of continuous waves with frequencies and amplitudes determined by its Fourier components [9]. According to the “propagating wave” model description, a limited number of these components, having frequencies within the bandwidth of the transducer loaded with the sample, will be converted to mechanical waves by the transducer and propagate through the medium under investigation [10,11]. For the present experiment with tri-distilled water at room temperature maintained at 25 °C, water is taken in cylindrical

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containers of same inner diameter of 3.4 cm and of different lengths (l). A circular reflector plate of diameter same as the inner diameter of the liquid cell with plane surface is kept at the bottom to reflect ultrasonic wave so that reflection coefficient (r) remains same at each measurement. The distance (l) from the transducer face to the reflector plate is measured using slide calipers. A single transducer mounted in a circular casing with diameter 2.95 cm is tightly fitted on the top of the cell using Teflon holder such that the vibrating transducer face remains well within the liquid with the face parallel to the bottom reflector surface. The diameter of the vibrating face of the 1 MHz transducer is 1.6 cm. In the operating condition, d and l are large compared to the wavelength of the ultrasonic wave ensuring plane wave propagation inside the liquid cell. The component waves of the input signal lying within the bandwidth of loaded transducer will suffer successive multiple reflections at the water-reflector interface at the bottom of the container and water-transducer interface at the transducer end which are kept parallel to each other. At each reflection, the amplitude of the wave will be modified by a factor r with associated phase reversal since in this particular case the reflection is from the boundary of higher mechanical impedance. All of these reflected waves will superpose inside the sample and in the steady state the displacement wave at any position x at time t may be written as [1],

$$U(x,t) = \sum_{\omega} A_{\omega} e^{i\omega t} \tag{1}$$

The summation is over all the relevant frequency components. The wave amplitude A_{ω} is given by,

$$A_{\omega} = \frac{a\left[e^{-ik'x} - re^{-ik'(2l-x)}\right]}{1 - rr'e^{-2ik'l}} \tag{2}$$

Here, a is the amplitude of the component wave of frequency ω at source point, k is the propagation constant (=2πf/v), r is the reflection co-efficient at water-reflector interface, r' is the reflection co-efficient at water-transducer interface, $k' = k - i\alpha$ and x is the position measured from the transducer face. For simplicity, we take $r = r'$. In the present experiment, since a single transducer is used as the transmitter as well as the receiver, the response observed in the oscilloscope will be proportional to the wave displacement at x = 0, i.e. $U(0,t)$.

The echo trains for n different sample lengths, $l_1, l_2, \ldots, l_n$, are captured using digital oscilloscope DL 1640 and stored in PC for further analysis. From the average separation Δt between successive echoes, ultrasound velocity v is determined ($v = 2l_n/\Delta t$) and k is calculated. From exponential fitting of the echo heights, effective attenuation α_e is determined. To get the intrinsic attenuation constant α the following procedure is adopted. The Fast Fourier Transform (FFT) of the echo trains obtained for n lengths are determined. For each frequency component, n wave amplitudes are obtained for n different sample lengths. Oak Ridge and Oxford method for parameter fitting [8] is used to fit these n amplitudes according to relation (2) by adjusting the parameters k, r, α and a. The computational method requires input guess values for k, r, α and a. Input k is obtained from experimentally measured v, input α is the lowest value of α_e obtained for large l, input r is calculated using the relation $r = (\rho_1 v_1 - \rho_2 v_2)/(\rho_1 v_1 + \rho_2 v_2)$, ρ being the density, with suffixes 1 and 2 designating the reflector material and water respectively, and input a is chosen arbitrarily. The experiment is repeated using steel, copper, brass, lead and glass reflectors.

3. Results and discussion

The velocities (v) and effective attenuation constants (α_e) are determined for various lengths (l) of water columns in pulse-echo experiment with five different reflecting surfaces. The values for v are close to each other within experimental error. Average v is determined to be 1.4775×10^5 cm sec^{-1}. Fig. 1 shows the dependence of α_e on l for glass reflector. We see that attenuation values are widely different particularly for small values of l. Similar variation in the attenuation constant has been reported by Martinez and co-workers [2]. Their work shows clearly that at short distances from the transmitting transducer, the attenuation values measured in pulse-echo method show wide variation. At long distances however, the results are consistent and it is possible to get an average value of 0.04417 np/cm for the attenuation constant though it is not in agreement with other reported values [3–6]. Their measurement in through-transmission method uses two transducers aligned face-to-face, parallel to each other. By this the water medium in between behaves effectively like a bounded medium as in pulse-echo method and no better solution is obtained. The attenuation value obtained in this method is 0.04654 np/cm.

Measurements with other four reflectors, viz., steel, copper, brass and lead show similar nature of variation of α_e with l and this is illustrated in Fig. 2. No significant difference is noticed due to the

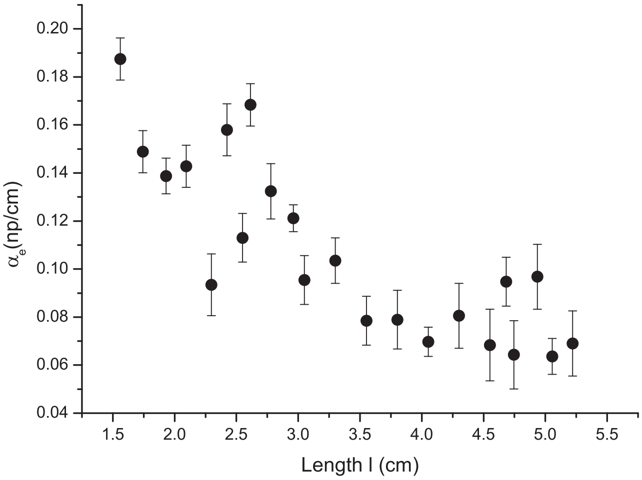

Fig. 1. Variation of effective attenuation α_e with length l of water column using glass reflector.

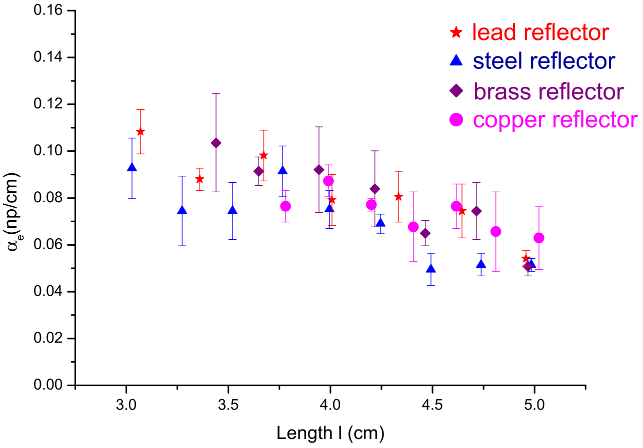

Fig. 2. Variation of effective attenuation α_e with length l of water column for lead, steel, brass and copper reflector.