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Characterization of mechanical properties of materials using ultrasound broadband spectroscopy

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ABSTRACT

This article explores the characterization of homogenous materials (metals, alloys, glass and polymers) by a simple broadband ultrasonic interrogation method. The novelty lies in the use of ultrasound in a continuous way with very low input power (0 dBm or less) and analysis of the transmitted acoustic wave spectrum for material property characterization like speed of sound, density and dimensions of a material. Measurements were conducted on various thicknesses of samples immersed in liquid where continuous-wave, frequency swept ultrasonic energy was incident normal to the sample surface. The electro-acoustic transmission response is analyzed in the frequency domain with respect to a specifically constructed multi-layered analytical model. From the acoustic signature of the sample materials, material properties such as speed of sound and acoustic impedance can be calculated with experimentally derived values found to be in general agreement with the literature and with pulse-echo technique establishing the basis for a non-contact and non-destructive technique for material characterization. Further, by looking at the frequency spacing of the peaks of water when the sample is immersed, the thickness of the sample can be calculated independently from the acoustic response. This technique can prove to be an effective non-contact, non-destructive and fast material characterization technique for a wide variety of materials.

1. Introduction

Precise non-destructive quantification of the mechanical properties of solid samples (including dimensional and morphological information) is of interest for both fundamental studies to establish accurate values of material constants and in various applications involving sample identification and quantifying sample quality. Though there are many techniques available to establish dimensional and/or morphological information across various length scales, extraction of fundamental material constants (e.g. elastic moduli and density), often is relatively tedious and complex in terms of sample preparation, measurement methods and data analysis. Furthermore, many of the existing methods are not fundamentally scalable or are significantly limited by practical constraints for sample dimensions below a few millimeters.

Among the various approaches for materials characterization currently pursued, acoustic techniques provide some of the most accurate methods for extracting fundamental material constants through non-destructive means. Pulse-echo ultrasonic methods are commonly pursued to determine the speed of sound in solids, where a single short pulse of high frequency is incident normal to the surface and a time-of-flight record of the reflected ultrasonic wave from the solid is analyzed to estimate speed of sound given the distance traveled in the round trip. Various methods for velocity measurement using pulse-echo methods have been previously described in a number of reviews including Truell et al. [1]. However, pulse-echo techniques require good transducer-to-sample coupling and the signal-to-noise ratio (SNR) can be limited by inaccuracies in phase measurements, particularly in dispersive and attenuating media [2]. On the other hand, other methods based on continuous wave systems such as resonance methods and composite oscillators have also been employed [1]. Continuous wave techniques that rely on the measurement of resonance frequencies [3] (rather than signal amplitudes and/or phase) are not limited by the same practical issues outlined above for pulse-echo measurements. The resonance frequency of the lowest mode is related to the path length and the phase velocity of the continuous wave corresponding to the standing wave field [1]. Characterization of macroscopic solid or liquid samples is usually conducted using ultrasound transducers operating in the audio frequency or low

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hundreds of kHz regime [1]. Techniques such as a resonant ultrasound spectroscopy (RUS) [4] interrogate the sample at higher frequencies but are limited by constraints on extensive sample preparation and sample alignment, as well as on data analysis and interpretation.

In this paper, we propose the use of continuous wave methods at higher frequencies (several MHz) with a view toward ultimately enabling a miniaturized version of the device. Samples are characterized in a non-contact mode wherein the sample is immersed in a liquid-filled chamber and held between two high frequency broadband ultrasound transducers. The measured transmission response is then interpreted using a multi-layered transmission-matrix (T-matrix) based analytical model to obtain estimates on parameters such as the speed of sound, acoustic impedance and sample thickness. In the simplest format, this analytical model considers one-dimensional wave propagation through at each interface taking into account the material properties in the various media. An excellent agreement has been obtained for experiments conducted on thin homogenous plate samples corresponding to different materials. This paper also discusses some of the scaling considerations involved in the construction of a miniaturized portable format for this setup enabled by micro-fabrication technology with potential application to the characterization of micron-scale samples in microfluidic devices [5].

2. Theoretical model

2.1. Acoustic wave propagation – analytical basis

The simplest model for such a device is developed by considering propagation of acoustic waves through 3 layered media. In this model, two identical layers are separated by a homogenous sample medium of uniform thickness L. Acoustic plane waves are assumed to be normally incident on the layers with no reflections following the interface between the second and third media. In this analysis, we assume negligible losses at the piezoelectric–liquid interface and minimal scattering of ultrasound; viscosity in the media has also been ignored. The schematic representation of the model is shown in Fig. 1(a). The incident, reflected and transmitted waves across each interface are shown under steady-state. The incident wave has a mono-frequency carrier and by applying the continuity of normal specific acoustic impedances, the transmission coefficient can be derived [6,7].

Fig. 1 (b) shows a typical transmission response in schematic for a 3 layer system for one peak. The parameters are defined as shown in the figure. The peak frequency at the highest transmission is defined as f_{peak}. The half of the bandwidth at 50% pressure transmission coefficient is defined as Δf.

The density of the material is defined by ρ. The bulk speed of sound is defined as c (Eq. (1)), the bulk moduli is given by K and the shear moduli is given by G. The acoustic impedance of the material Z (Eq. (2)) is obtained from the density and the speed of sound in the material. k_m, also known as wave number, is a complex quantity with real part defined as the ratio of angular frequency to the speed of sound in the medium m-and imaginary part expressed by the acoustic attenuation factor α_m (Eq. (3)). For water the attenuation is taken as 25×10^{-15} Np s^2/m [6].

$$c^2 = \frac{K + 4/3G}{\rho} \tag{1}$$

$$Z = \rho * c \tag{2}$$

$$k_m = \frac{\omega}{c_m} - j\alpha_m \tag{3}$$

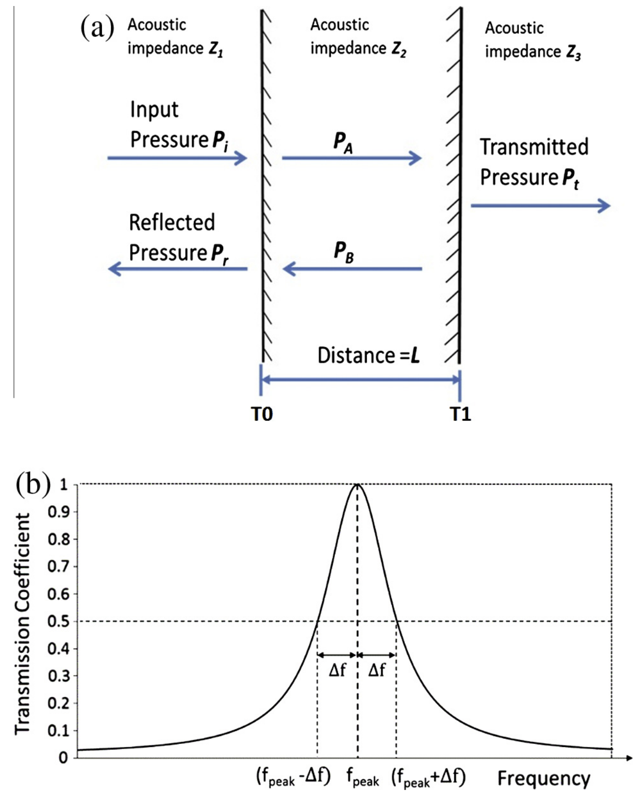

Fig. 1. (a) Schematic model for sound wave propagation in 3 layered media with boundaries as $T0$ and $T1$. (b) Typical transmission response for a 3 layer model with definition of parameters.

By applying the following boundary conditions at each interface – (i) conservation of acoustic pressure and (ii) conservation of normal component of particle velocity – on both sides of the boundary – we can solve the system of sinusoidal incident, reflected and transmitted wave equations. In this way the pressure transmission coefficient T_p can be expressed as in Eq. (4) when the 1st and 3rd media are assumed to have the same acoustic impedance Z_{ref}. Z is the acoustic impedance for the second sample media that is sandwiched between the transmitting and receiving layers [6,7].

$$T_p = \frac{2 * Z * Z_{ref}}{2 * (Z_{ref} * Z) * \cos(kL) + i(Z_{ref}^2 + Z^2) * \sin(kL)} \tag{4}$$

A MATLAB 4.3a® model can now be constructed with material property values chosen from Table 1. For example, for a PZT–Water–PZT system, with the width of water channel

Table 1
Material properties used in models.

Material	Material properties			Reference
	Density ρ (kg/m^3)	Speed of sound c (m/s)	Characteristic impedance Z (MRayl)	
Water	998	1481	1.47	[6]
Brass, Naval	8860	4430	37.3	[10–12]
Cu	8960	4660	41.61	[9–11]
Al	2700	6320	17	[6,9–12]
Perspex	1410	2730	3.85	[9,10]
Phosphor bronze	8900	3530	31.4	[12]
PZT5H	8550	4000	34.2	[11]