Wave Speed Propagation Measurements on Highly Attenuative Heated Materials

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Abstract

Ultrasonic wave propagation decreases as a material is heated. Two factors that can characterize material properties are changes in wave speed and energy loss from interactions within the media. Relatively small variations in velocity and attenuation can detect significant differences in microstructures. This paper discusses an overview of experimental techniques that document the changes within a highly attenuative material as it is either being heated or cooled from 25°C to 90°C. The experimental set-up utilizes ultrasonic probes in a through-transmission configuration. The waveforms are recorded and analyzed during thermal experiments. To complement the ultrasonic data, a Discontinuous-Galerkin Model (DGM) was also created which uses unstructured meshes and documents how waves travel in these anisotropic media. This numerical method solves particle motion travel using partial differential equations and outputs a wave trace per unit time. Both experimental and analytical data are compared and presented.

1. Introduction

Ultrasonic through transmission coupled with analytical analysis is a promising method for monitoring the ultrasonic wave velocity as a material’s internal temperature increases or decreases. Research has documented that wave speed is highly sensitive to thermal changes within a material [1, 2]. One advantage of using ultrasonic techniques is its ability to provide a non-invasive method of collecting quantitative data for the material properties as it undergoes either heating or cooling. A second advantage is it can be correlated to conventional thermocouple data. The principle of measuring material properties by ultrasound is based on the dependence of the ultrasonic wave velocity with density. For a general orthotropic material, the relationship between ultrasonic phase velocity and the
stiffness matrix is given by the Christoffel equation [3]. For the case of a transversely isotropic material, the 6 X 6 stiffness matrix can be expressed in terms of five independent elastic constants. In orthotropic materials, the directional dependence of the elastic properties of these materials manifests directional dependencies of wave speeds and even particle displacements. There are three types of wave speeds that can be found in isotropic materials (longitudinal, shear and surface). These wave speeds need to be redefined for anisotropic [4 – 6]. One example is the term quasi-shear. This wave has particle motion not purely perpendicular to the wave propagation direction. The velocity measurement in anisotropic media will vary with the symmetry properties of the medium. The fundamental elastodynamic wave equation can then be written as:

\[
\rho \frac{\partial^2 u_i}{\partial t^2} - C_{ijkl} \frac{\partial^2 u_k}{\partial x_j \partial x_l} = 0
\]  

(1)

where: \(C_{ijkl}\) is the general tensor of elastic constants, \(u_i\) and \(u_k\) are the displacement vectors, \(x_j\); \(x_l\) are orthogonal directions, \(\rho\) is the density, and \(l\) is the direction of wave propagation.

2. Experimental Setup and Results

Ultrasonic transducers were placed in a through transmission configuration on four highly attenuative materials: wax-sugar mixture, modeling clay, modeling clay-sand mixture, and wax. A B-scan curve was generated from the recorded waveforms as thermal energy was applied to the material. Ultrasonic probes operating between 50 KHz to 1 MHz were placed on top of a glass container of wax-sugar mixture. Ultrasonic data was collected using the equipment below (Figure 1). A mixture of probes operating at 100 KHz and 180 KHz produced consistent signals through the clay. The measured sound velocity in clay is 0.156 cm/μsec. The clay-sand mixture produced a consistent signal at an operating frequency of 100 KHz. The measured sound velocity of clay-sand mixture is 1.32 cm/μsec. A clay-sand mixture was heated to 90 °C and poured into a fixture (Figure 2a). Two cut-outs held the ultrasonic probes stationary and allowed ultrasonic measurements to be collected as the mixture cooled. Sound propagation data was not captured until 40 °C. As the material cooled (Figure 2b) from 38 °C (green) to 35 °C (red) the signal voltage (wave amplitude) increased by 1.1 volts; the time delay moved closer by 37 μseconds and acoustic velocity increased by 0.33 mm/μsec.

A steel can was filled with a combination of wax and sugar. The sugar settled to the bottom and the wax stayed near the top of the first pour. As the second pour was added, it melted some of the first pour and mixed the layers together in the center of the can. This mixture was less attenuative than the clay-sand mixtures so higher frequency probes (500 KHz and 1.0 MHz) could be used. The measured sound velocity for wax-sugar mixture is 0.218 cm/μsec. In the final experiment, we performed ultrasonic measurements with a 3.8 liter steel bucket of high attenuative wax in an oven. The temperature chamber was set to 90 °C (Figure 3a). Once the wax was completely melted, the chamber was turned off and the wax was allowed to solidify. During the entire experiment, ultrasonic data and thermocouple data were collected. Figure 3b displays the ultrasonic velocity versus wax temperature. The figure shows the maximum ultrasonic signal within the gate (microseconds). Signal variation is due to temperature changes (heating and cooling). As expected, the temperature slowly rises and the ultrasonic signal increases from baseline noise to a detectable signal (velocity - blue). The signal also shifts further in time. As the wax continues to melt from the outside the un-melted wax shifts and causes unstable velocity readings (velocity- red). Once the wax is completely melted, the signals become more consistent. Ultrasonic velocity measurements were lost when the wax cooled and pulled away from the steel bucket (velocity – blue).

Figure 1. Data collection system with ultrasonic probes placed on a sugar-wax sample.
3. Development of Analytical Discontinuous Galerkin Model

Discontinuous-Galerkin (DG) methods have been employed on a variety of complex problems from linear acoustics to fully chemical-reacting compressible flows. It is well suited to solving hyperbolic equations on unstructured meshes at arbitrary high order, where 8th to 14th order solutions are commonplace. Additionally DG methods can easily use spatially varying polynomial-order presentations across elements and can incorporate non-conformal meshes to reduce the computational costs. Although DG methods can be applied to both spatial and temporal dimensions, most researchers primarily utilize the discontinuous solutions in space [7 - 8]. High-order discontinuous Galerkin Runge-Kutta methods allow for inhomogeneous material variations within each element that can represent wave propagation in a variety of materials, including orthorhombic and attenuative media. Second-order effects such as attenuation strongly affect the wave propagation by scattering and absorbing wave energy, and are successfully being incorporated into models using the three-dimensional stress-velocity equations [9 - 10].

To successfully model attenuation, the complex mechanisms that cause amplitude decay and dispersion (e.g., viscous porous effects, wave scattering, and material grain friction) must be incorporated into the simulation. Often the Generalized Maxwell Body (GMB) model (a spring and dashpot model) is used to simulate the effects of attenuation for time-domain computations. Both the wave amplitude and phase contain important information about the material properties, e.g., the molecular-grain structure and anisotropic parameters. Figures 4a and 4b display the model and mesh creation and the acoustic wave pattern in the wax bucket placed into the temperature chamber. Figure 4c displays the ultrasonic wave trace versus the generated DG model signal for the wax bucket experiment.
4. Conclusions

The through transmission experimental results show the distortion experienced by the ultrasonic stress wave in highly attenuative materials. The materials are dispersive in nature and have a varying group velocity as the internal temperature changes. The results also found that the wave contains frequency components only within the bandwidth of the carrier frequency. All higher frequencies are attenuated. If the liquid to solid interface is of the same order of the magnitude as the wavelength, the sound will scatter from the surfaces due to diffraction effects. Wax-sugar mixture is less attenuative than the clay-sand mixture. Higher frequency probes can be used to interrogate the full thickness. The material characteristics will vary with the pouring technique. Large voids or planar cracks near the probe will not allow the sound to travel through the full thickness of the material. Velocity and attenuation values are averages over the field depth. The experimental and analytical waveforms have the same wave structure (phase and amplitude). The code still contains a high frequency component superimposed on the ultrasonic signal. Code development will continue until the signal inversion matches the experimental data.

Full waveform acoustic inversion is a flexible numerical method that can accurately handle strong inhomogeneities in highly attenuative dispersive materials. The partial differential equations governing acoustic wave propagation scatter and attenuation properties must be written in a conservation form to allow arbitrary variation within each element.

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