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Research paper

A program to calculate pulse transmission responses through transversely isotropic media

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ABSTRACT

We provide a program (AOTI2D) to model responses of ultrasonic pulse transmission measurements through arbitrarily oriented transversely isotropic rocks. The program is built with the distributed point source method that treats the transducers as a series of point sources. The response of each point source is calculated according to the ray-tracing theory of elastic plane waves. The program could offer basic wave parameters including phase and group velocities, polarization, anisotropic reflection coefficients and directivity patterns, and model the wave fields, static wave beam, and the observed signals for pulse transmission measurements considering the material's elastic stiffnesses and orientations, sample dimensions, and the size and positions of the transmitters and the receivers. The program could be applied to exhibit the ultrasonic beam behaviors in anisotropic media, such as the skew and diffraction of ultrasonic beams, and analyze its effect on pulse transmission measurements. The program would be a useful tool to help design the experimental configuration and interpret the results of ultrasonic pulse transmission measurements through either isotropic or transversely isotropic rock samples.

1. Introduction

Pulse transmission techniques have been used since the first half of the last century to study the high-frequency mechanical properties of materials for applications in a wide assortment of disciplines. In Geophysics, these techniques were adopted early by a number of researchers (Hughes and Cross, 1951; Hughes and Kelly, 1952; and Wyllie et al., 1956) becoming popular and leading to Birch's (1960, 1961) studies of P- and S-wave speeds on rocks to high pressure and Mattaboni and Schreiber's (1967) discussions of the complexities involved to make such measurements in real, fluid saturated earth materials. Since that time, the pulse transmission method has perhaps become the most important technique for the laboratory determination of elastic wave speeds and moduli through geomaterials although the complications of dispersion between the ultrasonic laboratory measurements and field seismic tests remain problematic to this day.

That said, researchers often strive to obtain precise measures of wave speeds and attenuation in order to probe material's intrinsic structure or to provide reference values useful to the broader community. There are a number of obstacles to overcome in order to ensure that the observations are as accurate as possible. In the context of pulse transmission in transversely isotropic solids the two main, and often ignored, difficulties result from beam diffraction and from beam skew. The former arises from the fact that we must work with finite-dimensioned transducers and hence deal with spreading and energy distribution within the beam front particularly at its point of reception (Seki et al., 1956; McSkimin, 1960; Lévêque et al., 2007). The latter relates to the difference between the real direction that the wave energy (and hence the beam) transits through an anisotropic material and the straight trajectory one expects in a simpler isotropic material. This is a consequence of complications of wave propagation in anisotropic elastic media where generally the group (or ray) and phase (or plane wave) propagation speeds and directions differ (e.g. Musgrave, 1970). One manifestation of this difference is that the axis of the beam skews from that of the transmitting element as elegantly demonstrated independently by Merkulov and Yakovlev (1962) and Merkulov (1963) and Staudte and Cook (1967) using Schlieren photography of beams moving through a quartz single crystal, the latter's examples are reproduced here in Fig. 1 in order to illustrate these effects. A consequence of this is that a receiver facing immediately opposite the transmitter will generally not lie in the beam's main energy path; and the resulting signal cannot provide correct measures of wave speed or attenuation (Papadakis, 1990; Sahay et al., 1992; Dellinger and Vernik,

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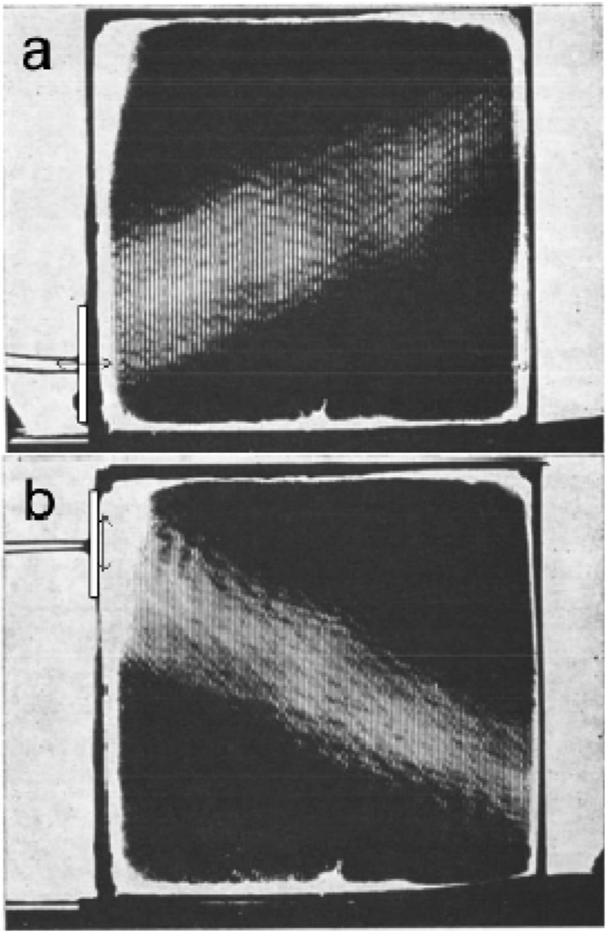

Fig. 1. a) Quasi-longitudinal (*qP*) and b) quasi-shear (*qS)* standing waves generated in the same piece of natural quartz as visualized using Schlieren photography. Transmitting crystals highlighted by superimposed white rectangles that show attached wires. Image from Staudte and Cook (1967) used with permission from the Acoustical Society of America.

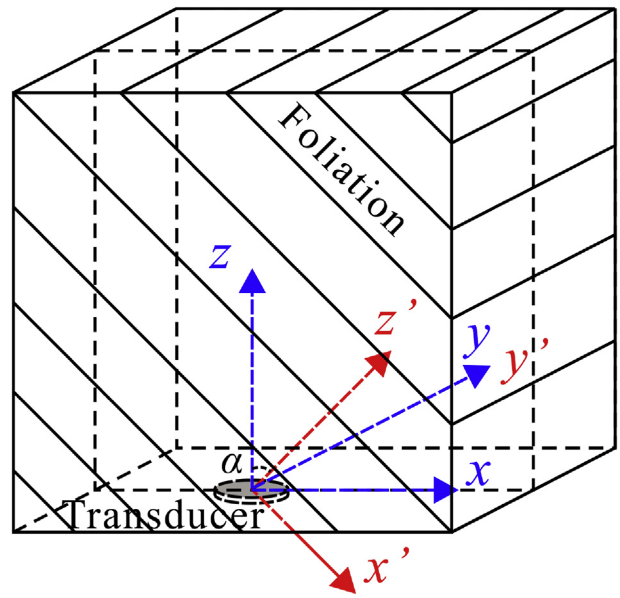

Fig. 2. The symmetry of a transversely isotropic medium and the coordinate systems. The blue arrows indicate the observation coordinate system and the red arrows indicate the material coordinate system which can be rotated to the observation coordinate system with the tilt angle α around the *y*-axis. The *x*-*y* plane is parallel to the transmitting and receiving surfaces. The dashed square shows the plane that the rotation happens within and *x*-, *x*'-, *z*- and *z*'-axis are in this plane. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

1994). A number of workers have looked at this issue in the context of laboratory measurements on rocks. Meléndez-Martínez and Schmitt (2016) provide a recent overview of the literature on this topic as it relates to wave speed measurements in the geosciences. As such, the problem is well known, but few of these studies have attempted to provide a full quantitative evaluation.

Doing this necessitates consideration of the proper experimental geometry and signal character. Vestrum (1994) and Spies (1994) all developed models with varying degrees of sophistication to analyze the effects of the diffraction and the beam skew on the response of finite-size transducers used to measure pulse transmissions through arbitrarily oriented transversely isotropic media. Recently Kolkoori (2013) and Fooladi and Kundu (2017) both modeled the wave field of finite-size transducers with the distributed point source method. The transmitter and the receiver were both constructed from a distribution of point sources or detectors, respectively. The observed transducer output can be treated as an integration of the individual point receiver responses (Placko and Kundu, 2004). The responses of each point source were calculated according to the ray tracing theory (Wu et al., 1990, 1991; Cerveny, 2005).

To our knowledge, there is no readily accessible tool that allows one to model the responses of transducers used for pulse transmission measurements through transversely isotropic materials. To overcome this, we develop a Matlab program named AOTI2D to model pulse transmission responses through transversely isotropic media in two dimensions. The program is designed to model the snapshot of the wave field, the static

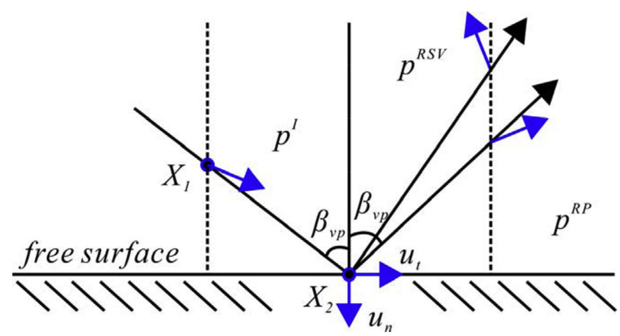

Fig. 3. The schematic illustration of reflection and reciprocity theorem at a free half surface. Considering that Snell's law is about slowness, the black and blue arrays indicate the directions of slowness vectors and polarizations, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

beam and the received signals of a finite-size transducer in transversely isotropic media with different transmitting and receiving transducer sizes, sample thicknesses, wavelengths, and propagation directions.

2. Theory

The propagation of elastic plane waves could be modeled by a variety of techniques. We chose the distributed point source approach as it allows a number of factors, such as the source and receiver directivities, to be incorporated relatively easily. In the approach, the transmitter is treated as the superposition of a series of point sources according to Huygens' Principle and the wave field excited by each point source is solved by the ray tracing theory. In this study, we assumed the anisotropic material is bulk and homogeneous.