Accurate determination of the polarization direction of an acoustic shear transducer

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Abstract

This paper presents an experimental method of determining the polarization direction of an acoustic shear transducer using a single crystal. The <110> direction of a silicon single crystal is chosen as the propagation direction to determine the polarization direction of a piezoelectric Pb(Zr,Ti)O_3 (PZT) shear transducer. For an arbitrary rotation angle of the transducer against the single crystal, the shear wave is split into the fast transverse (FT) mode polarized in the <001> direction and the slow transverse (ST) mode polarized in the $<1\bar{1}0>$ direction. Variation of the amplitude of the FT and ST waves with the rotation angle is more sensitive around minimum than around maximum. The minimum amplitude can be used to locate the polarization direction of the transducer with 1^o accuracy with a digital oscilloscope. The ratio of the amplitude between the FT and ST modes exhibits the resonance-like peaks at the polarization direction aligned along either the <001> or the $<1\bar{1}0>$ direction and can be used to determine the polarization direction of the shear transducer with better than 0.5^o accuracy, which is far better than 5^o accuracy that has been reported to date.

Keywords: Shear transducer; Polarization direction; Single crystal; Elastic constants

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1. Introduction

The shear properties of materials such as the shear modulus, shear strain, shear wave speed, etc., can be easily determined by using a shear transducer. It is not necessary to know the polarization of the shear transducer for an isotropic material to determine the shear properties. However, it is required to know the polarization direction of the shear transducer accurately for precise determination of these properties for anisotropic materials, such as single crystals and composite materials. For an accurate determination of equations of state of solids, precise measurements of ultrasonic wavespeeds including those of FT and ST modes are essential. The

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initially isotropic materials exhibit stress-induced anisotropy and for investigation of the acoustoelastic behavior of these materials under stress, it is often necessary to align the polarization direction of a shear transducer either along the loading direction or along the direction perpendicular to loading. Because of small acoustoelastic effects, the precise determination of acoustoelasticity requires accurate knowledge of the polarization direction of the shear transducer. In the case of transmitting the shear waves into nonsymmetric directions of anisotropic materials it is even more required to know the polarization direction of the shear transducer accurately in order to obtain the precise elastic constants.

An earlier work for determination of the polarization direction of an acoustic shear transducer was carried out by Hsu and Sachse [1], who observed the amplitude of a shear wave to be maximum, when the polarization direction of a shear transducer aligns perpendicular to the stacked glass slides they used as a medium of shear wave propagation. Zuidema and van Soest [2] used the <112> direction of a Cu single crystal for shear wave propagation and reported that among the two shear waves observed with the $<\bar{1}10>$ and $<33\bar{4}>$ polarized vibrations, respectively, the shear wave polarized in the latter direction disappears on the oscilloscope screen when the vibration direction of the rotating shear transducer coincides with the $<\bar{1}10>$ direction. The accuracy of these measurements of polarization direction is reportedly about $\pm 5^o$. These are the qualitative observations by watching the signals on the oscilloscope screen. In this paper we choose the <110> direction of a cubic silicon crystal as a propagation direction of the shear wave and describe the quantitative observations of the two shear wave amplitudes with much better accuracy $\pm 0.5^o$ for determination of the polarization direction. There is a considerable advantage to using a silicon crystal because of its ubiquitous availability at an affordable price due to widespread semiconductor industries, relatively easy fabrication and polishing of the crystal, and high stability in humid and rusty environments.

Commercially available, thin-disk shaped crystalline shear transducers, such as those of quartz and lithium niobate ($LiNbO_3$) crystals, have a side cut (Y or AC cut) of finite width, the perpendicular direction to which is a fairly accurate indication of the polarization direction. These are a narrow-band resonance-type transducer with very high Q. Because of their relatively weak piezoelectric constants, the most widely used acoustic longitudinal and shear transducers are made of the PZT thin disk, the piezoelectric constants of which are much higher than the single crystalline piezoelectrics, such as quartz and $LiNbO_3$. The PZT bulk is produced by employing a power metallurgy technique and is an aggregate of randomly oriented crystallites. When the PZT bulk is poled by applying a high electric field, the individual ferroelectric PZT crystallites are clustered around the poled direction [3], which is a good indication of the polarization of the shear transducer.

A thick disk of single crystalline cubic silicon acts a medium of the transverse wave propagation in the [110] direction of silicon. The polarization direction of the shear transducer is determined when the polarization direction is aligned either along the [001] or the $[1\bar{1}0]$ direction of the silicon crystal, which is fixed in space.

2. Experimental methods

In this experiment we used the [110] oriented silicon single crystal disk with 76.2 mm diameter and 38.1 mm thickness in the oriented direction. The [110] orientation of the crystal was determined to an accuracy better than 0.5°. A PZT shear wave transducer of Panametrics, Inc., with 5 MHz bandwidth and 12.7 mm diameter excitation area is mounted on a rotating stage, which has 360 degree division with 60 second resolution for each degree. The transducer is attached on the front (110) surface of the crystal. Throughout the rotating stage of the transducer against the fixed silicon crystal, both the [110] orientation and the [001] direction on the (110) plane of the crystal are maintained to be horizontal and the $[1\bar{1}0]$ direction is kept vertical. Although the 5 MHz PZT shear transducer is used in this experiment, the same method can be applied for determination of the polarization of the crystalline shear transducers aforementioned and any other broadband transducers.

In the [110] propagation direction of a cubic medium, the longitudinal and two shear waves are of pure mode. Their group and phase velocities are equal to each other. [4,5] For waves launched from a shear transducer with its polarization oriented in an arbitrary direction of the (110) plane, two pure transverse waves are propagating: the fast transverse (FT) with wavespeed of $(C_{44}/\rho)^{1/2}$ = 5.841 mm/μs and the slow transverse (ST) with wavespeed of $[(C_{11}-C_{12})/2\rho]^{1/2}$ = 4.672 mm/μs, where C_{11}, C_{12}, and C_{44} are the elastic constants of silicon and ρ is its density. The vibration directions of the FT and ST waves are the [001] and the $[1\bar{1}0]$, respectively.

Because of these vibration characteristics of the shear waves propagating in the [110] direction of a cubic medium, the amplitudes of the FT and ST waves exhibit maximum when their polarization direction aligns with the [001] and $[1\bar{1}0]$ directions, respectively and they display minimum when their polarization direction aligns with the $[1\bar{1}0]$ and [001] directions, respectively. The latter criterion, the minimum amplitude, is used to determine the polarization direction, as shown in the following. In an ideal situation, these minima should be theoretically zero. However, in non-ideal conditions, such as the presence of system noises, slight deviation of the silicon orientation from the [110], etc., the minima are not exactly zero but close to zero in the order of a few mV. Because of the two-fold symmetry around the [110] direction of a cubic medium, these minima of each mode are separated by 180^{o}. Since the [001] and $[1\bar{1}0]$ directions are perpendicular to each other, the amplitude minima of the FT and ST waves are separated by 90^{o}. The purpose of this experiment is with what degree of accuracy these minima can be determined as the shear transducer rotates against the fixed silicon crystal.

A 200 MHz pulser-receiver (Panametrics model 5900PR) was used both to feed an excitation. signal to the transducer and to amplify the signal that was reflected on the rear (110) surface of the crystal in the pulse-echo mode. The amplified signal was displayed on a digital oscilloscope (Tektronics model TDS 3052) with the bandwidth of 500 MHz, which is capable of exhibiting on the screen a digital readout of the peak-to-peak voltage of the FT and ST waveforms with 8-bit resolution in the measurement mode. The signals on the oscilloscope are obtained after averaging 128 signals to enhance a signal-to-noise ratio.

Fig. 1 shows the waveforms of the FT and ST modes that travel a round trip distance 76.2 mm and arrive at 13.05 μs and at 16.31 μs, respectively, when the major direction of polarization of the transducer is oriented along 37^{o} away from the horizontal [001] direction of silicon, which corresponds to the 20° degree on the rotation stage. While the PZT transducer rotates with the polarization direction aligned around the [001] direction on the front (110) plane of the silicon crystal, the amplitudes of the observed FT and ST waves respectively exhibit maximum and minimum. Likewise, when the polarization direction of the shear transducer rotates around the $[1\bar{1}0]$ direction, the amplitudes of the observed FT and ST waves exhibit minimum and maximum, respectively. This behavior is displayed in Fig. 2, which shows that variation of the amplitude of the FT and ST modes with the rotating angle is more sensitive when they go through minimum. This fact can be used to locate the polarization direction of the shear transducer in the digital scope, which displays the peak-to-peak amplitude on the screen. In Figs. 2 and 3, negative angles α is identical with positive angles 360-α.

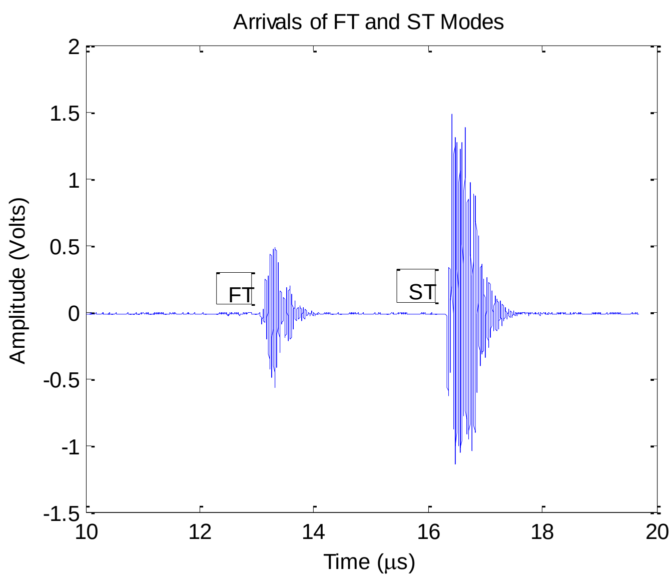

Fig. 1. Arrivals of FT and ST Modes

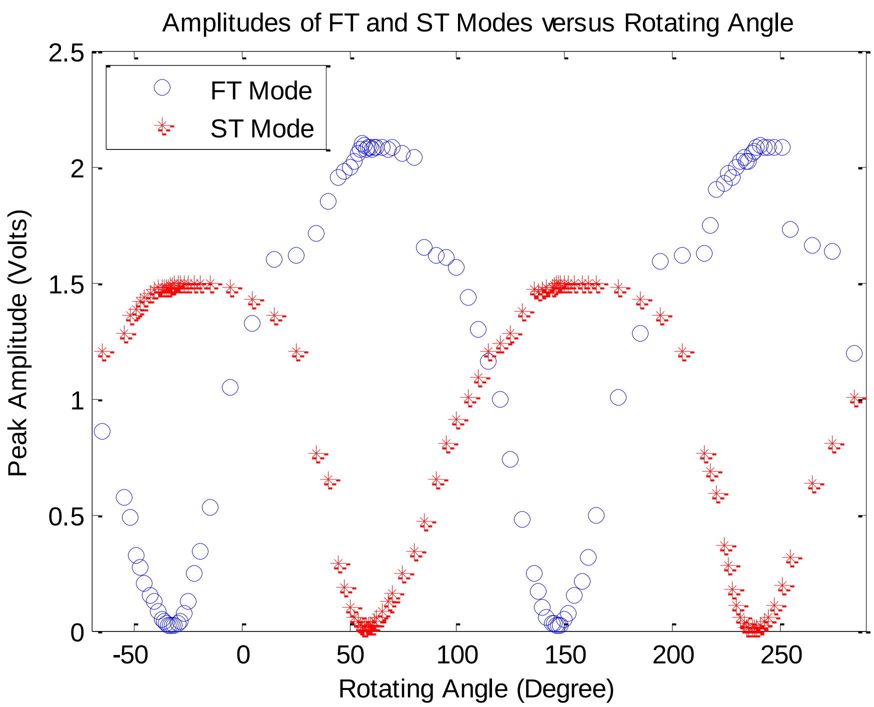

Fig. 2. Amplitudes of FT and ST modes vs. rotating angle

As we repeatedly rotate the transducer back and forth around the $[1\bar{1}0]$ direction to determine the angles that exhibit minimum amplitude on the scope screen, the minimum of the FT mode is found with an accuracy with the standard deviation of ±1° degree to be at the rotating stage angle -33° or 147°, at which the amplitude of the ST mode indicates maximum. At the either angle, the polarization of the shear transducer aligns along the vertical $[1\bar{1}0]$ direction of the silicon crystal. Likewise, the minimum of the ST mode is found with the accuracy of the standard deviation ±1° degree to be at the rotating stage angle 57° or 237°, at which the amplitude of the FT mode indicates maximum. At this angle, the polarization of the shear transducer aligns along the horizontal [001] direction of the silicon crystal. As anticipated, these four minimum amplitude angles are separated by 90°.

Since the amplitude of the ST mode increases with the decreasing amplitude of the FT modes and vice versa, enhancement in sensitivity with the rotating angle can be achieved by plotting the ratio between the amplitudes of the FT and ST modes with respect to the rotating angle. This is shown in Fig. 3, which exhibits a sharp resonance-like behavior of the ratio when the major polarization direction of the shear transducer is aligned along the [001] and $[1\bar{1}0]$ directions of the silicon crystal. The plot of the ratio of the amplitude of the FT mode to that of the ST mode versus the rotating angle shows a sharp resonance-like peak at the rotating angles 57°±0.5° and 237°±0.5°, at which the primary polarization direction aligns along the horizontal [001] direction of the silicon crystal. Similarly, the plot of the ratio of the amplitude of the ST mode to that of the FT mode versus the rotating angle shows a sharp resonance-like peak at the rotating angles -33°±0.5° and 147°±0.5°, at which the primary polarization direction aligns along the vertical $[1\bar{1}0]$ direction of the silicon crystal. These angles are again separated by 90° as aforementioned.

A slight asymmetry associated with the amplitude data in Fig. 2 with respect to the two folds or 180° rotational symmetry of the {110} plane of silicon is due to a slightly changing effect of the ultrasonic couplant (Krautkramer Branson SLC 70), as the transducer rotates against the fixed silicon crystal, and also due to a slight deviation of propagation from the ideal [110] direction, and the system signal noise, etc. The asymmetry is blown up near the peaks in Fig. 3, because the effect of the couplant on the amplitude is relatively larger when the FT and ST amplitudes pass through minimum, where the signal is also relatively more corrupted with noise than for other directions. However, the effect of the slightly varying couplant is, to first degree, eliminated in Fig. 3. If we assume that the relative variation of coupling is equal on the both FT and ST modes, the effect of varying couplant will be largely eliminated on the ratio between the amplitude of the FT and ST modes. Although mathematical division theoretically increases an error, it increases a measurement accuracy in determination of the polarization angle, because it largely removes the effect of the varying couplant. We fitted the ratio data that shows an approximate two-fold symmetry around the peak into Gaussian curve, which determines the peak angles with 0.3° standard deviation. The Gaussian fitting is shown in Fig. 4.

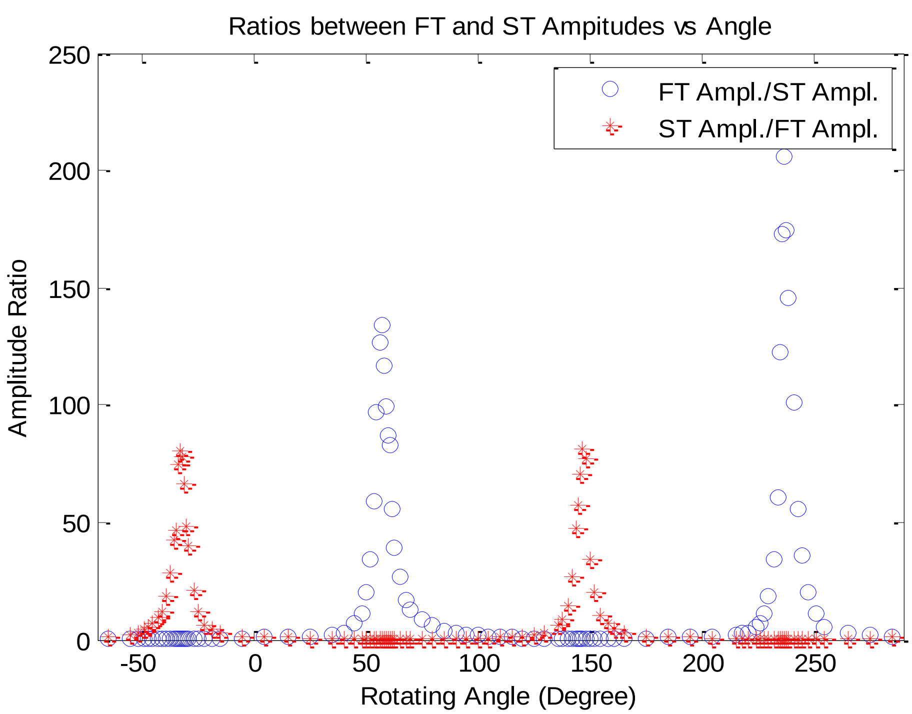

Fig. 3. The ratios between FT and ST amplitudes versus rotating angle

3. Conclusion

This work demonstrates an accurate experimental determination of the polarization direction of the shear transducer with the selection of the <110> direction of a silicon crystal as a propagation direction. The polarization direction can be determined with 1° accuracy by finding the direction that gives minimum amplitude of either the FT or ST mode in a digital oscilloscope screen, which displays the peak-to-peak amplitudes. The plot of the ratio of FT/ST or ST/FT amplitudes exhibits sharply defined peaks, which can be used to determine the polarization direction of the shear transducer with accuracy better than 0.5°.

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