Measurements of the longitudinal wave speed in thin materials using a wideband PVDF transducer

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A flat transducer was constructed, using a 9-μm-thick PVDF (polyvinylidene fluoride) film for generation and detection of high-frequency ultrasonic waves, and used for measurements of the phase velocity of longitudinal waves traveling along the thickness direction in a very thin material. The transducer has a useful wideband frequency characteristic extending from 10 MHz to over 150 MHz. Measurements of the phase velocity of the longitudinal waves are carried out using a 0.212-mm-thick glass slide and a 0.102-mm-thick stainless-steel shim, using water as a coupling medium. The thickness limit for this measurement appears to be approximately 20 μm. The phase velocity of the longitudinal mode is obtained as a function of frequency in the frequency domain by using a modified sampled continuous wave (cw) technique. It can also be measured in the time domain by using a broadband pulse of short duration. © *2003 Acoustical Society of America.* [DOI: 10.1121/1.1562650]

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I. INTRODUCTION

Accurate ultrasonic measurements of sound speed along the thickness direction in a plate specimen are usually based on the interference phenomenon between the successive echoes as the ultrasonic beams reverberate inside the plate. The phase comparison method (Williams and Lamb, 1958), pulse superposition method (McSkimin, 1961; McSkimin and Andreatch, 1962), and continuous wave (cw) resonance method (Bolef and Miller, 1971) are the typical examples that make use of the interference or alignment of the successive echoes, as one varies either the frequency of a tone-burst signal (pulse repetition rate) or its carrier frequency. A variation of these methods is the pulse–echo overlap method (Papadakis, 1976) in which best alignment or overlap of the successive echoes is sought to find their carrier frequency. Constructive and destructive interferences may occur at frequencies corresponding to the integral multiples of one half-wavelength. For a thin-plate specimen this requires a high-frequency transducer that generates and detects ultrasonic waves.

The spherically focusing (Smolorz and Grill, 1996) and line-focusing (Zou *et al.*, 2003) high-frequency transducers, which are both made of a 9-μm-thick piezoelectric PVDF (polyvinylidene fluoride) film, are reported to possess a wide-frequency bandwidth ranging from 10 MHz to over 150 MHz. Very recently, the authors (Zou *et al.*, 2003) demonstrated that a line-focusing PVDF transducer can be used to measure the phase velocity of a surface acoustic wave (SAW) in a $V(z)$ curve by employing either a sharp broadband pulse or a tone-burst signal having a carrier frequency chosen over a wide frequency region. It is quite natural to expect that a flat transducer made of the same piezoelectric PVDF film can be used to measure the phase velocity of longitudinal waves. Because of its high-frequency bandwidth, it can be applied to investigate very thin materials. We fabricated the flat PVDF transducer and used it both as a generator and as a detector of ultrasonic waves to successfully measure the phase velocity of the longitudinal mode propagating in the thickness direction of very thin glass slide and stainless-steel shim. Although both a broadband pulse and a tone burst of various carrier frequencies are used for this purpose, of particular interest is a modified sampled cw technique adapted to the flat PVDF transducer aligned parallel to a very thin-plate specimen using water as a coupling medium, as one sweeps frequency over the effective bandwidth of the PVDF transducer.

II. DESCRIPTION OF MODIFIED SAMPLED cw ULTRASONIC SPECTROSCOPY

A flat transducer using a 9-μm piezoelectric PVDF film is fabricated, following the design and construction technique similar to those adopted in a line-focusing transducer (Zou *et al.*, 2003), in which the geometry of a line-focusing part is simply replaced by the flat geometry. One flat transducer is used as a noncontact sensor to generate and detect ultrasonic waves, using water as a coupling medium to a thin specimen. We modified a sampled cw technique (Bolef and Miller, 1971) to observe a series of resonance frequencies corresponding to an integral multiple of half-wavelengths of ultrasound in the specimen as the frequency is swept over a wide bandwidth of the transducer.

An overall electronic block diagram for the measurement system is displayed in Fig. 1. For a radio frequency (rf) tone-burst operation, we used an electronic signal generator capable of generating both continuous and gated harmonic signals in the frequency range from 5 kHz to 1.5 GHz. The rf tone-burst signals derived from the signal generator are fed into a rf power amplifier, whose frequency bandwidth extends from 100 kHz to 250 MHz. The output of the rf amplifier is connected to one arm of the single-pole double-throw (SPDT) switch, in which the single pole always joins the PVDF transducer. The operation of the SPDT switch is controlled by the TTL pulse generator that is synchronized with the rf signal generator at the beginning of signal generation. The switching times of the SPDT switch are less

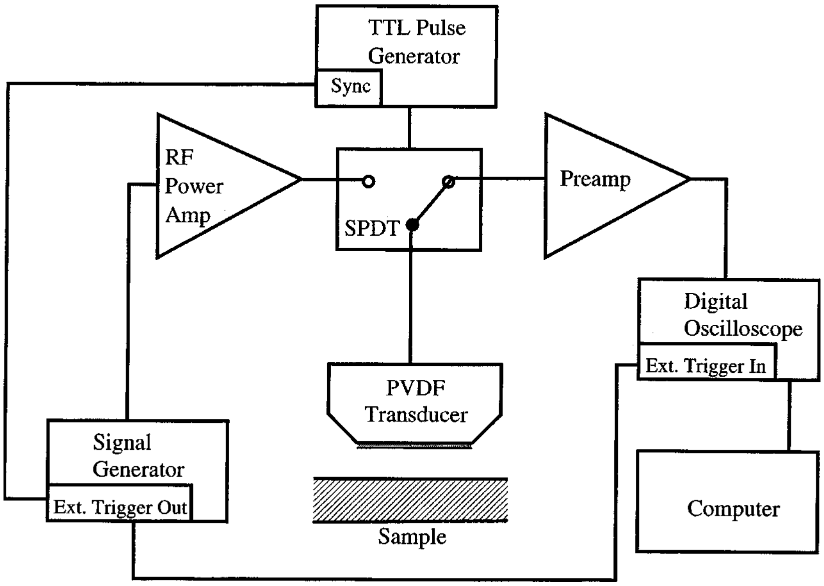

FIG. 1. Electronic block diagram for generation and detection of ultrasonic signals for the modified sampled cw technique.

than 20 ns and the width of the TTL pulse is maintained slightly longer than that of the rf tone-burst signals. During the time when the TTL pulses are on, the single pole of the SPDT switch is connected to the rf amplifier side arm of the switch, and the PVDF transducer generates longitudinal ultrasonic signals that transmit through water to a thin specimen. The ultrasonic signals are then reflected from the specimen surface, reverberate inside the specimen, and are transmitted back to the PVDF transducer.

In the modified sampled cw technique, a continuously running oscillator is gated on for a sufficiently long time, so that a steady-state cw acoustic response is established in the specimen. But, the gate pulse width is kept shorter than the round-trip time through water between the transducer and the specimen, so that signals generated and detected by the same transducer are separated from each other and not superposed together. After the steady-state conditions have been reached, the signal transmission gate is off and the signal detection gate is on. The distance between the PVDF transducer and the specimen is taken to be about 2 mm, which corresponds to an ultrasonic round-trip time of about 2.67 μs. We choose the gate width for the tone-burst signals to be 2.4 μs, which corresponds to slightly longer than 32 round-trip times of the longitudinal ultrasonic waves that undergo multiple reflections inside a 0.212-mm glass slide used as a thin specimen. The longer the gate width for tone-burst signals is, the sharper will be the mechanical resonance that is prompted by more reverberations in the specimen. The longer gating time, which is maintained slightly shorter than an ultrasonic round-trip time between the transducer and the specimen, requires a longer distance in water. However, attenuation in water increases in proportion to the square of frequency. As a result, high-frequency signals will attenuate severely as they travel a longer distance. The 2-mm water gap maintained between the transducer and the specimen appears to be an optimum distance, which allows a steady state to be set up in the specimen and still preserves high-frequency signals as they make a round trip through water from the transducer to the specimen. The pulse repetition rate chosen is 10 ms, which is long enough for the generated and reverberated signals to decay out almost completely before the next pulse for signal excitation is on.

During the time the TTL pulse is off, reflected and reverberated signals from the specimen arrive at the PVDF transducer, which via the single pole of the SPDT switch is in contact with the other arm of the switch connected to the input of a preamplifier whose bandwidth extends from dc to over 300 MHz. The SPDT switch prevents the preamplifier from being overloaded from the high-amplitude output of the rf amplifier, and keeps the electromagnetic leakage of a generated signal to a detected signal below 100 dB. The output of the preamplifier is brought into a digital sampling oscilloscope, which digitizes the signals at the sampling rate of 2.5 GHz and displays them on a phosphor screen for visual observation. Finally, the digitized signals are brought into a high-speed personal computer (PC) for processing and storage of the signals.

As the carrier frequency of tone-burst signals is swept, the shape of observed signals on the scope changes and displays a series of mechanical resonances evenly spaced in the frequency domain for nondispersive materials. Figure 2 shows two signals observed with a 0.212-mm glass slide, one at an off-resonance frequency of 127 MHz and the other at a resonance frequency of 120.6 MHz. For most of the frequency range corresponding to the off-resonance condition, signals similar to the upper one in Fig. 2 are observed. As the swept frequency approaches towards a resonance frequency in the narrow interval surrounding the resonance frequency, the trailing edge of the signal rapidly builds up in amplitude, which decays in time. The peak amplitude among the trailing edge signals occurs at a resonance frequency. To enhance the difference between the off-resonance and near-resonance signals, the magnitude of a trailing signal for 0.5-μs duration immediately after the termination of the excitation signal is integrated. These integrated values are plotted as a function of frequency and shown in Fig. 3, which exhibits sharp resonance peaks at an evenly spaced frequency interval (13.40 MHz) in the frequency range from 10 to 150 MHz. The sharp

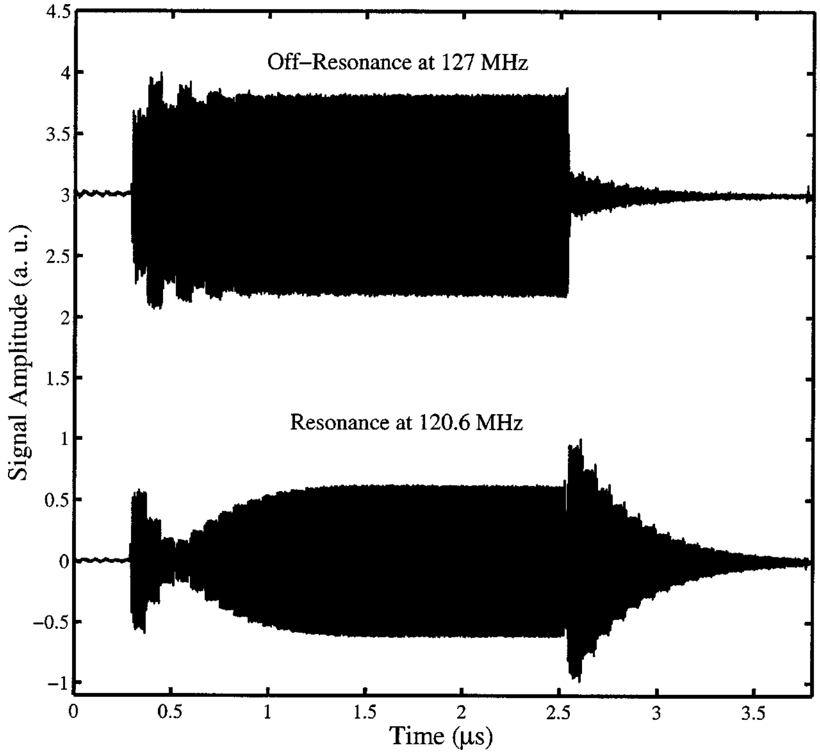

FIG. 2. Signals observed with a 0.212-mm-thick glass slide at off-resonance and resonance frequencies.

resonance peaks at the center of a mechanical resonance occur at frequencies corresponding to the integral multiples of one half-wavelength of ultrasounds as multiple reflections in the specimen constructively superpose to set up standing waves. The signal shapes shown in Fig. 2 and the overall shape of the envelope of the frequency domain sweep in Fig. 3 are discussed in detail in the literature (Bolef and Miller, 1971). From the evenly spaced frequency interval 13.4 MHz between successive resonance peaks in the 0.212-mm-thick glass slide specimen, the longitudinal phase velocity of 5.68 km/s is obtained for glass. We conducted a similar experiment using a 0.102-mm-thick stainless-steel shim, which displays resonance peaks evenly spaced at a frequency interval of 28.75 MHz. From this value, we obtain the phase velocity 5.84 km/s of the longitudinal mode for stainless steel. Supposing that the first resonance peak can be observed near 140 MHz, the thickness limit of the specimen materials for measurement of the longitudinal phase velocity appears to be about 20 μm.

The frequency sweep is implemented with an interval of 0.1 MHz between 10 and 150 MHz at a total of 1401 frequencies. At each frequency 10 000 digitized signal points are brought to a computer at a sampling rate of 2.5 GHz. The resonance frequencies corresponding to the peaks in Fig. 3

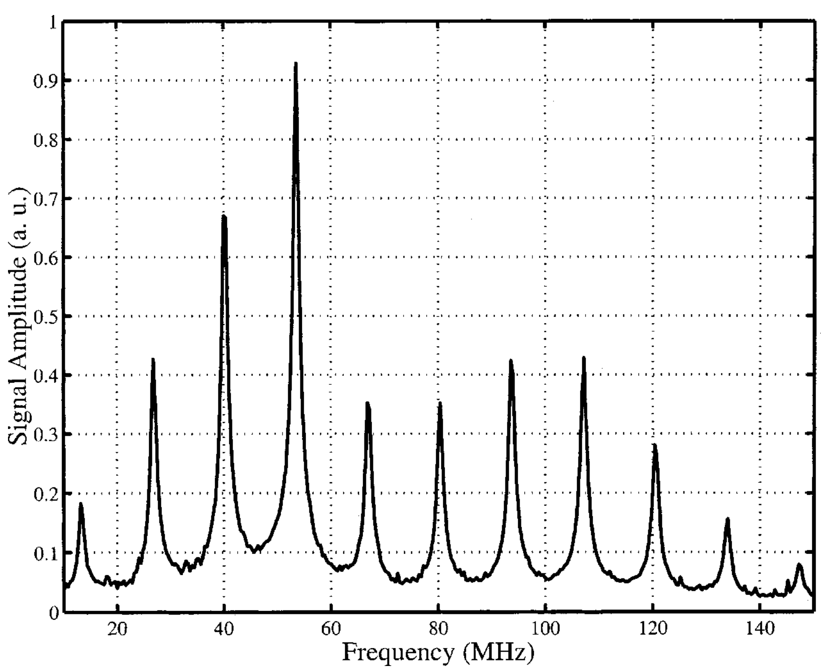

FIG. 3. Resonance spectroscopy of a 0.212-mm-thick glass slide in the frequency domain.

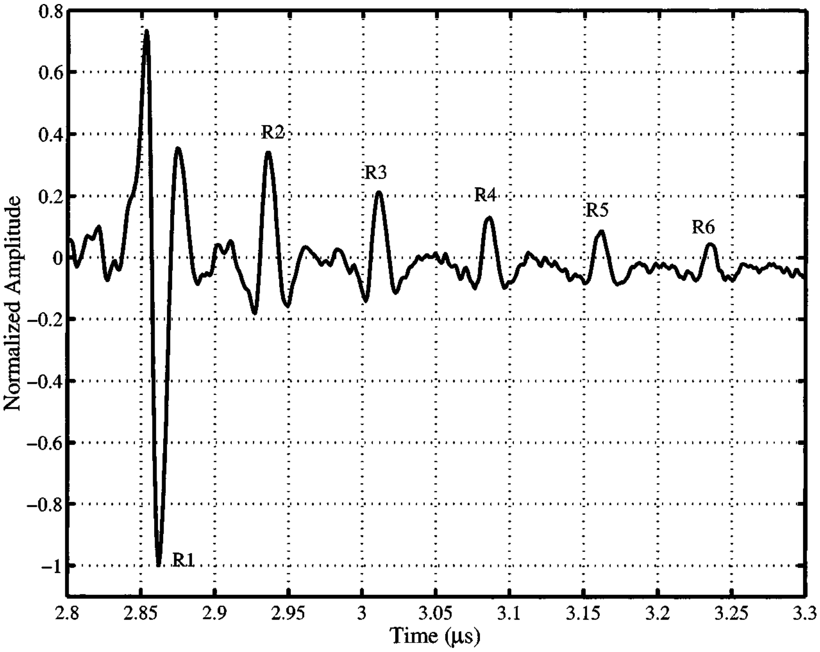

FIG. 4. Echoes observed from a 0.212-mm-thick glass slide, using a broadband sharp pulse.

are thus determined with an error ≤0.05 MHz over the frequency span over 100 MHz. As a result, an error in transit time measurement of the longitudinal wave across the specimen is better than 0.05%. The error in transit time measurements can be improved by taking a smaller interval in frequency sweep, say 0.01 MHz, at the cost of bringing more digitized points in computer storage. However, the thickness of a specimen is determined with an error of 1 μm, and therefore the errors in measurements of the longitudinal phase velocity both in glass and in stainless-steel specimens are estimated to be about 0.5% and 1%, respectively.

III. BROADBAND PULSE RESPONSE

For nondispersive materials, such as glass and stainless steel used as a specimen material, a broadband pulse generated and detected by the flat PVDF transducer can be used to measure in the time domain the phase velocity of longitudinal waves traveling a thin-plate specimen. For this purpose, we used the 200-MHz-bandwidth pulser/receiver (Panametrics model 5900PR). The broadband pulse response of the system, obtained by using 5-GHz sampling rate and the 0.212-mm-thick glass slide, is shown in Fig. 4, which displays multiple reflections undergone in the glass specimen. In the figure, R1 is the first echo reflected from the specimen surface facing the transducer, and R2, R3, R4, etc., are the echoes which are first transmitted through the specimen boundary facing the transducer, which make then one round trip, two round trips, three round trips, etc., respectively, in the specimen, and which are finally transmitted back to the transducer. Note that the phases of R1 and the rest of the echoes are reversed. The rest of the echoes are observed at a regular time interval, from which we obtain the phase velocity 5.68 mm/μs of the longitudinal mode in glass. This value is identical to the phase velocity measured by the modified sampled cw technique.

IV. CONCLUSIONS

We have demonstrated that a broadband, high-frequency, flat PVDF transducer, which is constructed with a 9-μm-thick piezoelectric PVDF film, can be used to measure the phase velocity of the longitudinal waves traveling along the thickness direction in a very thin plate. A modified sampled cw technique using gated tone-burst harmonic signals, especially adapted to the noncontact configuration of the transducer, works successfully to show sharp resonance peaks in the frequency-domain spectroscopy. For nondispersive materials, a broadband, sharp pulse can also be used for the flat PVDF transducer to measure the longitudinal phase velocity in the time domain.

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