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An Experimental Approach for Detection of the Acoustic Radiation Induced Static Component in Solids

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We propose an experimental approach to directly detect the acoustic radiation induced static component (SC) of primary longitudinal (L) wave propagation in solids using an ultrasonic pitch-catch technique, where a low-frequency ultrasonic transducer is used to detect the SC generated by the co-propagating primary L-wave tone burst that is excited by a high-frequency ultrasonic transducer. Essentially, the experimental approach proposed uses a dynamic method to detect the SC generated. The basic requirement is that the central frequency of the low-frequency ultrasonic transducer needs to be near the center of the main lobe frequency range of the time-domain envelope of the primary L-wave tone burst. Under this condition, the main lobe of the frequency spectrum of the SC pulse generated adequately overlaps with that of the low-frequency ultrasonic transducer. This will enable the generated SC pulse to be directly detected by the low-frequency ultrasonic transducer. The performed experimental examination validates the feasibility and effectiveness of the proposed approach for direct detection of the acoustic radiation induced SC generated by L-wave propagation in solids.

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It is known that, in addition to generation of a second-harmonic component, there is generation of an acoustic radiation induced static component (SC) when a primary longitudinal (L) wave tone burst propagates through a solid with quadratic elastic nonlinearity.[1–6] Theoretically, the effect of the SC generation was first explored by Thurston *et al.*[1] Subsequently, a theory associated with the generation of the SC was proposed by Cantrell,[2] through which it can be found that the SC generated depends on the material nonlinearity parameter. Regarding the time-domain shape of the SC pulse (whose carrier frequency is zero) generated by a primary L-wave tone burst, some theoretical, numerical and experimental studies indicate that it has a flat-top shape and its peak is proportional to the propagation distance, as well as to the square of the carrier frequency of the primary L-wave tone burst.[3–6] Specifically, the shape of the SC pulse generated is similar to the time-domain envelope of the primary L-wave tone burst, and both have almost the same duration. Due to the fact that the SC generated is intrinsically associated with the elastic nonlinearity of material,[2] the detection is of significance for material characterization.[7]

Yost *et al.* reported the first direct experimental evidence for the SC associated with the propagation of acoustic waves in solids, where they used the low-pass filters to filter out the ac component of the received signal and to extract the dc component.[8] Jacob *et al.* demonstrated a method using an optical interferometer for extracting the SC generated by propagation of acoustic wave tone bursts in a solid.[3] Due to the asymmetry induced by the SC generated in the wave, Narasimha *et al.* investigated an experimental method to measure the SC in solids by extracting the positive and negative peaks of the received signal.[4] Although the methods described above can be used to detect the SC generated with some technical assistance, it is necessary to develop an approach that can be used to directly detect the response of the SC generated by L-wave propagation in solids.

In this letter, we try to develop an experimental approach that can be used to directly detect the response of the SC generated using an ultrasonic pitch-catch technique. Essentially, the experimental approach proposed uses a dynamic method to detect the SC generated. The experimental setup is shown schematically in Fig. 1. A computer controlled transmitter-receiver (Ritec 5000 SNAP system) is used to generate rf tone-burst voltages for excitation of the high-frequency L-wave piezoelectricity (PZT) transducer T_x (A405S, Panametrics Inc., central frequency 5.0 MHz and sizes $0.5'' \times 1.0''$), and to receive and process the signal detected by the low-frequency L-wave PZT transducer R_x (A413S, Olympus Inc., central frequency 0.5 MHz and sizes $0.5'' \times 1.0''$). To suppress the transient behavior from the rf amplifier, the amplified rf tone-burst voltages pass through a specific attenuator. When an N-cycle sinusoidal tone-burst voltage with a carrier frequency of f is applied to T_x, an ultrasonic L-wave tone burst will be excited and propagate in the solid (polyphenylene sulfide (PPS) with thickness 5 cm and L-wave velocity 2457 m/s). The pulse-echo response of the primary L-wave tone

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burst is received by T_x via the duplexer, while the ultrasonic signal propagating through the solid is received by R_x.

According to the results obtained by some theoretical, numerical and experimental studies,[3–6] there is generation of the time-domain SC pulse that propagates along with the primary L-wave tone burst excited by T_x with the same group velocity. Meanwhile, it is also known that the time-domain shape of the SC pulse generated is similar to the envelope of the primary L-wave tone burst, and both have almost the same duration (schematically shown in Fig. 1). It should be pointed out that the magnitude of the SC pulse shown in Fig. 1 is shown schematically, and its absolute magnitude should be far less than that of the primary L-wave tone burst.[5,6]

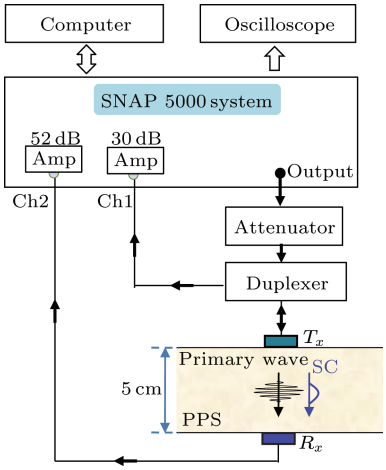

Fig. 1. Experimental setup, where the magnitude of the SC pulse generated is schematically shown and its absolute magnitude should be far less than that of the primary wave.

The question of how to directly detect the SC pulse generated by the co-propagating primary L-wave tone burst excited by T_x is an interesting one. Here we propose that a low-frequency L-wave transducer (i.e., R_x in Fig. 1, with central frequency much lower than that of T_x) is used to directly detect the SC pulse generated. The basic requirement is that the main lobe of the frequency spectrum of the SC pulse generated needs to adequately overlap with that of the receiving transducer R_x. Specifically, it is better that the central frequency of the receiving transducer R_x is near the center of the main lobe frequency range of the SC pulse to be detected. Under this condition, the SC pulse generated can be directly detected by R_x. For this purpose, we can adjust the duration and envelope shape of the primary L-wave tone burst excited by T_x, to fulfill the condition that the central frequency of R_x is near the center of the main lobe frequency range of the SC pulse generated.[3–6] Generally speaking, the duration of the primary L-wave tone burst is determined by its cycle number when its carrier frequency is given, while its envelope shape is largely dependent on the modulation window of the rf tone-burst voltages applied to T_x. Thus, when the frequency response characteristics of T_x and R_x in Fig. 1 are given, by choosing appropriate rf tone-burst voltages applied to the transducer T_x, the central frequency of R_x near the center of the main lobe frequency range of the SC pulse generated can be readily achieved.

Considering the fact that the main lobe of the frequency spectrum of the Hanning window is wider than that of the rectangular window with the same duration τ, and meanwhile the former has a better side lobe suppression, the Hanning rather than rectangular windowed sinusoidal tone burst voltages will be adopted in the following experimental examination. When the carrier frequency $f = 5$ MHz and the cycle number N of the Hanning-windowed sinusoidal tone burst voltages applied to T_x are given, based on the subsequent experimental observations, it can be seen that for the larger N (e.g., $N \geqslant 10$), the duration of the excited primary L-wave tone burst is approximately equal to $\tau = N/f$ and its time-domain envelope exhibits a Hanning window-like shape. Based on results obtained previously,[3–6] the SC pulse generated by the co-propagating primary L-wave tone burst excited by T_x also exhibits a Hanning window-like shape and its duration is approximately equal to $\tau = N/f$.

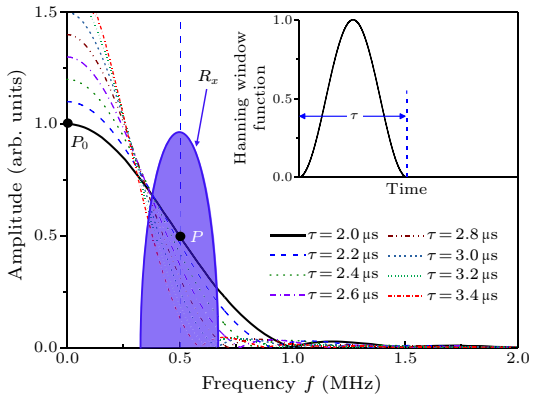

Fig. 2. Amplitude–frequency response curves of several Hanning windows with the same peaks, as well as a schematic amplitude–frequency curve of a low-frequency transducer.

Figure 2 shows the amplitude–frequency response curves (frequency spectra) of several Hanning windows with the same peaks and different durations, as well as a schematic amplitude–frequency curve (blue solid curve) of the low-frequency transducer R_x. It is found that, at the central frequency of R_x (i.e., 0.5 MHz), the response reaches the maximum (i.e., point P) at the duration of $\tau = 2\,\mu$s, while it decreases for other durations. Due to the fact that the central frequency of R_x (0.5 MHz) is at the center of the main lobe frequency range (0–1 MHz) of the Hanning

window ($\tau = 2\,\mu s$) and near the positions at which there exists adequate amplitude–frequency response, it is expected that the SC pulse generated by the co-propagating primary L-wave tone burst ($\tau = 2\,\mu s$) can be directly detected by R_x.

Next, experimental examination is conducted to validate the prediction that the SC generated can be directly detected by a low-frequency ultrasonic transducer. When the transducer T_x in Fig. 1 is driven by the 5-MHz ten-cycle Hanning windowed sinusoidal tone-burst voltages (provided by the output channel of the Ritec 5000 SNAP system, Ritec, Inc.), the echo signal of the primary L-wave tone burst excited and received by T_x is shown in Fig. 3(a). Through zooming-in on the partial echo signal along the time axis, it can be found that the duration of the primary L-wave tone burst is approximately ten cycles of 5-MHz sinusoidal signal (2 μs), and its envelope exhibits a Hanning window-like shape.

Based on results obtained previously,[3–6] it can be approximately assumed that the time-domain SC pulse generated by the co-propagating primary L-wave tone burst (shown in Fig. 3(a)) is a Hanning window-like pulse with a carrier frequency of zero. The time-domain signal received by R_x is shown in Fig. 3(b), where the amplifier gain for the signal fed into Ch2 is 22 dB larger than that fed into Ch1 (see Fig. 1). To discern the frequency components, a Fourier transform is performed on the initial (15–40 μs) and the last (55–80 μs) parts of the time-domain signal shown in Fig. 3(b), and the corresponding amplitude–frequency curves are shown in Fig. 3(c). It is clear that there are mainly two frequencies (0.5 MHz and 5 MHz) in the signal received by R_x for the 1st and 2nd times. Obviously, the peak near 0.5 MHz should be attributed to the contribution of the SC generated by the co-propagating primary L-wave tone burst excited by T_x (see Fig. 2). Note that, although the central frequency of the transducer R_x (i.e., A413S) is 0.5 MHz, through adequate gain amplification (see Fig. 1), its amplitude–frequency response curve (provided by Olympus, Inc.) shows that adequate sensitivity exists at the carrier frequency (i.e., 5 MHz) of the primary L-wave tone burst. This also makes $A_{SC}^{(1)}$ have the same order of magnitude as $A_f^{(1)}$ (see Fig. 3(c)).

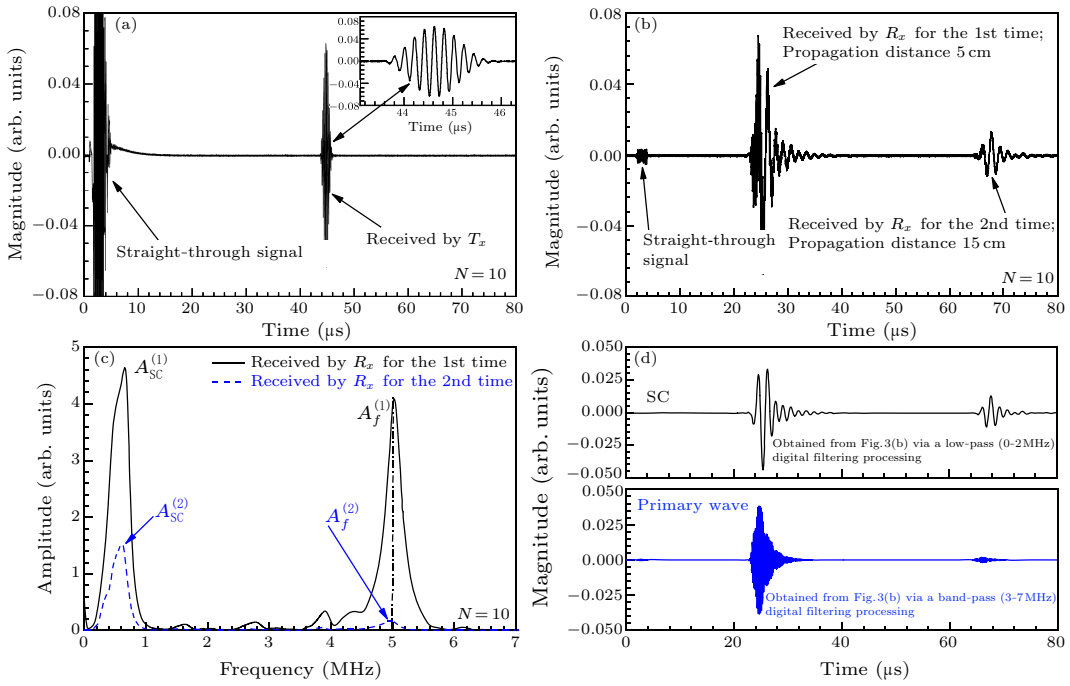

Fig. 3. (a) Echo signal of the primary wave tone burst, (b) time-domain signal received by R_x, (c) amplitude–frequency curves of the signal shown in (b), and (d) time-domain signals of the SC generated and primary wave via digital filtering processing.

To directly observe the time-domain signals of the primary wave and the SC generated, low-pass (0–2 MHz) and band-pass (3–7 MHz) digital filtering processes are applied, respectively, on the signal shown in Fig. 3(b), and then the corresponding time-domain signals are presented in Fig. 3(d). Clearly, both the primary L-wave tone burst and the SC pulse generated do propagate with the same group velocity. Due to the fact that the attenuation of wave propagation generally increases with increase in the carrier frequency, it is expected that the propagation attenuation of the SC pulse generated should be smaller than that of the primary L-wave tone burst. This has been verified in Figs. 3(b) and 3(d), where the primary L-wave tone

exhibits a much larger propagation attenuation than the SC pulse generated. Accordingly, the minor propagation attenuation of the SC pulse generated may also be beneficial for experimental measurements.

According to the illustration in Fig. 2, due to the bandwidth limitation of the low-frequency PZT transducer R_x, the real amplitude at zero frequency (i.e., point P_0 in Fig. 2) cannot be detected by R_x. However, the amplitude measured at the central frequency of R_x (i.e., point P) is closely related to the real amplitude at zero frequency (point P_0). Thus, the amplitude measured at the central frequency of R_x (denoted by $A_{\rm SC}$) can be used to indirectly represent that of the SC generated at zero frequency. The relative acoustic nonlinearity parameter, defined as $\beta_R^{(i)} = A_{\rm SC}^{(i)}/(A_f^{(i)} \cdot A_f^{(i)})$,[8] can be calculated from the values of $A_{\rm SC}^{(i)}$ and $A_f^{(i)}$ given in Fig. 3(c), where the superscript $i = 1$ or 2 corresponds to the 1st or 2nd measurement by R_x, while $A_{\rm SC}^{(i)}$ and $A_f^{(i)}$ are the amplitudes of the SC (indirectly represented by that measured at 0.5 MHz) and the primary wave (5 MHz). The calculated results for $\beta_R^{(1)}$ and $\beta_R^{(2)}$ are, respectively, 0.24 and 48.56, in arbitrary units. Considering the fact that the propagation distance of $\beta_R^{(2)}$ is three times that of $\beta_R^{(1)}$, the result $\beta_R^{(2)} > \beta_R^{(1)}$ implies that the SC generated does grow with the propagation distance. It is worth noting that the experimental approach proposed essentially uses a dynamic method to detect the SC generated by the primary L-wave tone burst, which can reduce interference with the extraction of the SC by using the low-pass filters.[3,4,8]

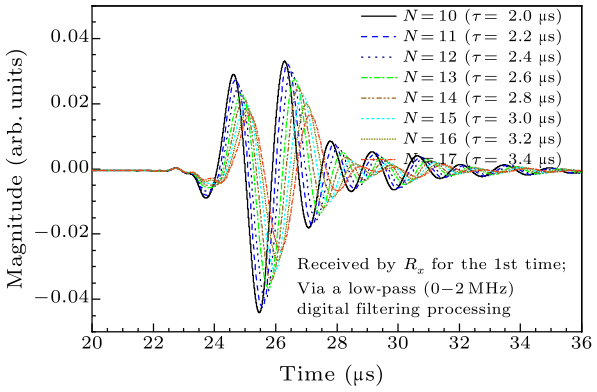

Fig. 4. Time-domain signals of the SC generated under different tone burst durations.

When the peak of the 5-MHz Hanning-windowed sinusoidal tone-burst voltage applied to T_x in Fig. 1 is kept unchanged, increasing its cycle number N will lead to an increase in the duration of the primary L-wave tone burst (akin to that in Fig. 3(a)), as well as the SC pulse generated.[3–6] The similar measurement and digital filtering processing shown in Figs. 3(b) and 3(d) are performed only by changing the cycle number N, and then the corresponding time-domain SC signals detected by R_x for the 1st time are shown in Fig. 4. It is clear that with an increase in the cycle number N (or duration τ), the response of the SC pulse detected by R_x gradually becomes weaker, which is in good agreement with the prediction shown in Fig. 2.

In conclusion, the acoustic radiation induced SC can be generated by the co-propagating primary L-wave tone burst in a solid with quadratic elastic nonlinearity. To directly detect the generated SC, we propose an experimental approach using an ultrasonic pitch-catch technique, where a low-frequency ultrasonic transducer is used to directly detect the SC generated by the co-propagating primary L-wave tone burst excited by a high-frequency ultrasonic transducer. The basic requirement is that the central frequency of the low-frequency ultrasonic transducer needs to be near the center of the main lobe frequency range of the SC pulse generated. Based on the result that the shape of the SC pulse generated is similar to the time-domain envelope of the primary L-wave tone burst, and both of them have almost the same duration, the basic requirement for direct detection of the SC generated can readily be fulfilled by applying appropriate rf tone-burst voltages to the high-frequency ultrasonic transducer. The experimental examination performed in this study validates the feasibility of the proposed experimental approach for direct detection of the SC generated by L-wave propagation in solids.

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