Observation of ultrasonic backward beam displacement in transmission through a solid having superimposed periodicity

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The backward displacement of an ultrasonic beam on a periodically corrugated liquid–solid interface was originally observed in 1976. Additional study of the phenomenon has occurred recently, as further studies of acoustic and elastic wave interaction with periodic surfaces and structures have been driven by increasing interest in phononic crystals. Until now, the phenomenon has only been observed in reflection. This study reports results from experiments that investigate whether a backward beam displacement can also occur in transmission through the interior of a solid. The results indicate that a backward shift may in fact be observed in all fields generated. Therefore, ultrasonic backward beam displacements are not only a reflection phenomenon but may also be observed in transmission. © *2010 American Institute of Physics*. [doi:10.1063/1.3469998]

The history of experimental research on the backward displacement of ultrasonic bounded beams can be found in Refs. 1–3. This type of beam displacement can occur when a bounded beam is incident on a periodically corrugated surface and a backward leaky surface wave generated along the surface causes a lateral backward shift in the specularly reflected beam. Although the theoretical prediction of this phenomenon was made by Tamir and Bertoni[4] for the case of optical beams, the actual existence of the phenomenon was confirmed by Breazeale and Torbett in 1976 (Ref. 1) using ultrasonic beams.

The experiments of Breazeale and Torbett employed a time-harmonic ultrasonic beam incident on a periodically grooved brass sample that was immersed in water. At the time of their experiments, the type of surface wave responsible for the displacement remained unknown. Eventually, a theoretical technique consisting of the Rayleigh–Fourier method to simulate diffraction on periodic surfaces in combination with the decomposition of a bounded beam in terms of inhomogeneous waves emerged and this enabled further study of the phenomenon.[5,6] The use of this technique revealed that the ultrasonic phenomenon was most likely due to the generation of backward propagating leaky Scholte–Stoneley waves along the corrugated surface.

The relationship between the frequency f, angle of incidence θ_i, surface periodicity Λ, sound velocity in the liquid v_{liq}, and velocity of the Scholte–Stoneley wave v_{SSt}, that must be fulfilled in order for a backward beam displacement to occur is described by Eq. (1)

$$f = \frac{1}{\Lambda\left(\dfrac{\sin\theta_i}{v_{\text{liq}}} + \dfrac{1}{v_{\text{SSt}}}\right)}. \quad (1)$$

This relationship is derived from the classical diffraction grating equation[7] where the diffraction order is equal to -1 and its direction of propagation is backward along the surface.

Until very recently, only time-harmonic waves had been employed in the study of the backward displacement phenomenon. However, it has been recently shown that pulsed ultrasonic beams also experience the phenomenon in the form of backward shifted frequency components.[2] In addition, spectrograms have revealed that these frequency components continue to radiate into the fluid well after the specularly reflected beam has passed. Since the backward displacement phenomenon has only been observed in reflection, the question has remained whether it can also be observed in transmission through a solid, since the energy of the leaky Scholte–Stoneley wave that is responsible for the displacement is mostly confined to the liquid side of the corrugated interface.

This letter reports experiments performed on the original corrugated brass sample that was employed in the initial observation of the backward displacement phenomenon by Breazeale and Torbett. The 12 mm thick brass sample has one side that is grooved with a spatial periodicity Λ of 0.178 mm and a corrugation height h of 0.025 mm, and it is immersed in water having a sound speed of 1479.5 m/s. The theoretical Scholte–Stoneley wave velocity v_{SSt} on the water–brass interface is taken to be 1471.7 m/s as described in Ref. 2.

Both the reflected and transmitted fields are measured and analyzed in order to observe any backward shifted frequencies present in the fields and these frequencies are compared with those that are theoretically predicted by Eq. (1). An illustration of the two experimental setups is shown in Fig. 1. For both cases, commercial immersion transducers with nominal center frequencies of 5 MHz and beam widths of approximately 12 mm serve as emitter and receiver. The emitter is stationary and is aimed at the sample surface with an angle of incidence equal to 30°.

In order to measure the reflected field, the receiver is aimed at the sample surface at an angle identical to that of the emitter. A scan is then performed by translating the receiver linearly along the length of the sample. Waveforms are collected at 0.1 mm intervals and Fourier analysis (fast Fourier transform) is performed on the appropriately time-windowed waveforms. The frequencies present in the re-

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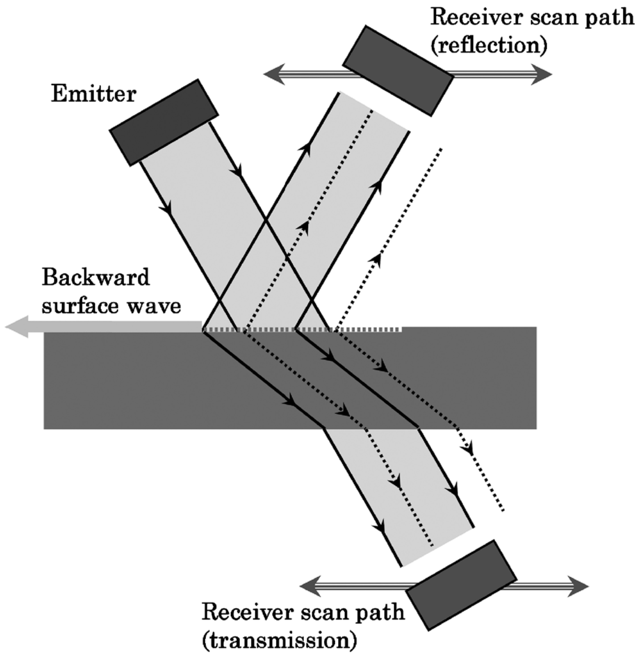

FIG. 1. Illustration of experimental setups for measurement of backward beam displacement in reflection and transmission. Specular beams shown in dotted lines and backward shifts shown in solid lines.

corded signals are plotted as a function of scan position in a spatial spectrogram in order to study the characteristics of the reflected field, including the specularly reflected beam and any backward shifted frequencies. All results are normalized with respect to the frequency spectrum of the incident pulse.

The linear spectrogram of the reflected field obtained for the 30° angle of incidence is shown in Fig. 2. A narrow range of frequencies (indicated by the circled area) is observed to have shifted backward several millimeters with respect to the specular beam which is indicated by the dotted lines. The frequency having maximum amplitude in this range is 5.51 MHz. This is observed to be in good agreement with the theoretical f_{SSt} of 5.52 MHz that can be calculated using Eq. (1).

Using procedures and analysis identical to those employed for the reflected field, the spatial spectrogram showing frequencies detected as a function of position for the transmitted field is shown in Fig. 3. The backward displaced frequencies are circled in the figure and the specular beam is contained within the dotted lines as in Fig. 2. Backward displaced frequencies are observed in the vicinity of 5.52 MHz (frequency of maximum amplitude) and this is in good agreement with the results obtained in reflection and the theoretical f_{SSt}.

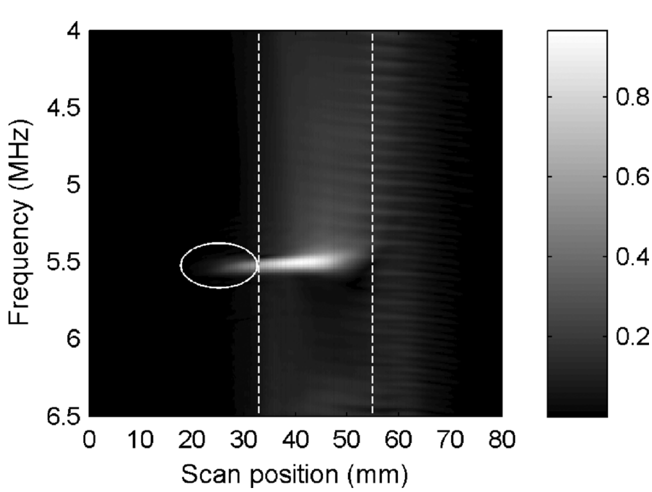

FIG. 2. Spatial spectrogram showing reflected ultrasonic field for an angle of incidence of 30°. Backward displaced frequencies (circled) observed in the vicinity of 5.51 MHz. Specular beam shown with dashed lines.

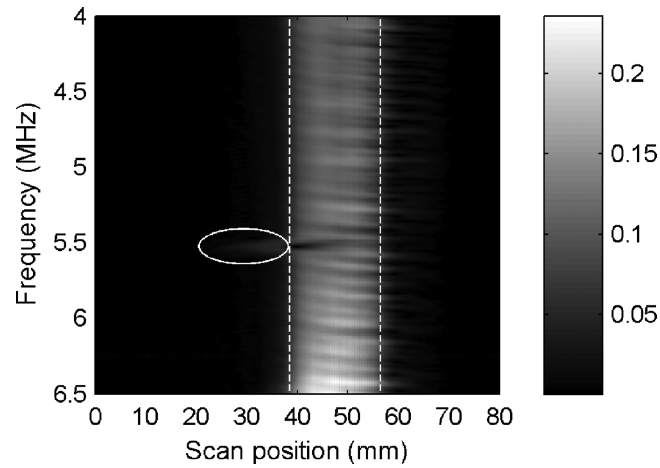

FIG. 3. Spatial spectrogram showing transmitted ultrasonic field for an angle of incidence of 30°. Backward displaced frequencies (circled) observed in the vicinity of 5.52 MHz. Specular beam shown with dashed lines.

Upon close inspection of both the reflection and transmission spectrograms, additional energy in the form of faint horizontal bands is seen to the right of the specular beam. This is due to the inclusion of an additional specular beam reflection from the bottom of the sample in the time windows under analysis. It is necessary to include this additional beam reflection in the time windows used to calculate the spectrograms because, as discussed in Ref. 2, the backward displacement is time-dependent. A large time window is required to capture the energy associated with backward shifted frequency components since they radiate into the reflected (and transmitted) fields over time. The energy appears as horizontal bands due to some overlap with the detection of the specular beam, which is not unexpected since beam spreading has been observed to occur in schlieren images of ultrasonic beams on periodic surfaces.[3] The effect of additional beam reflections from the bottom of the sample has been minimized through the use of an angle of incidence well beyond the critical angle (approximately 17.8°) for longitudinal waves in brass. This maximized the distance between any reflection and the specular beam, and the waves within the solid are only shear so the number of potential beam reflections is reduced by half.

In order to verify that the backward shift in transmission is in fact caused by the backward propagating Scholte–Stoneley wave on the upper surface of the sample, particle displacements parallel and perpendicular to the interface have been calculated for a 5.5 MHz Scholte–Stoneley wave along a water–brass interface. These are shown in Fig. 4 where the interface is represented by a solid line with the fluid medium above (positive distance from interface) and the solid medium below (negative distance from interface). Expressions for the displacements[8] can be derived according to the methods outlined by Viktorov[9] and material parameters used in the calculation are identical to those in Ref. 6.

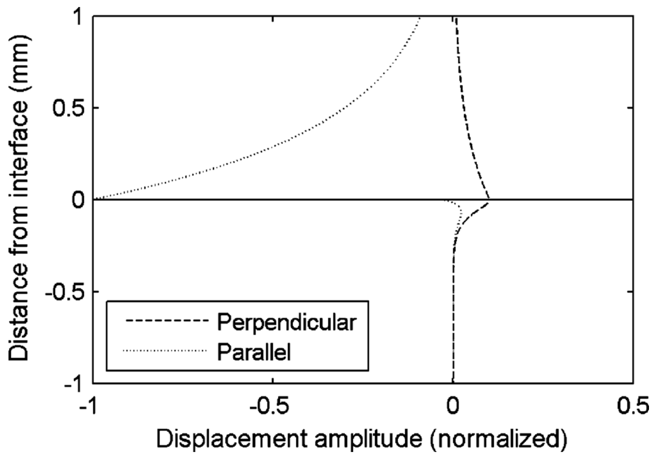

FIG. 4. Particle displacement amplitudes calculated for a 5.5 MHz Scholte–Stoneley wave propagating on a water–brass interface. Displacement perpendicular to the interface shown with dashed lines and displacement parallel to the interface shown with dotted lines. Displacement amplitudes are observed to decrease dramatically with penetration depth in the solid (negative distance from interface).

Since the displacement amplitudes are dependent on an arbitrary constant, they have been normalized. It can be seen, however, that the amplitude of the displacement drops off dramatically with increasing depth in the solid so that for a depth of 0.5 mm, there is virtually no energy from the wave present. Therefore, the backward propagating Scholte–Stoneley wave is confined to the upper surface of the sample.

In summary, backward shifted frequencies that are observed in reflection from a periodically corrugated liquid–solid interface are also observed in transmission through the solid. These frequencies correspond very closely to each other as well as to the theoretically predicted Scholte–Stoneley frequency for the given experimental parameters. The shift observed in transmission may also be attributed to the backward Scholte–Stoneley wave generation on the upper (corrugated) surface of the sample.

The agreement between theory and experiment is despite the assumption of a constant Scholte–Stoneley wave velocity equal to that measured by Breazeale and Torbett for the case of a 6 MHz emitting transducer and a 22.5° angle of incidence.[1,2] This assumption is based on a nondispersive nature of such surface waves, which may not be fully accurate and requires further study. In addition, although this study examined transmission of shear waves through the solid sample, the insight gained implies that a backward propagating Scholte–Stoneley wave generated for a certain frequency on a periodically corrugated surface may result in a backward shift for that frequency in all fields generated. Thus, ultrasonic backward beam displacements are not only a reflection phenomenon but may also be observed in transmission.

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