Backward displacement of ultrasonic waves reflected from a periodically corrugated interface

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Experiments using the schlieren technique to image sound incident on a corrugated, water-brass interface show a backward displacement of the reflected beam at an angle of 22.5°, confirming the observations of Breazeale and Torbett [Appl. Phys. Lett. **29**, 456 (1976)]. However, the present theory hypothesizes that this beam displacement results from excitation of a type of leaky surface wave. Further experiments with a sufficiently narrow incident beam reveal a backward displacement also at angles around 44°, resulting from excitation of Rayleigh surface waves, as predicted by the theory of Tamir and Bertoni [J. Acoust. Soc. Am. **61**, 1397 (1971)]. Thus, a wide beam gives a backward displacement at 22.5° only. A narrow beam gives a backward displacement also at angles around 44°. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1858880]

I. INTRODUCTION

The Goos–Hänchen theory predicts that light incident near the critical angle on a dielectric interface from an optically denser medium has a reflected beam that is laterally shifted from the position predicted by geometrical optics.[1] The incident light beam transfers a portion of its energy into the optically rarer medium and excites an electromagnetic field that travels longitudinally for a certain distance along the interface. This energy is leaked back into the denser medium and interferes with the specularly reflected beam. This interference results in a reflected beam which exhibits a lateral displacement that appears as a forward beam shift. More complex structures such as multilayered media and periodically corrugated configurations of the optical-grating-type guide electromagnetic fields of the leaky-wave variety as well. The lateral displacement of a light beam reflected from a leaky-wave structure when a Gaussian light beam is incident upon it was studied by Tamir and Bertoni.[2] The theory of Tamir and Bertoni[2] predicts that at a certain critical angle, a reflected beam shift may occur either in the forward or in the backward direction with respect to the incident beam.

The early experiments of Schoch[3,4] using the acoustic analog of the Goos–Hänchen effect for an ultrasonic beam reflected from a liquid–solid interface showed a forward lateral displacement of the reflected ultrasound beam. Later, Breazeale and Torbett,[5] using a schlieren photographic technique, observed a backward beam shift of a 6-MHz ultrasonic beam of 10-mm width, reflected from a superimposed periodic grating, confirming the backward beam displacement predicted by the theory of Tamir and Bertoni.[2] Angles of incidence are measured from the normal to the surface. According to the theory of Tamir and Bertoni,[2] the angle of incidence θ_i at which the phenomenon occurs is 41° for an ultrasonic beam of frequency of 6 MHz and is imaginary for 2 MHz; thus the effect would not be observed at 2 MHz. If this theory is valid, at $\theta_i = 41°$, leaky Rayleigh surface waves with a velocity of 2015 m/s should be excited on a corrugated brass reflector leading to a backward beam shift. The experiment confirmed the existence of a surface wave at 6 MHz, but not at 2 MHz, when frequency was the only parameter altered in the system. The predicted angle for a 6-MHz beam is significantly different from the value of 22.5° measured by Breazeale and Torbett.[5] Using the measured angle of incidence of 22.5°, they calculated the velocity of this leaky surface wave as 1470 m/s, which is considerably smaller than that of the Rayleigh surface wave. This suggests that either the theory of Tamir and Bertoni[2] does not accurately describe the backward displacement phenomenon or that the surface wave that is responsible for the phenomenon differs from the leaky Rayleigh wave.

Recently, Declercq *et al.*[6,7] used the inhomogeneous wave theory to account for the discrepancies between the predictions of Tamir and Bertoni[2] and the experimental observations of Breazeale and Torbett.[5] They represented a bounded ultrasonic beam as a sum of infinite inhomogeneous waves and applied the theory of the diffraction of inhomogeneous waves to account for the behavior of each individual wave upon incidence on the periodically rough surface. Furthermore, they applied sign reversal rules, based on experiments, as described by Deschamps.[8] Using this approach, Declercq *et al.*[6,7] have calculated the angle of incidence for the generation of leaky surface waves in order to resolve disagreements between theory and experiment. Their calculated value of the angle of incidence agrees very well with our measured value. However, the most striking result of the inhomogeneous wave theory is the prediction of the excitation of a kind of leaky surface wave[7] on a periodically corrugated brass-water interface that is different from the leaky

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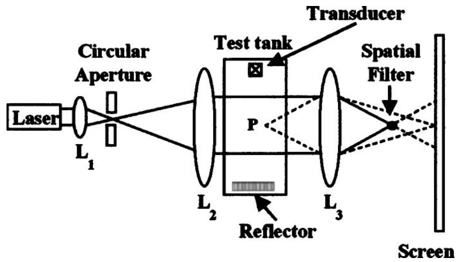

FIG. 1. Experimental setup of the schlieren optical system.

Rayleigh wave. Declercq *et al.*[7] also showed that in the vicinity of the angle of 44°, where Breazeale and Torbett[5] expected only a backward beam displacement due to leaky Rayleigh waves, there is excitation of propagating leaky Rayleigh waves which may result in changes of the beam profile but probably not in an outright backward beam displacement. It was also shown that any such changes in the beam profile can occur only near 44° when a bounded beam is used that is narrower than the one of 10-mm width that was used in the original experiments of Breazeale and Torbett.

Here, we report experimental results obtained with modern imaging techniques using a bounded beam with only 6-mm beam width. This allowed us to study the cause of the backward displacement at 22.5° and to verify the prediction of Declercq *et al.*[6,7] that changes in the beam profile can occur for such a narrow beam around 44°. These experiments indicate that the backward beam shift is caused by the generation of a Scholte–Stoneley-like surface wave and that indeed there are changes in the beam profile around 44° when a narrow beam is used instead of the wider beam used in the original experiments.

II. EXPERIMENT

The schlieren photographic technique was used to image an incident ultrasonic bounded beam reflected by a periodically corrugated brass surface. Figure 1 is a schematic of the experimental setup. To provide a large field of view, two large ($f/6.3$, 48-in. focal length) lenses were chosen. A monochromatic laser light is focused by the first lens L_1 onto a circular aperture (diameter of 15 μm) that is placed at the focal point of lens L_1. After passing through the aperture, the light is collimated by lens L_2 and passes through the test tank. Two extreme light rays from the source passing parallel through the test tank are shown in Fig. 1. The light rays are then focused by a third lens L_3. They pass through a focal point, provide an inverted image on the screen. An object placed inside the test tank, such as a reflecting surface or a transducer, thus can be imaged. A black ink spot is placed at the focal point of the third lens L_3 to act as a spatial filter.[9] The black spot obstructs all the light and produces a dark screen, except for regions where the medium is disturbed by sound or by a density gradient of any kind. In our experiments, the test tank is filled with water that is disturbed by ultrasonic waves which produced the beams seen in our pictures.

A 6-MHz apodized quartz transducer is used to generate the bounded ultrasonic beam of 6.0-mm width. This beam is reflected from a brass interface ruled with square parallel grooves of period $d=0.178$ mm and depth $t=0.025$ mm (Fig. 2). The angle of incidence of the beam is varied in order to observe the angles at which the backward beam displacement occurs. Figure 2 shows the arrangement of the transducer and the reflection diffraction grating. The inset in Fig. 2 is a photograph of a side view of the ruled section of the grating as seen under a microscope. The schlieren image on the screen is recorded by a digital camera connected to a computer with image acquisition and analysis software.

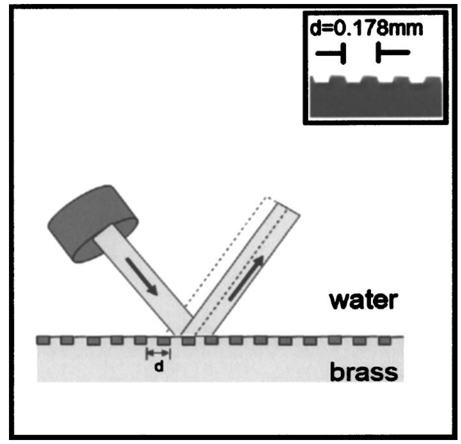

FIG. 2. Schematic arrangement of the transducer and grating shown in Fig. 1. The inset is a photograph of the ruled section of the grating.

III. RESULTS AND DISCUSSIONS

A schlieren image of an ultrasonic beam of frequency of 6 MHz and a width of 6 mm, reflected from a brass-water interface, is shown in Fig. 3. For many angles of incidence, the angle of the reflected beam is equal to that of the incident beam, and the reflected beam experiences no lateral displacement. As the angle of incidence is varied, the first-order diffracted beam appears in addition to the reflected beam, as is shown in Fig. 3. As the incident angle approaches 22.5°, in Fig. 4, the first-order diffracted beam approaches the tangent to the surface; also, illumination of the top surface of the brass reflector is visible. As is seen on the left of the figure, the illumination extends beyond the left edge of the corrugated sample. In fact, the illumination is caused by a surface

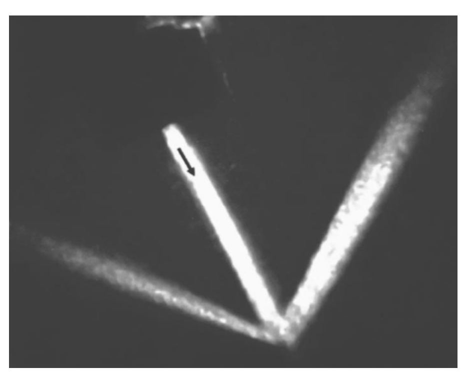

FIG. 3. Schlieren image of a 6-mm-wide ultrasonic beam incident upon a brass reflector at a certain angle of incidence different from any critical angle.

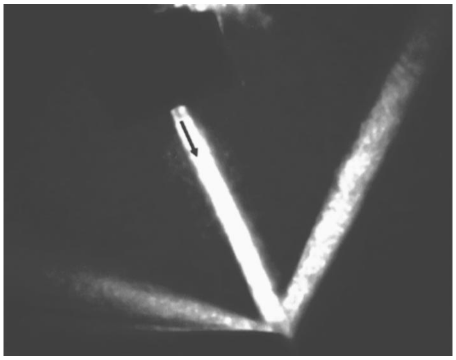

FIG. 4. Schlieren image of a 6-mm-wide ultrasonic beam incident upon a brass reflector at an angle of incidence slightly larger than 22.5°; besides a diffracted beam near the interface, a sound beam is visible which propagates along the interface, being scattered in the forward direction at the extremity of the sample.

wave that is scattered in the forward direction when reaching the edge of the sample. This suggests that the generated surface wave is of the Scholte–Stoneley type. According to Briers *et al.*,[10] such a surface wave is scattered primarily forward when reaching the edge of a plate.

Figure 5 shows the schlieren image in the case of a bounded beam incident at exactly 22.5°. Although illumination of the surface is still visible, a distinct backward displacement is not observed because the incident beam is much narrower than that in the original experiments of Breazeale and Torbett.[5] This phenomenon was predicted by Declercq *et al.*[6] Furthermore, they predicted that the backward displacement occurs naturally for wide beams, as is seen in Fig. 6 for a 12-mm wide beam. For narrow beams they also showed that at angles around 44° either forward or backward propagating leaky Rayleigh waves can be generated. Narrow beams are more likely to show variations of the beam profile at this angle. Indeed, in Fig. 7 we see that alterations of the beam profile of the reflected bounded beam are visible for a narrow beam of 6-mm width. For the wider beam they were not observed.[5]

As described, when the angle of incidence is equal to the angle of 22.5°, a reflected wide beam is laterally displaced backwards to a sizable extent, as is shown in Fig. 6. As can be seen from Figs. 3–5, the ultrasonic phenomenon is a dif-

FIG. 5. Schlieren image of a 6-mm-wide ultrasonic beam incident upon a brass reflector at 22.5°; a sound field is visible on the interface in the backward direction, being scattered in the forward direction at the extremity of the sample. This is evidence that it is a Scholte–Stoneley wave.

FIG. 6. Same situation as in Fig. 5, except that the width of the incident beam is now 12 mm.

fraction phenomenon, so the mathematical representation of the experiments by means of diffraction of inhomogeneous waves to account for the backward beam displacement seems appropriate. It is known that for a bounded ultrasonic narrow beam incident on a water-brass interface, the condition for total internal reflection is given by[5]

$$\sin \theta_i = \frac{1}{K_{\text{liq}}}\left(\frac{2\pi}{d} - K_R\right) = V_{\text{liq}}\left(\frac{1}{fd} - \frac{1}{V_S}\right), \tag{1}$$

where d is the period, f is the frequency, V_{liq} is the propagation velocity in the liquid, and V_S is the propagation velocity of the leaky wave. At this angle, the incident beam interacts strongly with the leaky-wave field since it is phase matched to one of the space harmonics of the leaky wave. This interaction leads to an additional reflected beam which is laterally displaced in the negative x direction. (Note that the right-hand side of Eq. (1) can become greater than unity for certain values of the frequency f corresponding to an imaginary angle of incidence, at which angle the phenomenon of backward displacement is not observed.)

Using the measured values of $\theta_i = 22.5°$, $d = 0.178$ mm, and $V_{\text{liq}} = 1490$ m/s, one calculates, using Eq. (1), the propagation velocity of the leaky surface wave $V_S = 1470$ m/s. This value is considerably smaller than the propagation velocity of a leaky Rayleigh wave (2015 m/s) and is reasonable for a Scholte–Stoneley wave. Nevertheless, its influence on the reflected beam can only be explained by considering it to be of the leaky type, again in agreement with Ref. 7.

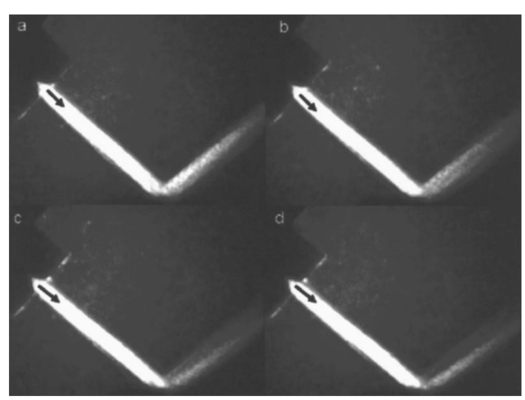

FIG. 7. Schlieren pictures of a 6-mm-wide bounded beam, incident at angles in the vicinity of 45. Changes of the reflected beam's profile are visible.

IV. POSSIBLE APPLICATIONS

Scholte–Stoneley waves are excellent tools to examine the smooth surface and subsurface region of a solid immersed in water. Their basic advantages are a small penetration depth and propagation without energy loss over large distances. Nevertheless, they are hard to generate. One of the techniques of Scholte–Stoneley wave generation is the use of a small diffraction grating created on the smooth surface. Only normal incidence has been studied in detail; however, for some applications in the field of nondestructive testing or in underwater acoustics, normal incidence is not realizable—then oblique incidence is required. It is shown[11] that the generation of Scholte–Stoneley waves is possible for oblique incidence in the forward direction and it is explained[7] that for oblique incidence, stimulation of Scholte–Stonely waves is less outstanding, and actually only results in a leaky form of these waves. The current paper proves for oblique incidence that Scholte–Stoneley waves are indeed leaky, and that it is possible to generate them in the backward direction—resulting in the backward beam displacement. This phenomenon is of interest when backward-propagating Scholte–Stoneley waves are to be generated in a situation where only forward oblique incidence is possible.

V. CONCLUSIONS

The experiments of Breazeale and Torbett[5] have been verified. When sound is incident on a corrugated brass surface, backward beam displacement can be observed. This backward displacement appears at 22.5°, rather than at 41°, as predicted by the theory of Tamir and Bertoni.[2] Present experiments show that there is a generation of some other type of surface wave with a velocity far below that of a Rayleigh wave. This work confirms the excitation of a leaky surface wave at 22.5°, and provides visual evidence that it exhibits the behavior expected by a Scholte–Stoneley-type of wave,[7,9] in agreement with the theory developed by Declercq *et al.*[6,7]

The narrow beam predictions of Declercq *et al.*[7] are also verified. A beam 6 mm in width (as opposed to the 10-mm beam used in the original experiments of Breazeale and Torbett[5]) causes the excitation of a leaky Rayleigh wave for angles of incidence near 44°, which is near the angle predicted by Tamir and Bertoni.[2]

The backward beam displacement is accompanied by backward-propagating leaky Scholte–Stoneley waves, which is of interest in nondestructive testing when only oblique incidence is feasible in the forward direction.

ACKNOWLEDGMENT

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