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Abstract
A Lamb wave resonance has been found that allows unusually efficient transmission of airborne sound waves through plates. This occurs at the zero-group-velocity point at the frequency minimum of the first-order symmetric (S1) Lamb mode. At this frequency, plane waves with a range of incident angles can couple between the air and the Lamb mode in the solid plate, dominating the spectrum of transmitted focused sound beams by 10 dB or more. We use this frequency for C-scan imaging, and demonstrate the detection of both a 3.2-mm-diameter buried flaw and a subwavelength thickness changes of .005l ~1%!.

Keywords
lamb waves, nondestructive testing, nondestructive evaluation

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Air-coupled acoustic imaging with zero-group-velocity Lamb modes

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A Lamb wave resonance has been found that allows unusually efficient transmission of airborne sound waves through plates. This occurs at the zero-group-velocity point at the frequency minimum of the first-order symmetric (S_1) Lamb mode. At this frequency, plane waves with a range of incident angles can couple between the air and the Lamb mode in the solid plate, dominating the spectrum of transmitted focused sound beams by 10 dB or more. We use this frequency for C-scan imaging, and demonstrate the detection of both a 3.2-mm-diameter buried flaw and a subwavelength thickness changes of .005λ (1%).
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The analysis of Lamb wave guided modes has long been used as a tool for materials testing. In their purest form, Lamb wave modes are propagating mechanical transverse resonances in plates. We have found a phenomenon of particularly efficient coupling that occurs at zero group velocity regions of Lamb guided modes when excited from the air. The Lamb wave resonance at the zero group velocity point at the minimum frequency of the S_1 mode dominates air-coupled transmission through plates, and can be used to enhance the sensitivity of a C-scan. Because it has zero group velocity, energy coupled into this mode does not propagate away from the region of excitation in the plane of the plate. We demonstrate the exploitation of this mode for high-sensitivity imaging applications.

Air-coupled ultrasonic testing dates from the 1971 work of Luukkala *et al.*,[1] who pioneered not only the experimental apparatus, but also the application of guided Lamb modes to air-coupled measurements. While Lamb mode resonances have long been used in water immersion for ultrasonic testing, and systems are now deployed industrially,[2] few air-coupled Lamb wave measurements have been performed until recently. The air-coupled C-scan was developed and exploited from the mid 1980s as a nondestructive testing technique.[3] Safaeinili *et al.*[4] introduced quantitative air-coupled measurement of viscoelastic stiffnesses through Lamb wave resonances in 1996. More recently, Wright and Hutchins[5] performed broadband air-coupled bulk wave resonance measurements on metals, and Hosten and Castaings[6] developed a broadband, focused transducer system by combining a flat broadband capacitive transducer with a parabolic mirror.

In this letter, we report measurements exhibiting an air-coupled zero group velocity resonance phenomenon, and the application of that resonance to noncontact acoustic imaging and nondestructive testing. We generate a broadband, focused ultrasonic effective impulse incident on one side of a plate, and measure, using an identical focused sensor, the transmitted wave form. This transmitted wave form is dominated by a resonance that occurs at the point of zero group velocity located at the minimum frequency in the first-order symmetric (S_1) Lamb wave guided mode. We spatially scan the transducers stepwise along the surface of the plate and plot variations in the transmitted amplitude at the resonance frequency as a C-scan image. A scan at or near the resonant frequency gives far better sensitivity and better consistency in discontinuity identification than scans at any other frequencies.

The transmission of airborne ultrasound through solid materials is seriously hampered by the difference in acoustic impedance between air and the solid. Nevertheless, acoustic resonances in a plate can allow full transmission of an airborne ultrasonic plane wave from one side of a plate to the other. Luukkala[1] showed analytically that plane waves in the air incident on a plate would, for particular frequencies and angles of incidence, be fully transmitted through the plate. These frequencies and angles of incidence correspond to phase matching into Lamb wave modes within the plate. Not every Lamb mode exhibits full transmission, but in general, plane waves at angles corresponding to Lamb wave phase matching exhibit much higher transmission than predicted on the basis of average acoustic impedance mismatch. Unfortunately, the range of angles that couple into a particular mode at a particular frequency is very small, as reported by Zhang,[7] so that actual transmission efficiencies remain quite low, whereas real (finite) transducers generate a spectrum of plane waves with only a fraction of the energy at the angles required for efficient coupling.

Figure 1 shows the Lamb wave dispersion relation, in which frequency is plotted as a function of in-plane wave number, for 5.46-mm Lucite™ (poly methyl methacrylate). In order to couple between the air and a guided mode, the trace velocities of the incident wave in the air and the guided mode in the plate must match. That is, the incident wave vector projected onto the plane of the plate must match the wave number of a guided mode. The group velocity of a mode, the speed of its in-plane energy propagation, is given

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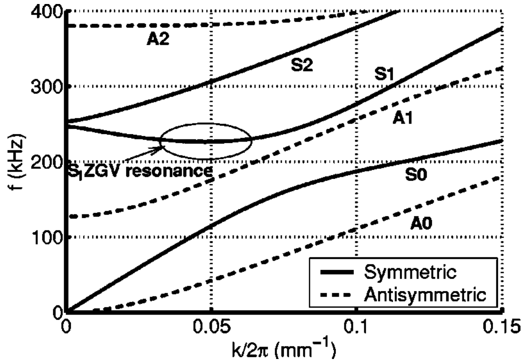

FIG. 1. Dispersion relation of Lamb modes for Lucite, calculated from theory and nominal elastic parameters ($C_{11}=8.6$ GPa, $C_{12}=4.1$ GPa, $\rho=1191$ kg/m^3).

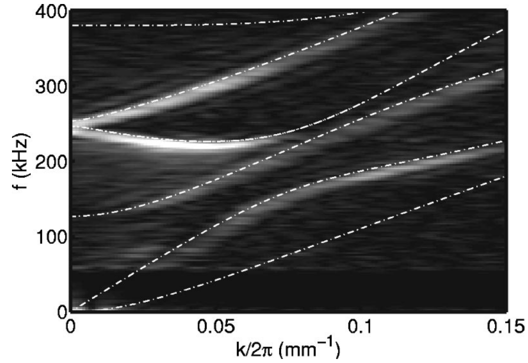

FIG. 3. Measured dispersion spectrum of 5.46-mm Lucite, with the calculated dispersion curves of Fig. 1 overlaid.

by its slope on Fig. 1, $v_g=d\omega/dk=df/d(k/2\pi)$. At a point of zero group velocity, a range of incident projected wave numbers, corresponding to a range of incident angles, can couple into the guided mode at nearly the same frequency, and therefore we find efficient transmission. Furthermore, because the energy at the zero group velocity point of the Lamb mode does not propagate in the plane of the plate, it remains localized where it was excited and reradiates into the air at that location. One such point of zero group velocity, marked with an oval on Fig. 1, exists at what we will call the S_1 minimum frequency zero group velocity resonance and abbreviate as S_1ZGV. Figure 2 shows the wave form and spectrum from a focused, broadband airborne impulse source transmitted through Lucite. We observe a phenomenon of strong transmission located approximately at the S_1ZGV resonance. In contrast, only limited transmission is observed at 246 kHz, the frequency corresponding to the lowest order longitudinal wave resonance in the plate. Figure 3 shows a measured dispersion spectrum of the 5.46-mm-thick Lucite. This spectrum was measured by extending the method of Fei and Chimenti,[8] position scanning of two focussed probes, to guided wave measurements in air. We fix the detector in one position and record the transmitted wave form as a function of source position (x,y). Figure 3 represents a measurement of the Lamb wave mode structure of the plate, and a bright spot, such as that at the minimum of the S_1 mode, corresponds to efficient coupling. For purposes of comparison, theoretical predictions of the plane wave transmission coefficient of Fig. 1 have been overlaid as dashed lines. From these results, the 223-kHz resonance observed in Fig. 2 corresponds to the S_1 ZGV point at the frequency minimum in the S_1 mode near $k/2\pi=.05$ mm^{-1}. In contrast to pure shear or longitudinal resonances such as the Lamb mode cutoffs, this resonance exists at nonzero in-plane k (finite phase velocity) and exciting it requires a small-diameter or focused transducer. This resonance consists of waves propagating in the plane of the plate, but with no net in-plane energy propagation.

We have observed this same resonance in transmission measurements on a variety of other materials, including aluminum and several composites. The amplitude of the S_1ZGV resonance is generally dominant over other frequencies by a factor of 10 dB or more. The efficient transmission of the S_1ZGV resonance and the inherent dependence upon dispersion characteristics lead to its utility as a measurement tool for nondestructive testing.

Air-coupled C-scans are useful as a nondestructive testing and imaging tool because of their noncontact nature. Typically, these C-scans are spatially scanned narrowband measurements of the transmission amplitude at a particular frequency that provide a spatial image of inhomogeneities. Selecting the C-scan frequency to be at or near the S_1ZGV resonance yields a dramatic improvement in signal strength compared to any other frequency. Figure 4(a) shows a 218-

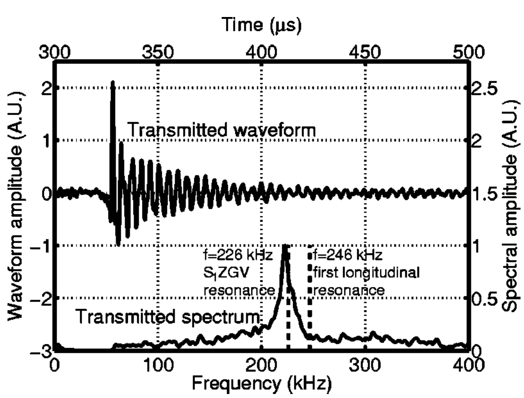

FIG. 2. Wave form and spectrum of ultrasound transmitted through 5.46-mm Lucite.

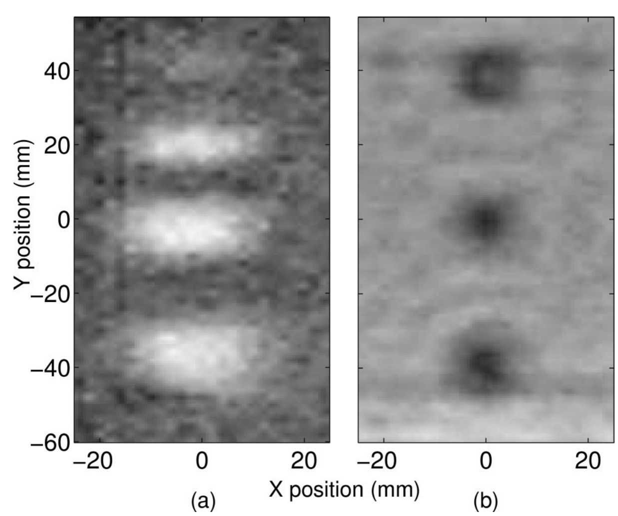

FIG. 4. (a) Air-coupled C-scan image of Scotch-tape strips on Lucite, 218 kHz, (b) Air-coupled C-scan image of Teflon inserts buried within carbon fiber epoxy, 186 kHz.

kHz C-scan of a series of strips of Scotch™ tape on 5.46-mm-thick Lucite, for a thickness change of 1% (.005λ). Strips of width 18.4, 13.1, and 8.8 mm are visible bottom to top in Fig. 4(a). A strip 3.7 mm wide was too small to resolve and does not appear in the image. Measurements at frequencies more than 14 kHz away from the S_1ZGV resonance show none of the strips. Figure 4(b) shows a 186-kHz C-scan of an 8.1-mm-thick graphite–epoxy composite plate with buried Teflon™ inserts that simulate flaws. The inserts, from bottom to top, have diameters of 6.4, 4.8, and 3.2 mm. While the 186-kHz scan does not differentiate between sizes of the inserts, it does detect the presence of each simulated flaw, even the smallest. Only at the 186-kHz resonant frequency were all the simulated flaws clearly visible. At other frequencies, a subset of flaws were visible.

The resonance at the minimum frequency of the S_1 Lamb wave mode has zero group velocity and couples extremely efficiently from air into a solid medium, dominating other modes by at least 10 dB. We have shown the ability to resolve a 1% thickness change for Lucite with a thickness of 8.8 mm and the ability to consistently identify Teflon inserts in a carbon fiber epoxy laminate. Unlike pure longitudinal or shear wave resonances, this resonance exists at nonzero k, and exciting it requires a small-diameter or focused transducer. Its efficiency and dominance combine to make it demonstrably useful for imaging and air-coupled ultrasonic nondestructive testing.

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