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The well known zero in the group velocity of the first-order symmetric (S_1) plate wave mode has been exploited in air-coupled ultrasonic imaging to obtain significantly higher sensitivity than can be achieved in conventional air-coupled scanning. At the zero group velocity point at the frequency minimum of the S_1mode, a broad range of wavenumbers couple into the first-order symmetric mode at nearly a constant frequency, greatly enhancing transmission at that frequency. Coupled energy remains localized near the coupling point because the group velocity is zero. We excite the mode with a broadband, focussing, air-coupled transducer at the frequency of the zero group velocity point in the S_1 mode. By exploiting the efficient coupling at the zero group velocity frequency, we have easily imaged a single layer of Scotch tape attached to a 6.4-mm thick Plexiglas plate and 3.2-mm Teflon inserts in a composite laminate.

Keywords

nondestructive testing, nondestructive evaluation, Lamb waves, Guided modes, Zero group velocity, Ultrasonic imaging, Air-coupled ultrasound, S1

Disciplines

Aerospace Engineering

Comments

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High contrast air-coupled acoustic imaging with zero group velocity Lamb modes

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The well known zero in the group velocity of the first-order symmetric (S_1) plate wave mode has been exploited in air-coupled ultrasonic imaging to obtain significantly higher sensitivity than can be achieved in conventional air-coupled scanning. At the zero group velocity point at the frequency minimum of the S_1 mode, a broad range of wavenumbers couple into the first-order symmetric mode at nearly a constant frequency, greatly enhancing transmission at that frequency. Coupled energy remains localized near the coupling point because the group velocity is zero. We excite the mode with a broadband, focussing, air-coupled transducer at the frequency of the zero group velocity point in the S_1 mode. By exploiting the efficient coupling at the zero group velocity frequency, we have easily imaged a single layer of Scotch tape attached to a 6.4-mm thick Plexiglas plate and 3.2-mm Teflon inserts in a composite laminate.

Keywords: Lamb waves, guided modes, zero group velocity, ultrasonic imaging, air-coupled ultrasound, S1 mode.

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1 Introduction

We have found a Lamb wave resonance that allows unusually efficient transmission of airborne sound waves through plates. This resonance occurs at a point of zero group velocity, located at the frequency minimum of the first order symmetric (S_1) mode. At the zero group velocity frequency there is particularly efficient acoustic coupling between the air and the plate, because a range of angles can couple at the same frequency. Energy at the zero group velocity point does not propagate along the plate, but instead remains localized. The net result is that this resonance dominates the transmission of focussed broadband sound waves. We apply this resonance to the non-contact air-coupled imaging of defects and discontinuities in plates.

Air-coupled ultrasonics was first developed as a tool for materials testing by Luukkala et al. [1] in 1971 using the capacitive air-coupled ultrasonic transducers of Kuhl et al. [2]. The development in the early 1990's of a highly optimized commercial system [3] made high sensitivity narrowband air-coupled ultrasonic measurement practical, with the limitation of operating only at a few preselected frequencies. While our imaging method, can be implemented with a narrowband system, we use broadband methods to identify optimal frequencies. In our measurements we use the broadband transducers of the type developed by Schindel et al. [4] combined with parabolic focussing mirrors and a pulse compression technique. In this paper, we expand and elaborate on our previously introduced [5] method for air-coupled ultrasonic imaging of discontinuities in plates.

2 Zero group velocity

Lamb waves are guided acoustic waves in plates. They have complicated, but well understood, modal structure and dispersion relations. At a point (ω, k) of zero group velocity, the spatial envelope of a guided Lamb wave of angular frequency ω propagating with in-plane wavenumber k remains fixed and does not move as the wave propagates. At a point of zero group velocity with non-zero phase velocity, the wave propagates spatially, but under a motionless envelope; energy does not propagate in the plane of the plate.

The dispersion relation of Lamb waves in a 5.72-mm glass plate, calculated from well known theory [6], is given in Fig. 1. On this plot, phase velocity at a point (ω, k) on a dispersion curve can be determined by measuring the slope of a line from the origin to that point, $c_{ph} = \omega/k$ or $f/(k/2\pi)$. The group velocity can be determined by measuring the slope of the dispersion curve itself, $c_{gr} = d\omega/dk$ or $df/d(k/2\pi)$. Any point of zero slope is a point of zero group velocity.

Each intercept with the vertical axis on Fig. 1, except those at zero frequency, is a point of zero group velocity. These mode cutoffs correspond to pure longitudinal or shear resonances with propagation normal to the plane of the plate. Most materials also have a zero group velocity point at finite phase velocity at the minimum frequency of the S_1 mode,

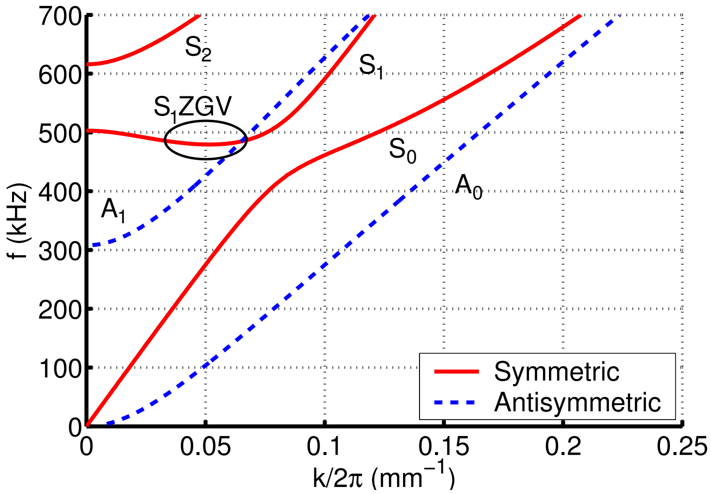

Figure 1: Calculated dispersion relation for 5.72-mm glass. c_l=5.8 mm/μs, c_s=3.5 mm/μs, ρ=2500 kg/m^3.

marked with an oval on Fig. 1. We will refer to the S_1 mode in the vicinity of this zero group velocity point as the S_1ZGV resonance.

External coupling to a Lamb wave requires a phase match of the incident beam to the guided mode; the incident beam must be at exactly the correct angle. At most frequencies, only a few discrete incident angles satisfy the phase match criterion, so only the small portion of incident energy at those angles can couple into Lamb modes. At a zero group velocity point, a range of incident angles (range of k) can couple at the same frequency. Therefore, when a focussed beam (range of angles) at the zero group velocity frequency is incident on a plate, the entire range of angles near the zero group velocity point is transmitted efficiently from the air to the plate and through the plate to the air on the opposite side at that frequency, leading to dramatically higher transmission. We have found in our measurements that the transmission spectra of focussed beams incident on plates tend to be dominated by the S_1ZGV resonance by a factor of 10 dB or more. One such waveform and spectrum, for 5.72-mm glass, is shown in Fig. 2. Here, the transmission peak is clearly located at the frequency minimum of the S_1 mode and is distinct from the expected frequency for the lowest order pure longitudinal wave resonance. A dispersion spectrum, measured by extending the methods of Safaeinili et al. [7] and Fei and Chimenti [8] to two dimensional scanning and by performing a three dimensional Fourier transform, is shown in Fig. 3. Transmission efficiency determines the brightness of modal curves in the dispersion spectrum, and clearly the S_1ZGV frequency dominates transmission. Unlike pure longitudinal or shear resonances (mode cutoffs), the S_1 mode at this point propagates in the plate with non-zero in-plane k (finite phase velocity), but with no in-plane energy propagation because of the zero group velocity. Exciting the S_1 mode at this point requires a small diameter or focussing transducer; a plane wave at normal incidence cannot couple. While the zero group velocity point dominates transmission of focussed air-coupled ultrasound through plates, in water immersion the loading effect of the water reduces the sharpness or quality factor (Q) of the Lamb wave resonances and widens the range of coupling angles, independent of frequency.

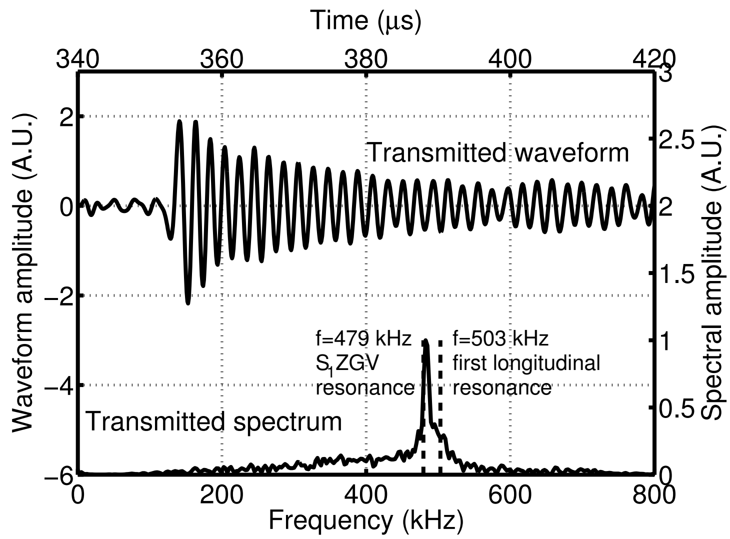

Figure 2: Waveform and spectrum of broadband signal transmitted through glass.

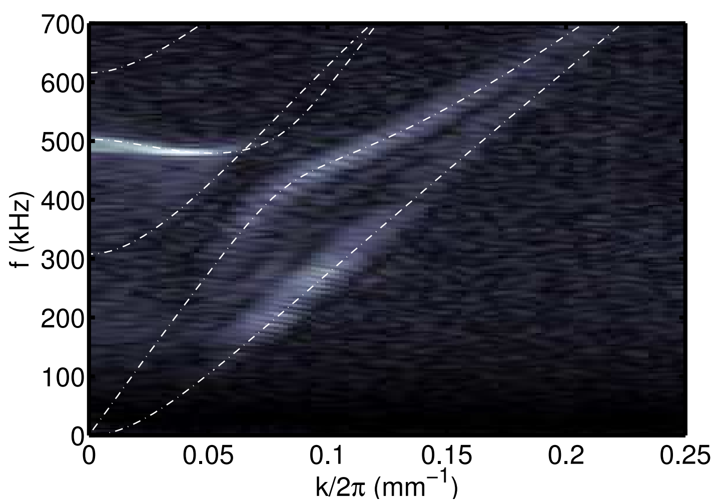

Figure 3: Measured dispersion spectrum for 5.72-mm glass. The calculated curves of Fig. 1 are superimposed as dashed lines.

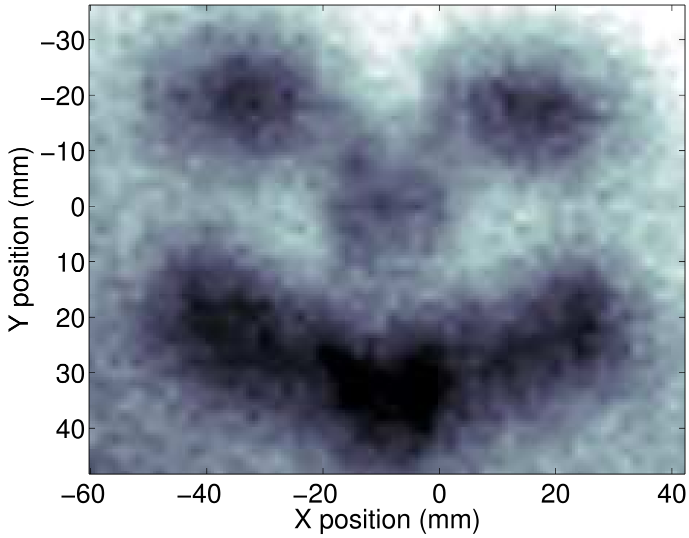

Figure 4: Image of a pattern of scotch tape on Lucite, 226 kHz.

Therefore, the zero group velocity transmission phenomenon is peculiar to the air-coupled environment where mechanical coupling to the fluid is much weaker than in water-coupled experiments.

3 Imaging

The efficient transmission of the S_1ZGV frequency allows transmission measurements with minimal averaging, despite the huge average acoustic impedance contrast between air and most solids. The sensitivity of the mode to changes in material parameter or to discontinuities makes it useful for air-coupled ultrasonic imaging. We create C-scan images of discontinuities by measuring the transmission of a particular frequency as a function of position (x, y). As would be expected, the best results are obtained for measurement frequencies at or near the minimum frequency of the S1 mode.

Fig. 4 shows a 226 kHz scan of a pattern made from one thickness of Scotch tape on 5.46 mm Lucite. The pattern is clearly visible, even though the addition of the tape corresponds to an effective thickness change of 1% (.05 λ). This result can be considered a test of the ability to image small changes in thickness or material parameter. Fig. 5 shows transmitted amplitude, the signal-to-noise ratio (SNR), and relative contrast between the taped and untaped areas of images of the sample in Fig. 4 as a function of the selected measurement frequency. The peak in transmitted amplitude at 222 kHz corresponds to the S_1ZGV transmission peak. The second peak at 480 kHz corresponds to the A_3 mode cutoff (second longitudinal resonance). Because the transmitted amplitude is highest under these conditions the S_1ZGV frequency, the SNR is also maximized in that region, except where there is no contrast and hence no signal.

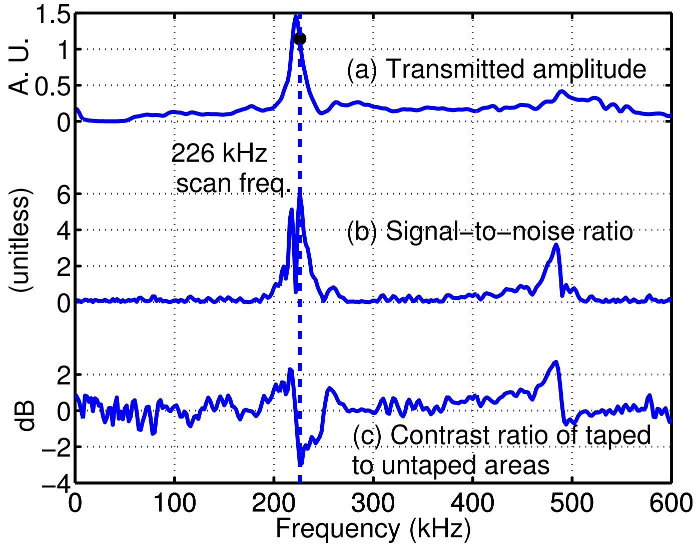

Figure 5: Variation in quality parameters of the image in Fig. 4 as scan frequency is varied: (a) Transmitted amplitude, (b) Signal-to-noise ratio, (c) Contrast ratio of taped to untaped areas of Lucite.

Maximum sensitivity (contrast) to small parameter changes is achieved by operating slightly away from the resonance peak, where the slope of the spectrum is large. The 226 kHz frequency of the Fig. 4 scan is marked by a dot in the transmitted spectrum of Fig. 5. When scanning at a frequency close to the resonance peak, a small shift in the spectral peak caused by a change in material parameters or thickness will lead to a large change in transmission at the scan frequency. This result is confirmed by the contrast plot in Fig. 5. Positive contrast is observed slightly below the spectral peak and negative contrast is observed above. Since the slope of the spectrum at the peak is zero by definition, for a small change in parameters only minimal contrast (in this case -0.2 dB) is observed precisely at the spectral peak.

Often, consistency in identifying discontinuities is more important than absolute sensitivity. The measured amplitude at precisely the peak frequency tends to be reduced by a discontinuity. For example, if the discontinuity causes either the resonance peak to shift or the resonance Q to be reduced, a scan at exactly the resonance frequency would show reduced amplitude and would therefore be expected to provide the best consistency in identifying discontinuities. Fig. 6 shows a 184 kHz scan of a carbon fiber epoxy plate containing embedded Teflon inserts ranging in diameter from 3.2 to 6.4 mm. All inserts have been detected with negative contrast in the 184 kHz scan. Fig. 7 shows how the contrast varies as a function of scan frequency for the different Teflon inserts. Each inclusion size and type has non-zero contrast and is therefore visible over a separate range of frequencies, but all the inclusions appear with negative contrast at the S_1ZGV frequency.

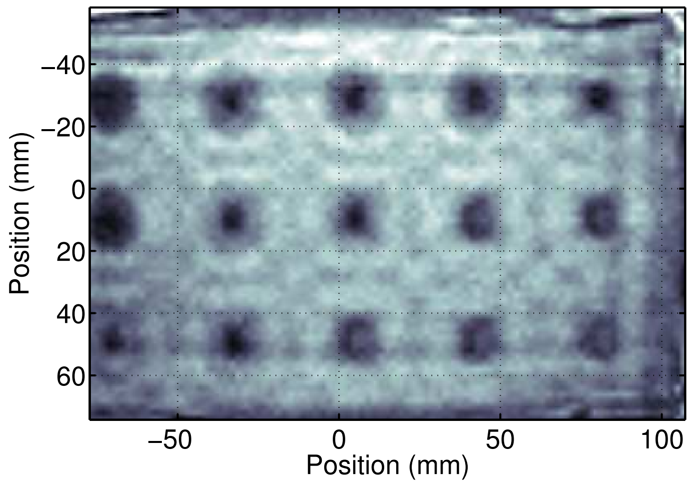

Figure 6: 184 kHz scan of carbon fiber epoxy with 3.2-6.4 mm Teflon inserts

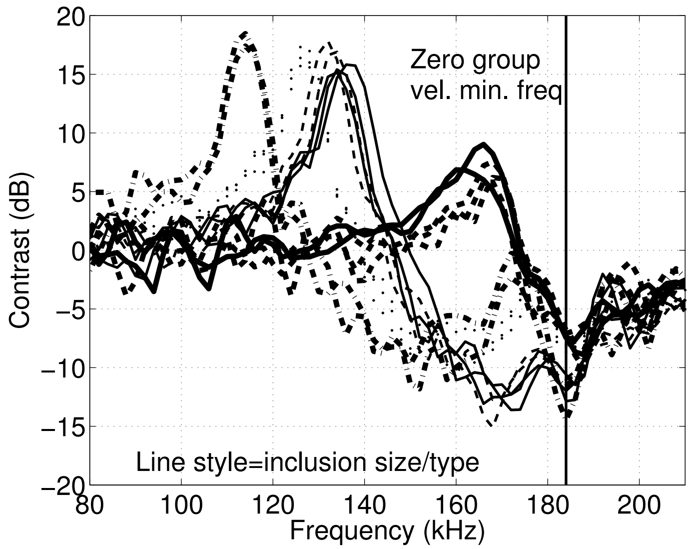

Figure 7: Contrast of inclusions relative to background as a function of scan frequency.

4 Conclusions

The transmission through plates of focussed air-coupled sound beams is dominated by a Lamb wave resonance at the S_1ZGV frequency. Unlike pure longitudinal or shear resonances, the S_1 mode at this point propagates but does not transfer energy in the plane of the plate. We have applied this resonance to C-scan imaging of discontinuities and flaws, and found that selecting the imaging frequency to be at or near the S_1 minimum frequency provides optimum consistency or sensitivity respectively. Use of the S_1 mode minimum frequency zero group velocity point for C-scan imaging provides improved signal to noise ratio and better quality images than conventional techniques.

5 Acknowledgments

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Figure captions

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