7-2003

High-Sensitivity Air-Coupled Ultrasonic Imaging with the First-Order Symmetric Lamb Mode at Zero Group Velocity

Stephen D. Holland
Iowa State University, sdh4@iastate.edu

Dale E. Chimenti
Iowa State University

High-Sensitivity Air-Coupled Ultrasonic Imaging with the First-Order Symmetric Lamb Mode at Zero Group Velocity

Abstract
A new method for high-sensitivity non-contact, through-transmission, air-coupled imaging of small material property changes or discontinuities in plates is demonstrated. Our approach exploits the excitation of the first-order symmetric Lamb wave mode at its minimum frequency point of zero group velocity. Because this Lamb wave resonance couples energy extremely efficiently with the air and does not propagate energy in the plane of the plate, it is the dominant mode of transmission of an airborne focussed-beam broadband impulse through the plate. We take advantage of the sensitivity of this mode by performing C-scans at the frequency of the group-velocity zero to image spatial discontinuities and property changes. Our results show that images measured at this frequency are more sensitive and more consistent than those measured elsewhere in the plate-wave spectrum.

Keywords
ultrasonic imaging, nondestructive testing, plates (structures), Lamb shift, dispersion hardening, signal processing, nondestructive evaluation

Disciplines
Aerospace Engineering

Comments

This article appeared in *AIP Conference Proceedings*, 700 (2004): 687–693 and may be found at http://dx.doi.org/10.1063/1.1711688.

HighSensitivity AirCoupled Ultrasonic Imaging with the FirstOrder Symmetric Lamb Mode at Zero Group Velocity

Stephen D. Holland and D. E. Chimenti

Citation: AIP Conf. Proc. **700**, 687 (2004); doi: 10.1063/1.1711688

View online: http://dx.doi.org/10.1063/1.1711688

View Table of Contents: http://proceedings.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=700&Issue=1

Published by the American Institute of Physics.

HIGH-SENSITIVITY AIR-COUPLED ULTRASONIC IMAGING WITH THE FIRST-ORDER SYMMETRIC LAMB MODE AT ZERO GROUP VELOCITY

Stephen D. Holland[1] and D. E. Chimenti[2]
[1]Center for NDE, Iowa State Univ, Ames, Iowa 50011
[2]Center for NDE and Aerospace Eng Dept, Iowa State Univ, Ames, Iowa 50011

ABSTRACT. A new method for high-sensitivity non-contact, through-transmission, air-coupled imaging of small material property changes or discontinuities in plates is demonstrated. Our approach exploits the excitation of the first-order symmetric Lamb wave mode at its minimum frequency point of zero group velocity. Because this Lamb wave resonance couples energy extremely efficiently with the air and does not propagate energy in the plane of the plate, it is the dominant mode of transmission of an airborne focussed-beam broadband impulse through the plate. We take advantage of the sensitivity of this mode by performing C-scans at the frequency of the group-velocity zero to image spatial discontinuities and property changes. Our results show that images measured at this frequency are more sensitive and more consistent than those measured elsewhere in the plate-wave spectrum.

INTRODUCTION

We have discovered a Lamb guided mode resonance that allows particularly efficient transmission of focussed airborne sound waves through plates. This resonance occurs at the zero group velocity point at the frequency minimum of the first order symmetric (S_1) guided Lamb mode. The plate transmits sound unusually efficiently at the resonance frequency because an unusually wide range of angles can be coupled at that frequency and also because the zero group velocity inhibits propagation of the coupled energy. As a result, this resonance dominates the transmission of focussed sound beams through plates. We demonstrate this phenomenon through both theoretical calculation and experimental measurement, and apply it to the non-contact air-coupled imaging of defects and discontinuities in places.

We can trace air-coupled ultrasonic testing back to the 1971 work of Luukkala et al. [1], who used capacitive ultrasonic air-coupled transducers to measure the Lamb mode structure and mechanical properties of paper. A highly optimized commercial system [2] for narrowband measurements made air-coupled ultrasonics broadly accessible as a research tool starting in the 1990's. We use broadband capacitive micromachined ultrasonic transducers of the type developed by Schindel et al. [3], combined with parabolic focussing mirrors and arbitrary waveform excitation. We use a pulse compression technique [4] and phase-noise excitation to measure impulse-response waveforms. In this paper, we expand and elaborate on our previously introduced ([5] and [6]) discussion of the zero-group-velocity resonance phenomenon and its applications for air-coupled ultrasonic imaging of discontinuities in plates.

CP700, *Review of Quantitative Nondestructive Evaluation Vol. 23,* ed. by D. O. Thompson and D. E. Chimenti

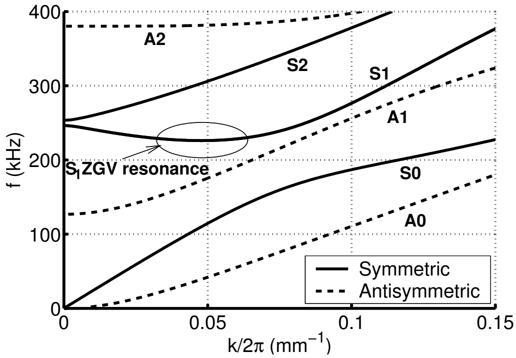

FIGURE 1. Calculated dispersion relation for 5.46-mm Lucite.

ZERO GROUP VELOCITY

A zero group velocity mode is a propagating guided wave where the speed of energy propagation, the group velocity, is zero. Phase and group velocities are determined from the dispersion relation of the waveguide. Figure 1 shows the calculated dispersion relation for a 5.46-mm thick Lucite plate. The phase velocity of a mode at a particular frequency and wavenumber is given by the slope of a line from the origin to $(f, k/2\pi)$ on the dispersion relation. Group velocity is given by the slope of the dispersion curve itself, $df/d(k/2\pi)$. There are four zero group velocity points (horizontal slope) on Fig. 1: The A_1 mode and S_1 modes at cutoff (k=0) have zero group velocity and are equivalent to the lowest order resonances of shear and pressure waves respectively between the faces of the plate. Higher order modes, such as the S_2 and A_2 modes at cutoff, also have zero group velocity and correspond to higher order shear or longitudinal resonances in the plate. Finally, the S_1 mode at its frequency minimum exhibits zero group velocity. We will refer to this zero group velocity point as S_1ZGV. It is unusual because it exists at non-zero k and therefore has non-zero phase velocity. Unlike the other zero group velocity points, it does not correspond to any pure longitudinal or shear resonance, but instead waves at this point contain both shear and longitudinal components. The S_1ZGV wave consists of propagating wavetops under a motionless envelope; energy does not propagate in the plane of the plate.

Zero group velocity modes in general, and the S_1ZGV mode in particular, exhibit unusually strong coupling to sound waves in the air. In general, transmission of sound across an air-solid interface is very small because of the huge contrast in acoustic impedance between the air and the solid. However, it has been shown analytically [1] that under idealized conditions it is possible to achieve full transmission through a solid plate at certain frequencies and angles corresponding to guided modes within the plate. Although in practice full transmission is not possible because attenuative losses spread the Lamb wave resonance peaks, airborne sound does couple through the solid much more efficiently at the angles and frequencies which match phase with guided Lamb modes. Figure 2 shows a measured transmission-mode dispersion spectrum for 5.46-mm Lucite, measured by the scan and transform method of Holland et al. [7]. It shows transmission through the plate as a function of frequency and (horizontally-projected) wavenumber, and illustrates that transmission occurs primarily at angles (wavenumbers) and frequencies corresponding to Lamb modes. The brightness of the S_1ZGV point circled on Fig. 2 illustrates the efficiency of transmission of the S_1 mode at that point.

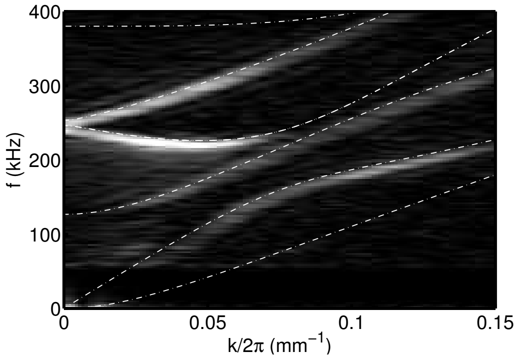

FIGURE 2. Measured transmission dispersion spectrum for 5.46-mm Lucite.

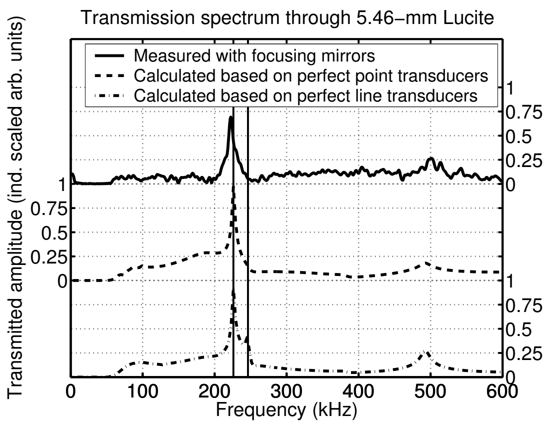

FIGURE 3. Experimental and calculated transmission spectra for 5.46-mm Lucite. The vertical lines indicate the S_1ZGV frequency and the lowest order longitudinal resonance frequency.

We have found that the S_1ZGV frequency dominates transmitted focussed broadband waveforms. At most frequencies, transmission of sound from the air through the sample and into the air on the other side occurs only at or near the discrete wavenumbers (angles) corresponding to Lamb modes. The total transmission at a particular frequency will be the integral of the transmission at each angle over the angular sensitivity range of the transducer. At zero group velocity points, coupling occurs at a single frequency for a much wider range of angles (wavenumbers) than elsewhere. Provided the transducers involved have a wide enough angular range to excite and detect these angles, the zero group velocity frequencies will show much higher transmission. In addition, because the in-plane energy propagation speed is zero at zero group velocity points, energy does not propagate in the plate away from the sensor, but instead stays fixed and reradiates near the point of excitation. Fig. 3 shows measured and calculated spectra of an airborne focussed impulse transmitted through 5.46-mm thick Lucite. The uppermost trace shows an experimentally measured spectrum. The middle and bottom traces are calculated spectra based on assumed point- and line-focus transducers respectively. Vertical lines mark the S_1ZGV and lowest order longitudinal wave resonance frequencies. All three spectra are dominated by the spectral peak at the S_1ZGV frequency. There is also a secondary peak at the lowest order longitudinal wave resonance

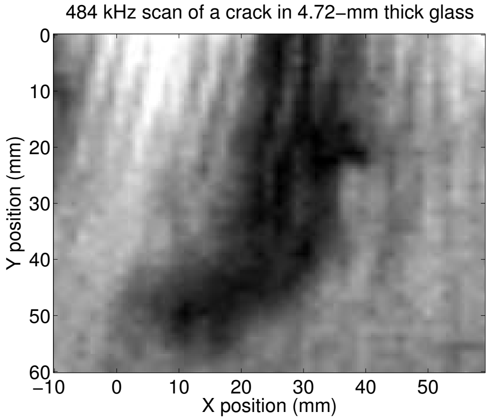

FIGURE 4. S_1ZGV C-scan image of a crack in 4.72-mm thick glass.

(S_1 cutoff at k=0) in the calculated line-focus spectrum. The simulated line-focus transducer transmits the longitudinal resonance better than the simulated point-focus transducer because the line-focus transducer transmits comparatively more energy at normal incidence than the point-focus transducer. Each spectrum also shows a secondary peak at the second longitudinal resonance (A_3 cutoff) at 490 kHz. All of these are zero group velocity modes.

The synthetic transmission spectra were calculated from the elastic parameters of the material and air. This was done by Fourier-decomposing the air-coupled source field into a sum of infinite harmonic plane waves. Boundary conditions were written for the air-solid interfaces on both sides of the plate, and the equations of elasticity for the plate and air were then solved numerically to calculate the transmission of each harmonic plane-wave component. All of these components were added together to calculate the synthetic spectra.

We have observed the S_1ZGV resonance peak to dominate the spectrum of transmitted waveforms, typically by approximately 10 dB, both in experiment and in calculation. This phenomenon is dependent on the use of focussed or point transducers, for sensitivity over the range of angles (wavenumbers) near the S_1ZGV point. It is also dependent on the large acoustic impedance mismatch between air and the solid, because this mismatch both limits transmission to the Lamb modes and maximizes the sharpness of the Lamb mode transmission peaks by maximizing the quality factor (Q) of the Lamb wave resonance.

IMAGING

The high transmission peak and sharp slopes of the S_1ZGV resonance make it useful for imaging. A small change in elastic properties or thickness can cause a large change in transmission. By measuring transmission of a frequency at or near the S_1ZGV point as a function of space, we can generate an image of spatial property variations or discontinuities. Figure 4 shows an image of a crack in 4.72-mm thick glass, measured at the peak S_1ZVG transmission frequency of this sample, 480 kHz. While the resolution observed here is quite limited – apparent resolution is approximately λ or about 1 cm – the actual crack opening is much smaller. So despite the limits on resolution caused by relatively low frequencies and long wavelengths, this method is indeed able to identify cracks with openings much smaller than that.

Figure 5 shows a 218-kHz C-scan of a series of four strips of different width of 60 μm

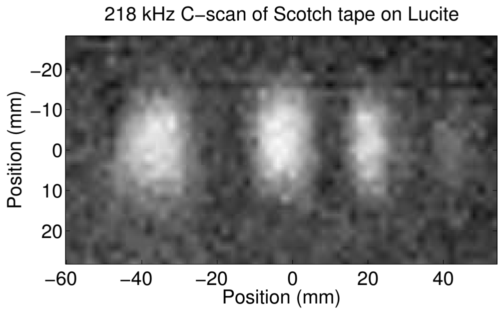

FIGURE 5. S_1ZGV C-scan image of strips of Scotch tape of different widths.

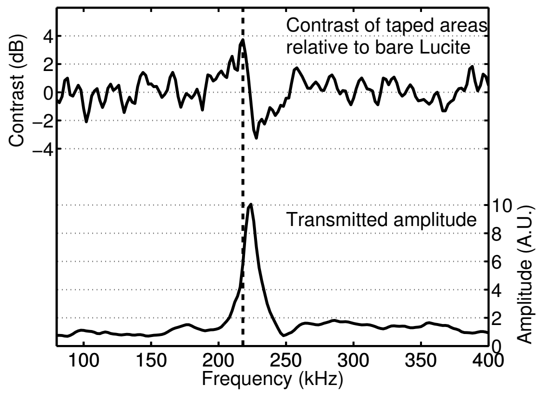

FIGURE 6. Contrast of the tape in Fig. 5 and overall transmitted amplitude as a function of frequency.

Scotch tape on 5.46-mm Lucite. The strips have widths of 18.4 mm, 13.1 mm, 8.8 mm, and 3.7 mm. All but the 3.7-mm strip are clearly visible. This can be considered a resolution test of sensitivity to small (1%) thickness changes, and indicates that the S_1ZGV imaging method has resolution down to order λ even for infinitesimal changes in thickness or material parameter. Figure 6 shows the contrast of the 18.4-mm strip and overall transmission as a function of frequency. Optimal contrast is achieved by using a frequency slightly away from the S_1ZGV peak so where the slope of the spectrum is highest. The vertical dashed line in Fig. 6 indicates 218 kHz, the frequency at which the image in Fig. 5 was measured.

Figure 7 shows a series of three transmission C-scans at different frequencies of a carbon fiber epoxy laminate with 15 embedded inclusions with different sizes and positioning. Fig. 7c shows a transmission scan at the S_1ZGV frequency of 184 kHz. All 15 inclusions are visible as dark spots in a scan at this frequency. For comparison, Figs. 7a and 7b show 124 and 146 kHz scans respectively. We observe that only subsets of the 15 inclusions are visible on Figs. 7a and 7b, and that some appear as bright spots and others as dark spots, while for comparison all inclusions are visible as dark spots on the S_1ZGV scan in Fig. 7c. Figure 7d illustrates why this is the case. It shows contrast as a function of frequency for each of the different types of inclusion. Positive contrast indicates that the inclusion shows up as bright relative to the background, while negative contrast indicates that it shows up dark. We observe that the different inclusions show up arbitrarily as bright, dark, or invisible at different frequencies, except that all show up as dark near the S_1ZGV frequency. The S_1ZGV transmission peak gives the maximum possible air-coupled transmission through the

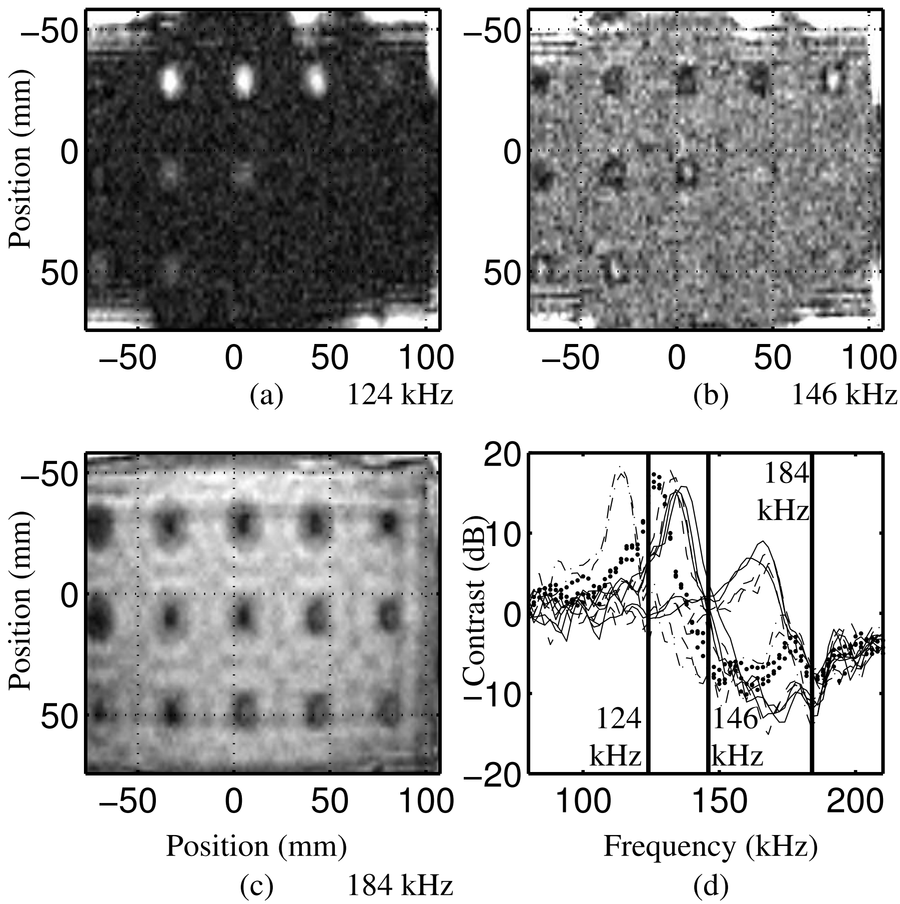

FIGURE 7. (a) 124 kHz transmission C-scan of 8.1-mm carbon fiber epoxy laminate with 3.2-6.4 mm diameter Teflon inclusions. (b) 146 kHz C-scan. (c) 184 kHz S_1ZGV C-scan. (d) Contrast of the different inclusions as a function of frequency. Different line styles indicate different inclusion size and position.

plate, so a change to material properties, such as insertion of an inclusion, will tend to reduce the transmitted amplitude (negative contrast). Measurement at the S_1ZGV frequency will tend to consistently identify inclusions regardless of size or placement (Fig. 7c), while measurements at other frequencies may show some but not others (Figs. 7a and 7b).

CONCLUSIONS

The transmission of broadband air-coupled ultrasound through plates is dominated by a zero-group-velocity Lamb wave resonance at the frequency minimum of the S_1 mode. This is a propagating guided mode but with zero in-plane energy velocity. We have demonstrated the high transmission efficiency of this mode both through experiment and theory-based calculation, and shown its utility for imaging applications. Images with optimal contrast or sensitivity can be obtained selecting a C-scan imaging frequency at or near the S_1ZGV resonance peak.

ACKNOWLEDGMENTS

This material is based on work supported by NASA under award NAG-1-029098. Thanks to Jill M. Cattrysse for performing some of the measurements.

REFERENCES

1. M. Luukkala, P. Heikkila, and J. Surakka, Plate wave resonance – a contactless test method, Ultrasonics **9**, 201-208 (1971).
2. W. A. Grandia and C. M. Fortunko, NDE Applications of Air-Coupled Ultrasonic Transducers, Proc. 1995 IEEE Ultras. Sympos. 697-709 (1995).
3. D. W. Schindel, D. A. Hutchins, L. Zou, and M. Sayer, The design and characterization of micromachined air-coupled capacitance transducers, IEEE Trans. Ultrason. Ferroelec. Freq. Control, **42**, 42-50 (1995)
4. T.H. Gan, D. A. Hutchins, D. R. Billson, D. W. Schindel, The use of broadband acoustic transducers and pulse-compression techniques for air-coupled ultrasonic imaging, Ultrasonics **39** 181-194 (2001).
5. S. D. Holland and D. E. Chimenti, Air-coupled acoustic imaging with zero-group-velocity Lamb modes, Applied Physics Letters **83** 2704-2706 (2003).
6. S. D. Holland and D. E. Chimenti, High contrast air-coupled acoustic imaging with zero group velocity Lamb modes, Accepted for publication, *Ultrasonics International 2003 Proceedings* (2003).
7. S. D. Holland, S. V. Teles, and D. E. Chimenti, “Quantitative air-coupled ultrasonic materials characterization with highly focussed acoustic beams,” presented at *QNDE 2003*, July 27-August 1, 2003, Green Bay, Wisconsin. To be published in this volume.