Applications of the Zero-Group-Velocity Lamb Mode for Air-Coupled Ultrasonic Imaging

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Abstract
Airborne ultrasound couples particularly well into plates at the zero-group-velocity point of the first order symmetric (S1) Lamb mode. Applications of this mode to ultrasonic imaging of plate-like structures are discussed. The sensitivity and high Q of this mode makes it ideal for imaging. Images from a wide variety of materials and samples, including composites and honeycomb structures are presented. Transmission at the zero-group-velocity frequency is shown to be particularly sensitive to nearby flaws and discontinuities, and is therefore suitable for wide-area scanning for cracks or manufacturing flaws.

Keywords
ultrasonic materials testing, ultrasonic velocity, ultrasonic imaging, composite materials, crack detection, nondestructive testing, nondestructive evaluation

Disciplines
Aerospace Engineering

Comments
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APPLICATIONS OF THE ZERO-GROUP-VELOCITY LAMB MODE FOR AIR-COUPLED ULTRASONIC IMAGING

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ABSTRACT. Airborne ultrasound couples particularly well into plates at the zero-group-velocity point of the first order symmetric (S1) Lamb mode. Applications of this mode to ultrasonic imaging of plate-like structures are discussed. The sensitivity and high Q of this mode makes it ideal for imaging. Images from a wide variety of materials and samples, including composites and honeycomb structures are presented. Transmission at the zero-group-velocity frequency is shown to be particularly sensitive to nearby flaws and discontinuities, and is therefore suitable for wide-area scanning for cracks or manufacturing flaws.

INTRODUCTION

The transmission of focussed airborne ultrasound through plates is, as we previously introduced [1, 2], dominated by a zero group velocity Lamb wave resonance. The sharpness of this resonance makes it sensitive, and hence suitable for imaging and non-destructive testing applications. In this paper, we expand on our previous discussion and present additional results and applications.

ZERO GROUP VELOCITY

Any acoustic field in an idealized plate can be represented by a sum of Rayleigh-Lamb guided modes. Each mode has a particular phase velocity (speed of wave crests) and group velocity (energy propagation speed) at each frequency. Figure 1 shows the calculated dispersion relation of Lamb modes in a 5.46-mm Plexiglas plate. Phase velocity is given by the slope of a line from the origin to a particular point on Fig. 1, and group velocity is given by the slope of the dispersion curve itself at that point.

In order to couple from the air to a plate, the spatial distribution of the phase of an incident plane wave must match that of the transmitted wave in the plate. This is a Snell’s law criterion for which the transmitted Lamb wave by definition propagates directly along the plate: \( \sin \theta_i = c_{\text{air}} / c_{\text{Lamb}} \). Only those plane wave components of an incident sound wave at particular angles and frequencies which satisfy Snell’s law for the particular Lamb modes can enter into the plate; the rest must reflect. At a zero group velocity point, a range of angles (range of \( k \)) rather than a single angle can couple into the plate at the same frequency, and hence if the incident broadband beam is focussed (contains a range of angles), much more energy can couple at the zero group velocity frequency than at other frequencies. Moreover,
while energy coupled in to Lamb modes in general propagates through the plate away from the point of incidence, energy coupled to a zero group velocity mode stays at its point of incidence and reradiates from there.

Clearly there are several zero group velocity points on Fig. 1: Each of the $k = 0$ axis intercepts (cutoffs) for high order modes has zero group velocity, and the first order symmetric ($S_1$) mode has a point of zero group velocity at approximately $k/2\pi = 0.05\text{mm}^{-1}$. The $k = 0$ cutoffs are equivalent to through-thickness longitudinal and shear resonances; all points along the plate surface have the same phase (infinite phase velocity). The $A_1$ cutoff is equivalent to the lowest order shear resonance, and transmits poorly because of its lack of normal displacement. The $S_1$ cutoff is equivalent to the lowest order longitudinal resonance, and transmits poorly because the zero group velocity region (in $k$) is very narrow. The $S_2$, $A_2$ and $S_3$ cutoffs are higher order shear resonances and lack normal displacement. The $A_3$ cutoff is the second longitudinal resonance, and ultrasound couples efficiently at that point. In this paper, we will focus our discussions on the zero group velocity point in the $S_1$ mode near $k = 0.05\text{mm}^{-1}$. Unlike the other zero group velocity points, this mode exists at finite $k$; the wave crests move, but the wave envelope remains localized near the excitation point. This mode has substantial normal displacement, and a wide in wavenumber zero-group-velocity point, giving it very efficient coupling between air and a plate. In isotropic materials, its frequency is usually approximately $9/10$ of the longitudinal resonance frequency. In our experiments, we observe this mode to dominate transmitted waveforms by a factor of 10 dB or more. Figure 2 shows calculated and measured transmission spectra for 5.46-mm Plexiglas. The transmission peaks occur in both theory and experiment at the zero group velocity frequency of 226 kHz, not at the longitudinal resonance ($S_1$ cutoff) frequency of 246 kHz. Transmission at the second longitudinal resonance ($A_3$ cutoff) is just visible at 492 kHz, and its frequency is clearly more than twice that of the zero group velocity transmission peak.
FIGURE 2. Calculated spectrum of a transmitted impulse, calculated (top) and measured (bottom).

FIGURE 3. Diagram of the scanning apparatus.

IMAGING

Imaging is performed by scanning source and detector transducers together in \( x \) and \( y \), as illustrated in Fig. 3. Zero group velocity transmission can then be measured to identify discontinuities or to determine spatial variation of material properties. Figure 4 shows a zero group velocity transmission image of a crack pattern in Plexiglas. The presence of the crack inhibits transmission of the zero group velocity mode. The bright spot in the upper left comes from direct leakage of airborne ultrasound through the crack itself. Unlike traditional water-coupled ultrasonic measurement, the air-coupled zero group velocity method allows measurement of cracks in transmission as opposed to reflection. Figure 5 shows the effect of a crack and of a boundary on transmission of the zero group velocity frequency through Plexiglas. The crack and boundary have approximately the same effect, and inhibit transmission within approximately one thickness (5.5-mm) from the crack or boundary.

Figure 6 shows a scan of 50 \( \mu \)m thick strips Scotch tape of varying widths on 5.5 mm Lucite. This is a test of sensitivity and resolution for imaging small changes in thickness (1%). The experiment is clearly able to resolve strips down to 8.8-mm in width, or slightly greater than 1 thickness. Only the 3.7-mm wide strip is not visible in the scan. Figure 7 shows a scan of a 0.125-in thick specimen of carbon fiber epoxy composite. In the upper right, a
FIGURE 4. Zero group velocity scan of cracked Plexiglas.

FIGURE 5. Effect of a boundary on transmission at the zero group velocity frequency (Plexiglas).

FIGURE 7. Scan showing a triangle of prepreg backing within carbon fiber epoxy. The mechanical support of the sample is visible in the lower left.
triangle of prepreg backing that was left between the layers during manufacturing is clearly visible. Figure 8 shows a transmission scan of a carbon fiber/aluminum honeycomb structure with defects. On the left is a point where the honeycomb was damaged by a hammer blow. On the right, are two Teflon insert induced disbonds between the honeycomb and the facesheet. In all cases, reduced transmission at the zero group velocity frequency is clearly visible. We conclude from these measurements that the zero group velocity method is effective in locating layer disbonds in composite plate structures.

Figure 9 shows a measurement of spatial variation of material properties in a sample of reinforced carbon-carbon for which the through-thickness wavespeed varies for reasons related to its fabrication or service history. In this sample, the frequency of the zero group velocity resonance peak is identified at each measurement point, and that resonance frequency is converted to a wavespeed and plotted as a gray scale value on Fig. 9.

We have recently developed a new lensless spherically focussed capacitive transducer for performing these measurements. This transducer uses a spherical conformal copper backplate and Mylar film to generate a natively focussed beam. The beam function and directivity are shown in Fig. 10 for broadband impulse excitation. The focal length of this transducer is 25 mm. The middle $(x, y)$ image in Fig. 10 clearly shows a circular focal spot on the order of 2 mm diameter. Preliminary quantitative measurements indicate a 5 dB (per transducer) bandwidth of 116-518 kHz and 2.3-mm diameter focal spot. If signals below 400 kHz are filtered out, the spot size improves to 1.6-mm. We anticipate that these new transducers will dramatically improve the resolution and sensitivity of the zero group velocity method.

FIGURE 10. Scans of point-focus transducer directivity as functions of \((x,y)\), left, and \((x,z)\), right. The transducer surface is located at \(z = 0\).
CONCLUSIONS

The zero group velocity mode dominates the transmission of focused airborne ultrasound through plates. It is sensitive to discontinuities, thickness variations, and material property changes. The zero group velocity mode’s extreme sharpness and sensitivity make it ideal for imaging applications. It allows through-transmission imaging of cracks and disbonds in composites. Knowledge of the zero group velocity phenomenon allows a-priori selection of optimal parameters for air-coupled ultrasonic measurement.

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