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Composite Material Defects Characterization Using Leaky Lamb Wave Dispersion Data

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ABSTRACT

Leaky Lamb waves (LLW) propagation in composite materials has been studied extensively since it was first observed in 1982. The wave is induced using a pitch-catch arrangement and the plate wave modes are detected by identifying minima in the reflected spectra to obtain the dispersion data. The wave behavior in multi-orientation laminates was well documented and corroborated experimentally with a very high accuracy. The sensitivity of the wave to the elastic constants of the material and to its boundary condition led to several studies where the elastic properties were inverted and the characteristics of bonded joint were evaluated. Recently, the authors modified their experimental setup to allow measuring dispersion curves at a significantly higher speed than ever recorded. A set of 20 angles of incidence along a single polar angle of a composite laminate are acquired in about 45 seconds. The reflection spectra are acquired in real time while filtering the high frequency noise providing reliable data at amplitude levels that are significantly lower that were acquired in prior studies. This new method makes the LLW a practical quantitative tool for both inversion of the elastic properties and characterization of flaws. The emphasis of the current study is on the detection and characterization of flaws. The composite is modeled as transversely isotropic and dissipative medium and the effect of flaws is analyzed and compared to the experimental data using a C-scan mounted LLW scanner.

Keywords: NDE, LLW, Leaky Lamb Wave, Ultrasonics, Defects Characterization, Elastic Properties, Composites

1. INTRODUCTION

The integrity, stiffness and durability (residual life) of structures need to be determined nondestructively to assure the performance of these structures in service using smaller safety factors. While the integrity and stiffness can be extracted directly from NDE measurements, strength and durability cannot be measured nondestructively since they are associated with physical parameters that cannot be measured with such methods. NDE methods are developed to detect and characterize flaws and to determine the material properties of test specimens. For many years, composites as multi-layered anisotropic media, have posed a challenge to the NDE research community and pulse-echo and through-transmission were the leading methods of determining the quality of composites. However, these methods provide limited and mostly qualitative information about the material properties and defects. Following the discovery of the LLW and the Polar Backscattering phenomena in composites [1, 2], numerous experimental and analytical studies have taken place using obliquely insonified ultrasonic waves [3-5]. These studies led to the development of effective quantitative NDE capabilities to determine the elastic properties, to accurately characterize defects and even to evaluate the quality of adhesively bonded joints [6, 7]. In spite of the progress that was made both theoretically and experimentally, oblique insonification techniques are still academic tools and have not yet become standard industrial test methods for NDE of composite materials. The authors have investigated the issues that are hampering the transition of these methods to the practical world of NDE and are involved with extensive studies to address these issues. This paper covers the progress that was made by the investigators in tackling the theoretical and experimental issues to solidify the foundation of the LLW technique and its transition to practical NDE tools.

2. LEAKY LAMB WAVE PHENOMENON

A pitch-catch ultrasonic setup applied to a plate-like solid induces the phenomenon of leaky Lamb wave (LLW) when immersed in fluid. This phenomenon is the resonant excitation of plate waves that leak waves into the water and interfere with the specular reflection. This phenomenon was discovered in 1982 using Schlieren imaging system while testing a composite laminate [1]. This discovery led to numerous studies of ultrasonic wave propagation in composites and accurate analytical modeling of the wave behavior in composite materials. Towards the end of 1982, Bar-Cohen and Chimenti [1] made an extensive investigation of the characteristics of the LLW phenomenon and its potential for NDE applications. The initial efforts concentrated on experimentally documenting the observed modes and the effects of defects. This effort was followed by numerous studies of the phenomena [see, e.g., 3-5]. In 1987, Bar-Cohen and Mal, developed effective capabilities to accurately model the wave behavior [6] and to invert the elastic properties from the measured dispersion data. This study was later expanded to NDE of bonded joints [7]. Follow-on studies by these investigators showed that the capability to invert the elastic properties is limited to the matrix dominated ones [8]. To overcome this limitation, which is associated with the need for angles of incidence as small as 8^{o}, a methodology that is based on using ultrasonic pulses was developed for the determination of all stiffness constants [9]. Assuming that the material is transversely isotropic and using pulses in pitch-catch and pulse-echo experimental arrangements, it was shown that all the five elastic constants can be determined fairly accurately. A parametric study was conducted and the expected error was determined for the various determined constants in relation to experimental errors. It was also shown that, C_{12}, the constant with the most sensitivity to defects, while can be inverted, it is seriously affected by errors in the incident and polar angles.

The experimental procedure that is associated with the leaky Lamb wave phenomenon employs a pitch-catch setup where the impinging wave interacts with the material and the reflection represents the dispersive spectral characteristics of the layered material. A Schlieren view of a tone-burst before and after impinging onto a graphite/epoxy composite laminate is shown in Fig. 1, where the leaky wave component of the reflected wave is shown on the top right of this Figure. Evaluation of the minima in the reflection spectra at different angles of incidence provides information about the various wave modes in the form of dispersion curve. The dispersion curves for composite materials and bonded joints were analytically modeled and were very well corroborated experimentally confirming the accuracy of the model.

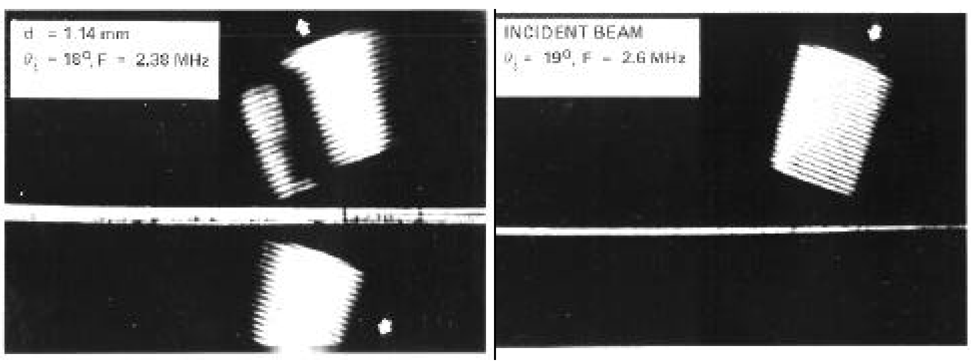

Figure 1: A Schlieren image of the LLW phenomenon showing a tone burst before and after impinging on the graphite/epoxy laminate.

The experimental acquisition of dispersion curves for composite materials requires accurate control of the angle of incidence/reception and the polar angle with the fibers. The need to perform these measurements rapidly and accurately was effectively addressed at JPL where a specially designed LLW scanner was developed. With the aid of a personal computer, the scanner controls the height, angle of incidence and polar angle of the pitch-catch setup. The LLW scanner controls the angle of incidence/reception simultaneously while maintaining a pivot axis on the part surface. A view of the LLW scanner installed on a C-scan unit is shown in Figure 2. It allows acquisition of dispersion curves with angles of incidence between 12^{o} and 70^{o}, polar angles in the full 360^{o} range and the height over a range of 10 cm. A computer code was written to control the incidence and polar angles, the height of the transducers from the sample surface, and the transmitted frequency. In the past, the data acquisition involved the use of sequentially transmitted tone-bursts at single frequencies over a selected frequency range (within the 20dB level of the transducer set). Reflected signals are acquired as a function of the polar and incidence angles and as well as saved in a file for analysis and comparison with the theoretical predictions. The minima in the acquired reflection spectra represent the LLW modes and are used to prepare the dispersion curves (phase velocity as a function of frequency). The incident angle is changed incrementally within the selected range and the reflection spectra acquired. For graphite/epoxy laminates the modes are identified for each angle of incidence in the range of 12^{o} to 50^{o} to allow the use of free-plate theoretical calculations; the influence of water loading on the dispersion curves is negligible. At each given incidence angle, the minima are identified and are added to the accumulating dispersion curves, and are plotted simultaneously on the computer display (Figure 3). While the data acquisition is in progress, the acquired minima are identified on both the reflection spectra and the dispersion curve.

3. THEORY AND DATA INVERSION

The location of the minima in the reflection coefficient is highly sensitive to the thickness and the stiffness constants of the plate and insensitive to the damping parameters over a broad frequency range. These minima are also affected by the presence of water as a coupling medium mostly at high angles of incidence, where the phase velocity approaches the level of $1.5\text{x}10^5$ cm/sec. Thus the dispersion data can, in principle, be used to determine accurately these properties and any changes in their values during service can be used to characterize defects. For phase velocities that are above $2\text{x}10^5$ cm/sec, the theoretical treatment of the guided waves in a composite laminate can ignore the water loading and the property values can be obtained from the theoretical model as a transcendental equation of the form,

$$G\,(\mathrm{v}, f, c_{ij}, H) = 0 \tag{1}$$

For a given data set $\{\mathrm{f}_\mathrm{k}, \mathrm{v}_\mathrm{k}\}$, c_{ij} and H can be determined by minimizing the objective function

$$F\,(c_{ij}, H) = \Sigma\, w_k\, |G_k|^2 \tag{2}$$

where w_k is a suitable weight function and G_k is the value of the dispersion function G at the k-th data set. The minimization can be carried out through a variety of available optimization schemes; which we accomplished effectively by using a SIMPLEX algorithm. Typical results for a unidirectional graphite/epoxy plate is shown in Figure 3. The material is AS4/3501-6 and the polar angle (i.e., the direction of Lamb wave propagation) is 0^o. The reflected spectrum for 39.9^o incident angle is shown at the top of the figure, and the accumulating dispersion curves are at the bottom. The inverted elastic and stiffness constants are given on the left.

Figure 2: A view of the LLW scanner (on the right portion of the bridge) installed on the JPL's C-scan system

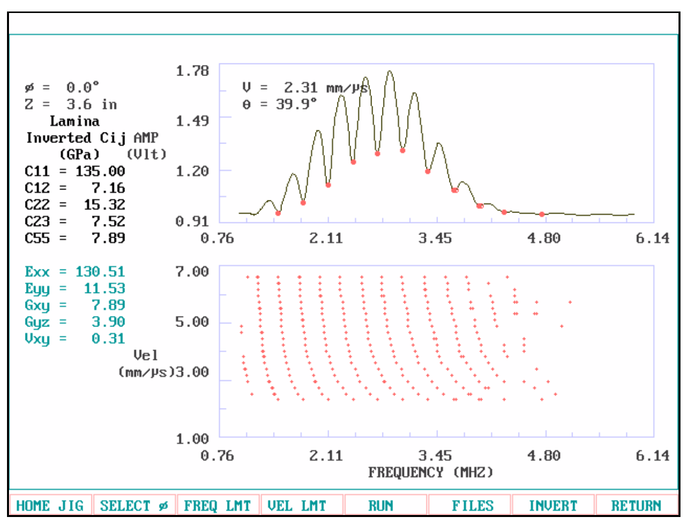

Figure 3: A view of the computer screen with the reflection spectra on the top and the accumulating dispersion curve on the bottom. The inverted elastic stiffness constants are shown on the left.

To demonstrate the capability of the method to characterize materials degradation of composites, a sample made of a unidirectional 24-ply laminate from AS4/3501-6 pregreg was tested after it was subjected to heat treatment.

The sample was exposed to a heat ramp from room temperature to 480° F for 15 minutes, and then was taken out of the oven to cool in open air at room temperature. The sample was tested at a specific location before and after heat treatment. The measured dispersion curves are shown in Figure 4. It can be seen that there are distinct differences in the dispersion data for the specimen before and after heat treatment. Since the heat damage occurs mostly in the matrix, the effect is expected to be more pronounced in the matrix dominated stiffness constants. The constants c_{11}, c_{12}, c_{22}, c_{23} and c_{55} obtained from the inversion process are 127.9, 6.32, 11.85, 6.92 and 7.43 GPa, before heat treatment, and 128.3, 6.35, 10.55, 6.9 and 7.71 GPa, after heat treatment. The most noticeable and significant change is in the stiffness constant c_{22}, which is the property most sensitive to variations in the matrix resulting in a reduction in the transverse Young's modulus.

It should be noted that equation (1) is strongly nonlinear in c_{ij} and H, and its solution is non-unique. Thus extreme care must be taken in interpreting the numerical results obtained from the inversion of the dispersion data. On the basis of extensive parametric studies of equation (1) we have concluded that only the thickness and the matrix dominated constants c_{22}, c_{23} and c_{55} can be determined accurately from the inversion of the dispersion data. This is due to the fact that the dispersion function G is not very sensitive to the fiber dominated constants c_{11} and c_{12}. These two constants can be determined from the travel times and amplitudes of the reflected short-pulse signals in the oblique insonification experiment.

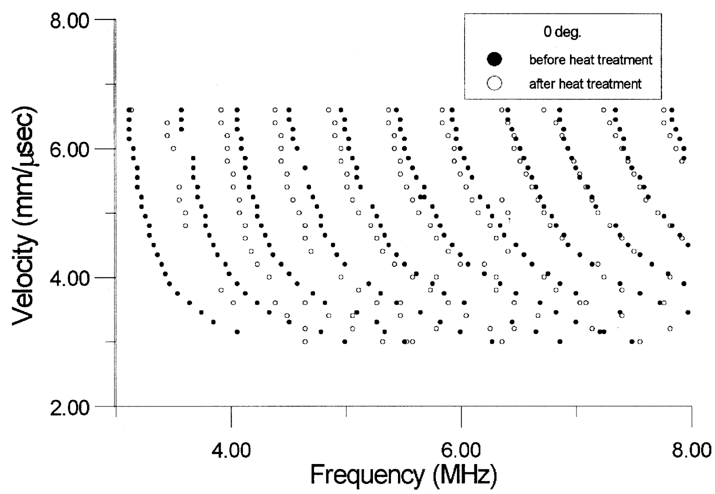

Figure 4. The measured dispersion curves of a $[0]_{24}$ graphite-epoxy panel before and after heat treatment.

4. LLW EXPERIMENTAL CAPABILITY ENHANCEMENT

To bring the LLW technique to a practical use, the issues that affect its industrial NDE applications have been investigated and they were identified to include:

a) Complex data acquisition - The LLW data acquisition experiment is complex and the related process has not been user friendly. We have significantly improved the data acquisition process through integration of software and hardware. The computer optimizes the setup height to assure the greatest ratio between the maxima and minima amplitude in the reflected spectrum. The polar angle with the laminate fibers is set using the polar backscattering technique [2] that allows identification of the direction of the first layer. Further, a user friendly control setup that operates on Windows platform is being written to allow interactive software control.

b) Material density - The inverted material constants assume that the material density is known. NDE measurement of the material density can be done by radiography but this method is not practical and an alternative method of measuring the density is needed. Preferably is should be done by ultrasonics to minimize instrumentation complexity.

c) Multi-orientation laminates - The inversion algorithm developed for the determination of the elastic properties has been very successful for unidirectional laminates. The analysis of laminates with multi-orientation layers using ply by ply analysis is complex and leads to ill-posed results. The authors are currently studying methods of inverting the material elastic properties without the necessity to deal with the individual layers.

d) Time-consuming process - Determination of dispersion curves is time consuming and used to take between 10 and 20 minutes for a single point, when employing the LLW scanner and sweeping through the spectral range. Recent development by the authors allows the measurement of the dispersion curves at a significantly higher speed than before. The experimental setup is depicted in Figure 5. At selected angles of incidence the reflection spectral data is presented in real time directly on the digital scope after being amplified and rectified by an electronic hardware. A function generator induces a frequency sweep in the selected range and is fed to the X-axis of the digital scope whereas the amplitude of the received signal is fed to the Y-axis. A reference frequency marker is employed to calibrate the acquired spectral data when converting the received signal from time domain to frequency domain. The reflection spectra are acquired in real time while filtering the high frequency noise and providing reliable data in a range of amplitudes that are significantly lower than were used in prior studies. Using this technique, a dispersion curve that is based on a set of 20 angles of incidence along a single polar angle is acquired in about 45 seconds. This method makes the process of acquiring LLW dispersion curves almost a real time one and is an important step towards making the method a practical quantitative tool for both inversion of the elastic properties and flaw characterization.

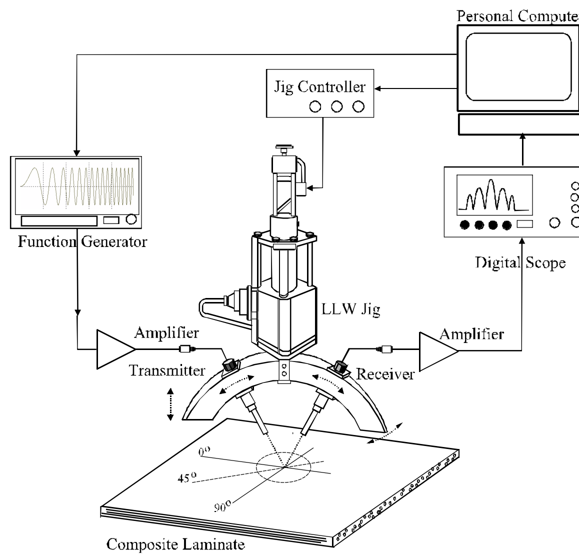

Figure 5: A schematic view of the rapid LLW test system.

Using the new setup the effect of the key composite material defects, i.e., delaminations and porosity was investigated. The reflection spectra were observed to identify the center of the specific flaws in order to obtain a typical representation of their response. In Figure 6 the reference experimental and theoretical dispersion data for a defect free area is shown and in Figure 7 the response from a porosity layer in half the thickness is shown. As can be seen the effect of porosity on the dispersion data becomes more pronounced at the higher frequencies. At frequencies below about 4-5MHz the response is close to that of a defect free, where as at high frequencies the response is closer to a delaminated area that appears thinner. Testing a delaminated area (simulated by a Teflon foil) shows that the defective area appears as a thinner laminate at all the spectral ranges. Figure 8a shows the spectra of delamination and the defect free area of a 16 ply whereas Figure 8b shows the spectra that is inverted for a defect free laminate with half the thickness of the original sample using the same properties.

5. CONCULSIONS

Theoretical and experimental studies of the LLW phenomenon have led to a significant progress in understanding the wave behavior in composites. Effective analytical tools were developed for the inversion of data for material property determination and defect characterization. Further, unique experimental tools were developed allowing rapid and accurate data acquisition. In spite of this progress, the phenomenon is still not being employed as a standard quantitative NDE method in industry. To pave the path of this method to become a practical tool, the authors have developed a rapid and user-friendly data-acquisition system as well as improved their analytical tools to automatically determine the wave speeds and elastic constants. This development simplifies the process of characterizing flaws in composites and bonded joints and the determination of the material properties degradation.

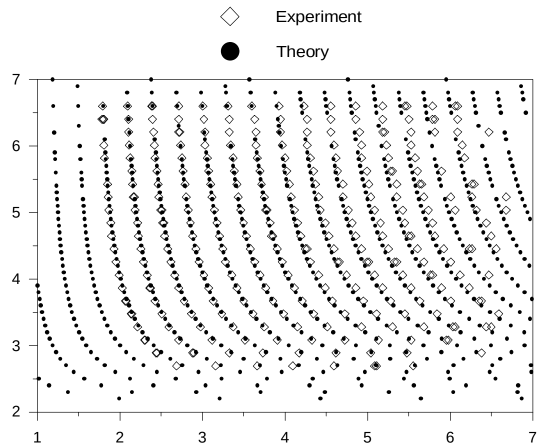

Figure 6: Dispersion data for a defect free 16 layer unidirectional laminate

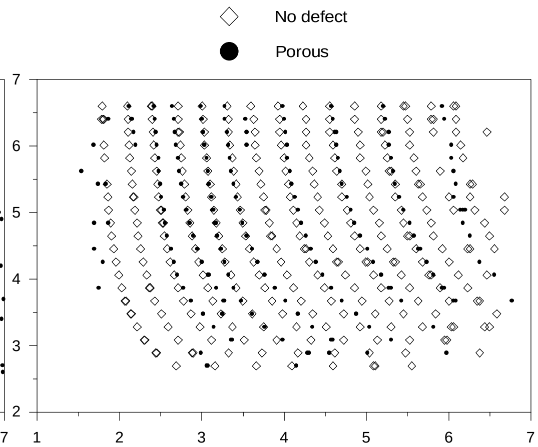

Figure 7: The effect of porosity layer (microballoons) between the 8th and 9th layers.

Note: Thickness = 2.81 mm, Density = 1.588 g/cc, and the inverted elastic properties C_{11} = 161.31 GPa, C_{12} = 6.10 GPa, C_{22} = 13.90 GPa, C_{23} = 6.53 GPa, C_{55} = 7.26 GPa

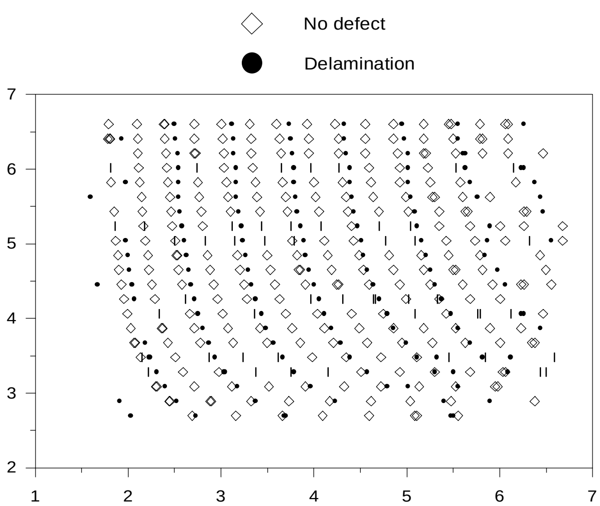

Figure 8a: Dispersion curves obtained at a delaminated area between the 8th and 9th layers.

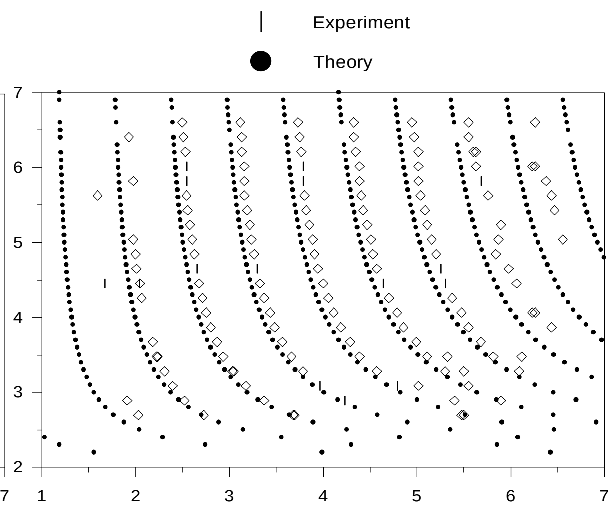

Figure 8b: Theoretical and experimental data for the delaminated area using 8 layers (Thickness = 1.405 mm)

6. ACKNOWLEDGMENT

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