Characterization of Defects in Composite Material Using Rapidly Acquired Leaky Lamb Wave Dispersion Data

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ABSTRACT

The phenomenon of Leaky Lamb waves (LLW) in composite materials was first observed in 1982 using a Schlieren system. It has been studied extensively by numerous investigators and successfully shown to be an effective quantitative NDE tool. In spite of the success, the method has not become a standard inspection technique due to shortcoming that will be addressed in this manuscript. The LLW phenomenon is associated with an ultrasonic pitch-catch setup and involves the measurements of the guided wave dispersion curves by identifying the minima in the reflected spectra. The sensitivity of the wave to the elastic constants of the material and the boundary conditions led to the development of methods of inverting the elastic properties and the characterization of bonded joint. Recently, the authors modified their experimental setup to rapidly measure dispersion curves allowing data acquisition speed that is faster than ever before. The reflection spectra are acquired in real time while filtering the high frequency noise providing reliable data at amplitude levels that are significantly lower than were acquired in prior studies. This new method makes the LLW more practical as a 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. Further, the effect of flaws is analyzed and compared to the experimental data using a C-scan mounted LLW scanner.

1. INTRODUCTION

Composite materials are used to construct flaw critical structures and they are taking a growing percentage of the makeup of aircraft and spacecraft structures. The cost of composite structures is significantly higher than the equivalent metallic made structures, reaching levels of orders of magnitude higher cost. A recent evaluation of the cost elements showed that about one third is spent on both mechanical and nondestructive testing. The key to the assurance of inspection efficiency is the ability to apply effective tests for the determination of the integrity, stiffness and durability (residual life) and thus allowing the use of less material, i.e. smaller safety factors, while assuring the performance of the structures. Also, it is necessary to minimize the amount of costly mechanical tests. NDE methods are developed to detect and characterize flaws and to determine the material properties (e.g., stiffness) of test specimens. The strength and durability are parameters that cannot be determined by NDE methods since they are associated with physical processes, which are statistical in nature and cannot be measured nondestructively.

The standard methods that are used to inspect metallic structures were adapted by the industry for inspection of composite materials, partially accounting for the multi-layered anisotropic nature of the material. The standard NDE methods provide limited and mostly qualitative information about the material properties and defects. The discovery of the LLW and the Polar Backscattering phenomena in composites [1, 2] enabled new capabilities that address the anisotropy and offered the potential of quantitative testing. 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 immersion techniques are still academic tools and have not yet become standard industrial NDE methods for 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 obstacles to solidify the foundation of the LLW technique and its transition to practical NDE tools. This involves the development of effective analytical and experimental tools as well as the direction of the recent efforts to employing dispersion data as a quantitative tool for the characterization of flaws.

2. LEAKY LAMB WAVE PHENOMENON

The phenomenon of leaky Lamb wave (LLW) is induced and measured in plate-like solids using a pitch-catch ultrasonic setup that is immersed in fluid. The phenomenon is a resonant excitation of plate waves that leak waves into the immersion fluid and interfere with the specular reflection. LLW was discovered in 1982 using Schlieren imaging system while testing a composite laminate [1]. 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. This discovery led to numerous studies of ultrasonic wave propagation in composite materials and to the accurate analytical modeling of the wave behavior. Towards the end of 1982, Bar-Cohen and Chimenti [1] made an extensive investigation of the LLW phenomenon characteristics and its potential for NDE applications. The initial efforts concentrated on experimentally documenting the observed modes and the effect of defects on the reflection spectra. This effort was followed by numerous studies of the phenomena [e.g., 3-5].

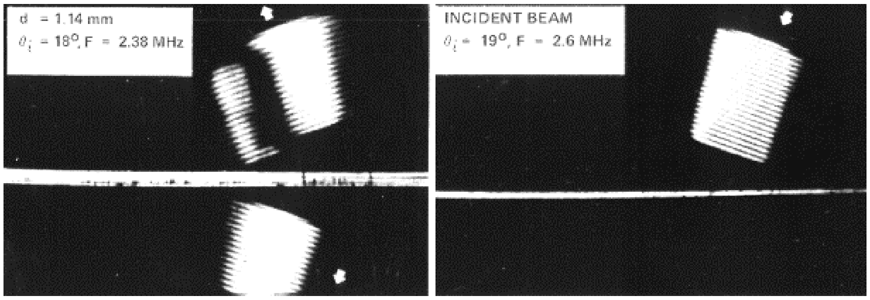


Figure 1: A Schlieren image of the LLW phenomenon showing a tone burst before and after impinging on the graphite/epoxy laminate.

Effective LLW data acquisition capability and accurate modeling are a key to the application of this phenomenon to NDE. To address this need, the principal investigators Bar-Cohen and Mal, started joint efforts in 1987 to develop the necessary capabilities to accurately and automatically acquire the LLW modes and to model the wave behavior [6]. The result of these efforts led to the development of a method for inverting the measured dispersion data to elastic properties. Later, this study was expanded to NDE of bonded joints [7]. Careful parametric analysis of the inverted elastic properties revealed that the method is limited to the matrix dominated ones [8]. To overcome this limitation, measurements were needed at angles of incidence that are as small as 8^o, which are not practical. Using ultrasonic pulses, an alternative approach 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 found that while C_{12} can also be inverted and it has the most sensitivity to defects, it is also seriously affected by errors in the incident and polar angles.

The LLW experimental procedure consists of oblique insonification of a layered test material and the reflection represents the dispersive spectral characteristics of the material. 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 curves. The dispersion curves for composite materials and bonded joints were modeled analytically and were corroborated experimentally confirming the accuracy of the model. 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 addressed effectively 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. A computer code was written to control the incidence and polar angles, the transducers' height 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 45^o to allow the use of

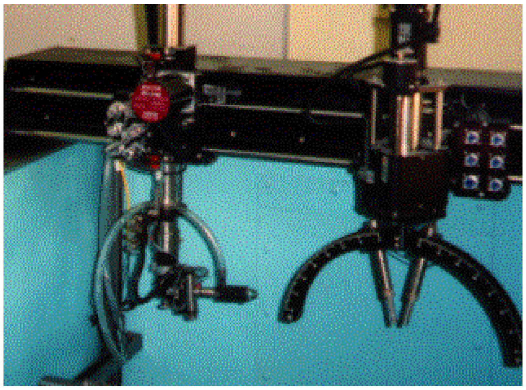
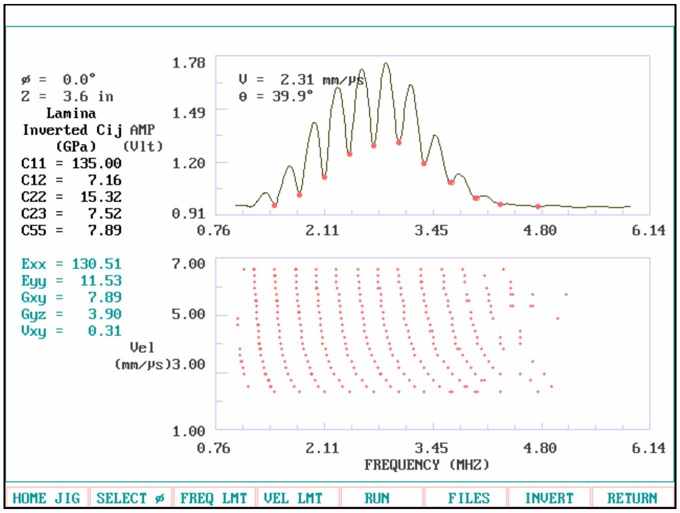


Figure 2: A view of the LLW scanner (on the right portion of the bridge) installed on the JPL's C-scan system

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 they 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.



ø = 0.0°
Z = 3.6 in
Lamina
Inverted Cij (GPa)
C11 = 135.00
C12 =   7.16
C22 = 15.32
C23 =   7.52
C55 =   7.89

Exx = 130.51
Eyy = 11.53
Gxy =   7.89
Gyz =   3.90
Vxy =   0.31

V = 2.31 mm/μs
θ = 39.9°

Figure 3: A view of the computer monitor 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.

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. An analytical model was developed to allow inversion of the dispersion data to determine the elastic properties. Evaluation of the changes in these properties value 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. Shown in Figure 3, a typical result for a unidirectional AS4/3501-6 graphite/epoxy plate tested along the fiber direction. The reflected spectrum for 39.9° incident angle is shown at the top of the figure, and the accumulating dispersion data are at the bottom. The inverted elastic and stiffness constants are given on the left.

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.

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:

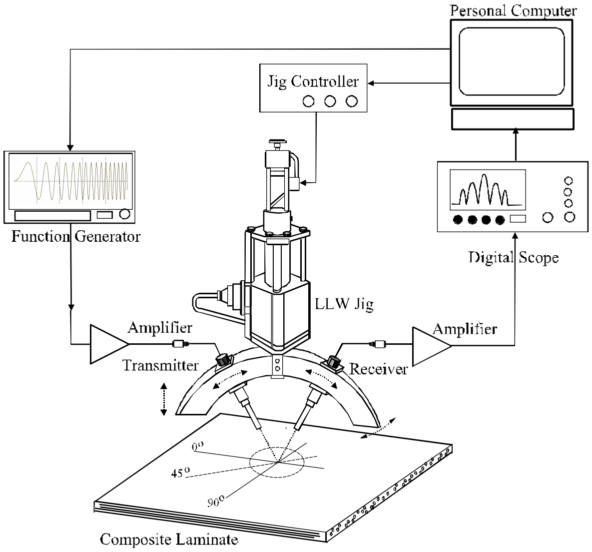
a) Complex data acquisition - The LLW data acquisition experiment is complex and the related process has not been user friendly. We addressed this issue by significantly improving the data acquisition process through integration of software and hardware. The computer optimizes the setup height to assure 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 are based on the assumption 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 4. 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 it makes an important contribution to making the method a practical quantitative tool for both inversion of the elastic properties and flaw characterization.

Figure 4: A schematic view of the rapid LLW test system.



FLAW CHARACTERIZATION USING LLW

The dispersion data acquired for LLW is a powerful characterization tool for physical discontinuities like delaminations and porosity as well as material property flaws. To determine the effect of discontinuities, the reference dispersion curve was documented for a unidirectional graphite/epoxy (see Figure 5) and the spectra at the center of porosity and delamination area was documented to obtain a typical representation of their response. Figure 6 shows the response from a porosity layer that is located at half the thickness of the laminate. 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 the defect free area, whereas at high frequencies the response is closer to a delaminated area and appears thinner. Testing a delaminated area (simulated by a Teflon foil) shows that the defective area appears as a thinner laminate at the complete spectral range. Figure 7a shows the spectra of delamination and the defect free area of a 16 ply whereas Figure 7b shows the dispersion curve that is inverted for a defect free laminate with half the thickness of the original sample using the same properties.

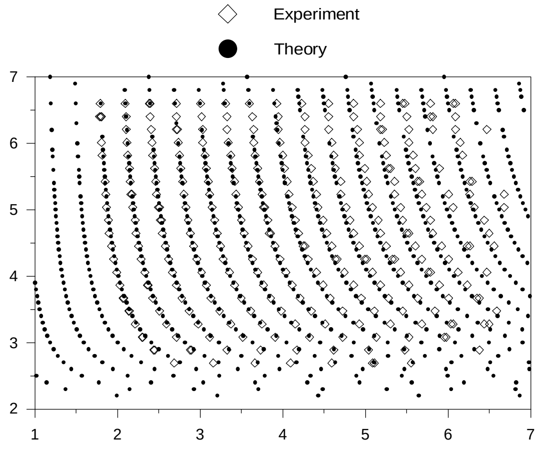


Figure 5: Dispersion data for a defect free 16 layer unidirectional laminate

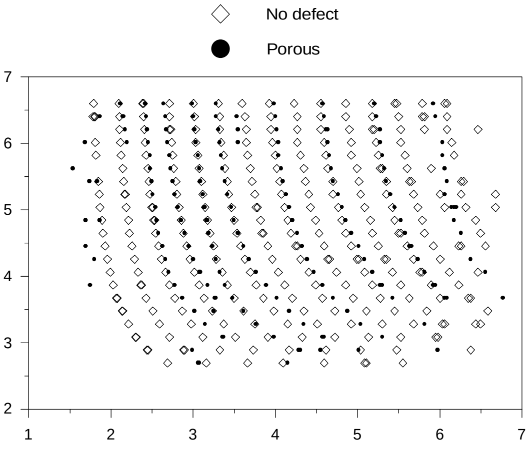


Figure 6: The effect of porosity layer (microballoons) between the 8th and 9th layers.

Note: Thickness = 2.81 mm, Density = 1.588 g/cc, and the inverted elastic properties are 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

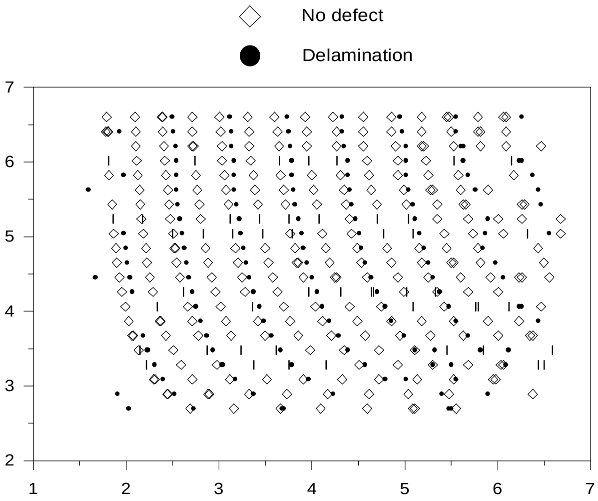


Figure 7a: Dispersion curves obtained at a delaminated area between the 8th and 9th layers.

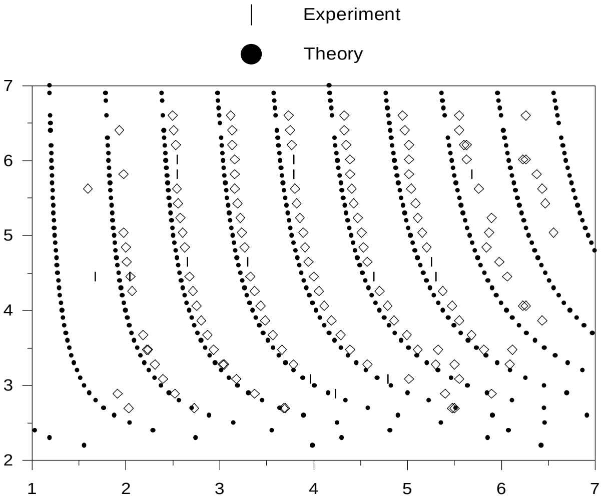
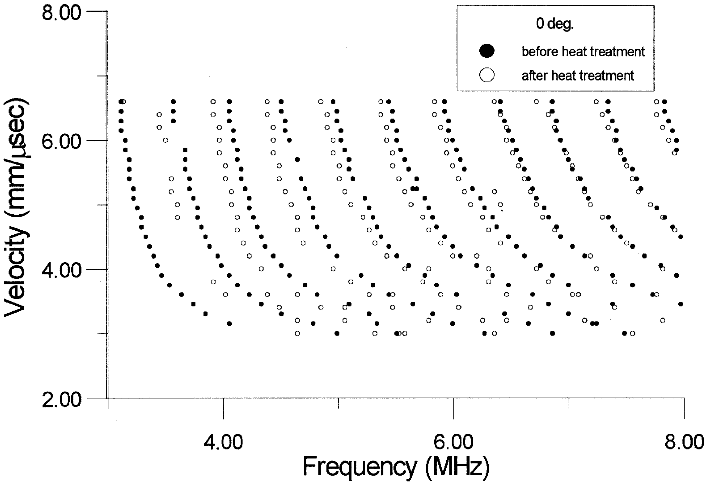


Figure 7b: Theoretical and experimental data for delaminated area using 8 layers (t= 1.405 mm)

As mentioned earlier, the ability to invert the elastic properties allows the characterization of flaws that are associated to the material degradation. To demonstrate this capability a sample made of a unidirectional 24-ply laminate from AS4/3501-6 prepreg was tested after it was subjected to excessive heating. This 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. A specific location of the sample was tested before and after heat treatment and the measured dispersion curves is shown in Figure 8. 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.

Figure 8. The measured dispersion curves of a $[0]_{24}$ graphite-epoxy panel before and after excessive exposure to heat.



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 degradation in material properties. The dispersion data was shown to allow characterization of discontinuities such as delamination, and porosity as well as material properties degradation such as thermal damage.

6. ACKNOWLEDGMENT

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