An ultrasonic test protocol for aramid aluminum laminates

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An ultrasonic test protocol for aramid aluminum laminates

by

Arnold H. Kettenacker

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Department: Materials Science and Engineering
Major: Materials Science and Engineering
Major Professors: Dale E. Chimenti and R. Bruce Thompson

Iowa State University
Ames, Iowa
1996
This is to certify that the Master's thesis of

Arnold II. Kettenacker

has met the thesis requirements of Iowa State University
To Maureen and our daughters, Kia and Nadege.
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CHAPTER 1. INTRODUCTION

Over the past quarter century, substantial advances have been made in the aerospace applications of composites. The designs of modern aircraft, particularly military fighter aircraft, demand high-strength, high-stiffness, low-weight materials. While multiphase composite materials of various kinds have been used for centuries, the development in the last 40 years of high-stiffness continuous fibers, either of graphite or glass, has changed the picture for aerospace materials. Coupled with reliable interfacial chemistry at the fiber-matrix interface and advanced epoxies and thermoplastics, composite laminates began appearing in high-performance aircraft around 1970. The boron-epoxy speed brake on the McDonnell-Douglas F-15A was one of the first such applications. With better control of the graphitizing process, high-stiffness, micron-sized carbon fibers began making their appearance in composite form.

These fibrous composite laminates have fulfilled the demand for ever stiffer and lighter materials, but not without some disadvantages. Fiber-epoxy laminates have a well-known sensitivity to impact damage and degradation due to environmental factors, such as ultraviolet light and moisture. Additionally, the cost of producing and maintaining fiber-epoxy laminates is very high. In order for combat aircraft to meet their performance objectives, these limitations must be accommodated. Military transport and commercial aircraft, however, are much more cost-sensitive and must be economically maintainable.
Over the past decade a new type of laminate has been developed, one that incorporates advantages of both traditional fibrous composites and conventional monolithic aluminum alloys. Under license to the Dutch inventors, Alcoa has been manufacturing an aramid/aluminum laminate (registered name ARALL™). The layered combination of the two materials produces a light-weight laminate with excellent stiffness and strength in the fiber direction. Currently, there are four types of ARALL manufactured, each designed for various applications. The material has been extensively tested and the results well documented [1-3]. Compared to conventional aluminum alloys of a similar thickness, ARALL can provide a 30% increase in tensile strength with a weight savings of 20%. When tested in a cyclical tension-tension environment, its fatigue life can range from 10 to 1000 times greater than that of monolithic aluminum alloys. Additionally, the aluminum outside surfaces protect the epoxy layers from impact damage, ultraviolet light, and moisture, while the aramid-epoxy layers provide better damping characteristics and increased lightning resistance. Finally, ARALL can be handled in the same manner as conventional aluminum alloys, in that it can be cut, sawed, drilled, and riveted. This compatibility yields a cost savings for on-aircraft maintenance. Overall, ARALL is ideal for weight savings in fatigue-critical and tension-dominated areas of aircraft such as the fuselage, lower wing, and tail skin [3].

Common industry practice for composite inspection includes normal-incidence ultrasonic, through-transmission amplitude scans in a fairly narrow bandwidth [4]. Such tests rely mainly on amplitude changes in the received signal to determine the physical characteristics of the plate. Although effective in detection of complete delaminations, or gross thickness variations, the normal-incident through-transmission technique generates only compressional elastic waves and generally ignores any signal complexity arising from internal structure. The omission of shear waves and absence
of detailed signal analysis in the test procedure limits the technique's capability to characterize the test specimen. For example, a normally incident compressional impulse will generally transmit through a smooth interface (with zero interlaminar shear strength) or a welded bond with the same amplitude. When this occurs, the smooth interface, or "kissing" bond will not be detected. This is a potentially serious omission, since a "kissing" bond can be equally as detrimental to the composite's structural integrity as a delamination.

The purpose of this thesis is to design a test procedure that is more encompassing than the standard practice, through-transmission scan. By employing the use of a broad bandwidth in combination with guided wave modes that include substantial shear wave energy, a more accurate and reliable characterization of the composite can be made.

In this thesis a new inspection protocol for aluminum aramid-epoxy laminates will be proposed and examined. In Chapter 2, background information will be presented and the scope of the protocol given. Chapter 3 will review the theory and principles required for an understanding of the experimental procedure. A detailed description of the experimental setup will be given in Chapter 4, followed by the results and discussion provided in Chapter 5. Finally, conclusions will be presented in Chapter 6.
CHAPTER 2. BACKGROUND

In this chapter, we will discuss some of the previous fatigue and characterization experiments that have been conducted on ARALL and review other work involving the application of ultrasound to ARALL. Next, we will discuss and compare some of the inspection techniques used to evaluate composites. Finally, we will conclude with a preview of the test protocol.

Previous ARALL Experiments

Morphologically, ARALL is a sandwich structure of alternating plies of aluminum and aramid (or glass) epoxy, each about 0.25 mm in thickness. It is available in several forms, two aluminum and one aramid layer (denoted 2/1), and on up to 5/4. Recent work has shown that delamination or internal damage to in-service ARALL will occur only after detectable damage has occurred to the outside aluminum layers.

Cyclical tension testing performed by Osiroff et al. [5] consisted of subjecting 254 by 38 mm ARALL specimens to high-cycle fatigue loading at upper stress levels below the ultimate tensile strength of the material. The results of the tests indicate that delamination will occur only after cracks in the aluminum plies have started. In another study, impact testing on ARALL specimens was performed by Sun et al. [6]. For this procedure, the specimens were impacted with a 12.7 mm diameter steel ball at velocities ranging from 20 to 70 m/s. After the tests were completed, the specimens were examined for strength degradation. Sun et al. concluded that strength degra-
dation in ARALL products resulting from impact will occur only after permanent indentations are found on the aluminum surfaces. With findings from the two studies mentioned above, one could conclude that a visual, instead of a nondestructive, inspection of exposed surfaces might suffice for in-service maintenance of ARALL laminates. However, visual inspections are insufficient to detect fatigue damage on the hidden surface of the laminate; neither can structural degradation through loss of bond quality be detected in this manner. Since this engineered material depends so critically on the integrity of the inter-facial bond, one important point in time for the application of NDE would be during and after manufacture. Here, the identification of varying ply thicknesses or delaminations resulting from poor bonding in plies is essential to assure product quality.

Due to the effects of the interfaces between the periodic plies of a composite, waves propagating through a layered composite behave differently from waves in a homogeneous plate. Using fluid-coupled leaky wave techniques similar to the method used for this protocol, Shull et al. [7] analyzed the effects of waves in ARALL plates. Varying the transmitter incident angle the ARALL plates were insonified with rf tone bursts stepped from .5 to 12 MHz. With the receiving transducer fixed at the opposite angle from the transmitter, the minima in the received signal were monitored and recorded as indications of guided waves present in the plate. Two conclusions pertinent to this paper were presented. First, it was discovered that the dispersion of the wave modes scaled as a function of the unit cell dimension in the layered plate. This is strikingly different when compared to a homogeneous plate whose Lamb wave dispersion scales with the overall thickness of the plate. Second, the theoretical and experimental minima observed for a given incident angle displayed a grouping characteristic in distinct frequency ranges. The groupings correspond to the excitation of plate modes where, for a given incident angle and frequency
range, acoustic energy will propagate through the plate. Outside the grouping, the wave energy is strongly reflected. Shull et al. cited the cyclical occurrence of the transmission and reflection zones as being characteristic of the Floquet behavior of an unbounded periodic medium. Further studies by Auld et al. [8] related the number of modes for a periodically layered plate to that of a Lamb wave mode for a homogeneous plate. Specifically, for each Lamb wave mode corresponding to a homogeneous plate, an accompanying branch is added for each unit cell in the layered media. As will be demonstrated later in the paper, the mode groupings and their dependence on the number of unit cells will provide information as to the condition of the plate.

**Composite Testing Techniques**

There are numerous ultrasonic nondestructive testing techniques available for application with composite materials. A conventional pulse-echo procedure was used by Lucht [9], as well as a through pitch-catch method. In his work, Lucht was able to detect delaminations in a composite damaged by impact. An illustration of the pulse echo method can be found in Figure 2.1. This method simply requires the observation of a reflected signal on an oscilloscope prior to the anticipated signal from the back wall. In Figure 2.1 the illustration on the left, identified as a good specimen, has the front and back surface signals marked I and II. The same signals are shown below on a voltage versus time diagram. On the right, the specimen with the flaw shows a third reflected signal coming from the surface of a crack. A gate is used to monitor signals that exceed a predetermined amplitude threshold between signals I and II; this occurrence is assumed to be a flaw indication.

The second method used by Lucht entailed the use of a through-transmission pulse technique. Here, a second transducer is placed below the laminate being exam-
ined, and the amplitude of the pulse is simply monitored for any change. A drop in amplitude indicates that some of the wave traveling energy in the composite is being reflected. These methods are commonly used when testing composites; however, they will not detect the presence of a smooth interface (with zero interlaminar shear strength) since the compressional impulse will still transmit through. Both these methods are very useful for their intended application of detecting delaminations, but they are limited to that purpose because the test acquires so little information.

Use of swept frequencies can provide more information with regard to ultrasonic inspection of layered material. A typical method for finding the depth of non-bonds
is shown in Figure 2.2 [10]. With this procedure, we can now find the depth of the flaw by careful selection of the frequency range. The frequency range is chosen so that the rectified signal will not show any resonance signals for the case of the entire plate. If there is a debond within the composite, however, the signal will show an increase in amplitude caused by the resonance of the now dimensionally thinner area excluding the layers below the debond. Since the incident wave is normal to the surface of the plate, mode conversion to a shear wave is not possible, and information that could be provided by shear wave propagation is omitted.

Test Protocol

The goal of this thesis is the design of a more encompassing test procedure that will provide the user with more information when testing aluminum aramid-epoxy laminates. The protocol will make use of a broadband method and carefully analyze
the transverse resonant modes of the periodically layered material. The procedure therefore calls for measurements to be made at incident angles other than normal. This choice opens the possibility to exploit the rich variety of phenomena connected with guided waves for the assessment of material quality.

In these experiments most tests have been conducted from one side of the sample, although through-transmission measurements are possible as well. As we show in our analysis, however, the reflection measurement yields as much information as there is to obtain. The protocol developed here only takes into consideration that there is one interface flaw present through the thickness of the laminate for any point on the plate. The target size of the flaw will be that of the surface area of the transducers used in the protocol. This arbitrary choice is, however, close to the industrial criterion for some versions of ARALL.
CHAPTER 3. THEORY

In this chapter we discuss the constitution of ARALL as an aerospace material and calculate its stiffness components required for this protocol. Also, we review principles and theories of ultrasound pertinent to the experiments of this paper. We begin with a brief overview of ultrasonic wave propagation, including mode conversion, and Snell's law. Next, the dispersion relation for plate waves in isotropic media is derived. A review of layered media is given next, detailing the development of the local and global transfer matrices. Finally, the solution for fluid-loaded layered media is presented, followed by a derivation of the ultrasonic reflection coefficient for fluid coupled plates.

Elastic Behavior and Materials Science of ARALL

Since the results of measurements presented later are based entirely on experiments with ARALL samples obtained for the purpose of this study, we begin with a short discussion of the samples, their structure, fabrication, and independent characterization. ARALL consists of alternating thin aluminum sheets and unidirectional aramid fiber reinforced epoxy. The number of layers ranges from three to nine with the outside layers, or top and bottom plies, being aluminum. The notation used for the numbers of layers is (# aluminum plies)/(# aramid-epoxy plies). For example, 4/3 denotes four aluminum plies and three aramid-epoxy plies. A schematic of a 3/2 laminate is illustrated in Figure 3.1.
Four types of ARALL are manufactured, each of them specifically tailored to meet different requirements. The aluminum alloys used for each type of ARALL are varied depending on the final desired characteristics. In addition to the selection of the alloy, two types of aramid-epoxy prepregs are used depending on the environmental temperature requirements destined for the finished product. A listing of the ARALL products is given in Table 3.1 [11]. The prepreg has for its matrix a thermo-setting epoxy resin. The numerical trade codes for the prepregs are AF-163-2U and AF-191, having a cure temperature of 120°C and 177°C, respectively. Dupont manufactures the aramid fibers and distributes them under the trade name Kevlar 49™; its chemical structure is shown in Figure 3.2 [12]. The fiber alignment of the prepreg is controlled mechanically via a comb adjustment procedure which inhibits "bunching" of the fibers.

Good adhesion between the matrix and aluminum is of the utmost importance;
Table 3.1: ARALL Products

<table>
<thead>
<tr>
<th>Product Variant</th>
<th>Description</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARALL 1</td>
<td>Alloy: 7475-T61</td>
<td>Superior fatigue</td>
</tr>
<tr>
<td></td>
<td>250°F (121°C) cure prepreg</td>
<td>High strength</td>
</tr>
<tr>
<td>ARALL 2</td>
<td>Alloy: 2024-T3</td>
<td>Excellent fatigue</td>
</tr>
<tr>
<td></td>
<td>250°F (121°C) cure prepreg</td>
<td>Increased formability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Damage tolerance</td>
</tr>
<tr>
<td>ARALL 3</td>
<td>Alloy: 7475-T61</td>
<td>Superior fatigue</td>
</tr>
<tr>
<td></td>
<td>250°F (121°C) cure prepreg</td>
<td>Controlled toughness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High strength</td>
</tr>
<tr>
<td>ARALL 4</td>
<td>Alloy: 2024-T8</td>
<td>Excellent fatigue</td>
</tr>
<tr>
<td></td>
<td>350°F (177°C) cure prepreg</td>
<td>High strength</td>
</tr>
</tbody>
</table>

therefore, surface preparation of the aluminum plays an integral part of the complete adhesive process. Prior to lay-up, the aluminum plies are chemically treated to remove contaminants. Next, the alloy layers are anodized by chromic and phosphoric acids to increase the porosity of the aluminum surface yielding better adhesive properties between the matrix and the aluminum.

After lay-up, the laminate is cured using an autoclave process at the appropriate temperature for the designated prepreg under a pressure of 69 kPa (100 psi). After curing, ARALLs 1 and 2 are given a 0.4% permanent stretch to relieve the residual stresses incurred during cooling.

While many precautions are taken to insure proper bonding of the product, there are two main hazards that can inhibit bonding between the aluminum and aramid-

![Figure 3.2: Chemical structure of Kevlar](image-url)
epoxy plies. Contamination and improper curing cycles are the major problems that manufacturers face when preparing ARALL [13]. These two problems can create poor bonds which are detrimental to the overall integrity of the composite’s strength. A third concern that can affect the manufacturing process involves the uneven supply of the epoxy resin matrix surrounding the aramid fibers. If too little matrix is present, voids will develop in the prepreg, again, resulting in poor or no bonds at all.

The samples used in this thesis were furnished by Alcoa. The laminates ranged in size from 100 by 170 mm to 129 by 251 mm. Some of the samples were prepared with Teflon inserts to replicate a poor bond. This aided significantly in the experimental procedure due to the consistent change in the physical characteristics of the laminate at the location of the tabs. Not all samples were properly identified with respect to the alloy or prepreg used; this meant having to use data collected from other papers.

For this particular procedure, only the cases in which the incident ultrasonic beam intersects the plate either perpendicular or parallel to the fiber direction of the aramid-epoxy plies are calculated. If the plies are assumed to be transversely isotropic, only the $C_{11}$, $C_{22}$, $C_{44}$, $C_{55}$, and $C_{12}$ components are required. In order to proceed in deriving the stiffness components, the moduli and Poisson’s ratios for the fibers and matrix are required. These properties are listed in Table 3.2 [13-15]. With the properties for the Kevlar and matrix known, the following equations to derive the moduli and Poisson’s ratios for the aramid-epoxy plies can be applied [14].

\[
E_{11} = E_f v_f + E_m v_m
\]  (3.1)

\[
E_{22} = E_m \left[ (1 - \sqrt{v_f}) + \frac{\sqrt{v_f}}{1 - \sqrt{v_f}(1 - E_m/E_f)} \right] \]  (3.2)

\[
\nu_{12} = \nu_{f12} v_f + \nu_{m} v_m
\]  (3.3)

\[
\nu_{21} = \frac{E_{22}}{E_{11}}
\]  (3.4)
Table 3.2: Material Properties for Aramid Fibers and Epoxy Matrix

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal Modulus</td>
<td>$E_{f1}$</td>
<td>GPa</td>
<td>130.0</td>
</tr>
<tr>
<td>Transverse Modulus</td>
<td>$E_{f2}$</td>
<td>GPa</td>
<td>41.0</td>
</tr>
<tr>
<td>Longitudinal Shear Modulus</td>
<td>$G_{f12}$</td>
<td>GPa</td>
<td>2.41</td>
</tr>
<tr>
<td>Volume Fraction</td>
<td>$v_f$</td>
<td>—</td>
<td>0.46</td>
</tr>
<tr>
<td>Longitudinal Poisson’s Ratio</td>
<td>$\nu_{f12}$</td>
<td>—</td>
<td>0.34</td>
</tr>
<tr>
<td>Matrix</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus</td>
<td>$E_m$</td>
<td>GPa</td>
<td>3.44</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>$G_m$</td>
<td>GPa</td>
<td>1.27</td>
</tr>
<tr>
<td>Volume Fraction</td>
<td>$v_m$</td>
<td>—</td>
<td>0.54</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>$\nu_m$</td>
<td>—</td>
<td>0.35</td>
</tr>
</tbody>
</table>

For a transversely isotropic ply, most of the stiffness components can be found by using

$$C_{11} = \frac{E_{11}}{1 - \nu_{12}\nu_{21}},$$  \hspace{1cm} (3.5)

$$C_{12} = C_{13} = \frac{\nu_{12}E_{22}}{1 - \nu_{12}\nu_{21}},$$  \hspace{1cm} (3.6)

$$C_{22} = C_{33} = \frac{E_{22}}{1 - \nu_{12}\nu_{21}}, \text{ and}$$  \hspace{1cm} (3.7)

$$C_{55} = C_{66} = \frac{1}{v_f/G_{f12} + v_m/G_m}.$$  \hspace{1cm} (3.8)

Following Christensen [15], the next three equations will be necessary to derive the final stiffness component, $C_{44}$.

$$E_{22} = \frac{4C_{44}K_{23}}{K_{23} + C_{44} + 4\nu_{12}^2C_{44}K_{23}/E_{11}}$$  \hspace{1cm} (3.9)

$$\nu_{21} = \frac{\nu_{12}^2C_{44}K_{23}}{E_{11}(K_{23} + C_{44}) + 4\nu_{12}^2C_{44}K_{23}}$$  \hspace{1cm} (3.10)

$$C_{12} = 2K_{23}\nu_{12}$$  \hspace{1cm} (3.11)
Table 3.3: Properties and dimensions used for experiments

<table>
<thead>
<tr>
<th>Material</th>
<th>$C_{11}$</th>
<th>$C_{22}$</th>
<th>$C_{33}$</th>
<th>$C_{44}$</th>
<th>$C_{55}$</th>
<th>$C_{66}$</th>
<th>$C_{23}$</th>
<th>$C_{13}$</th>
<th>$C_{12}$</th>
<th>$\rho$</th>
<th>$d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>110</td>
<td>110</td>
<td>110</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>2.7</td>
<td>.308</td>
</tr>
<tr>
<td>Aramid-epoxy</td>
<td>60</td>
<td>8.5</td>
<td>8.5</td>
<td>2.3</td>
<td>2.1</td>
<td>2.1</td>
<td>5</td>
<td>5</td>
<td>1.7</td>
<td>1.6</td>
<td>.205</td>
</tr>
</tbody>
</table>

$C_{ij}$ (GPa), $\rho$ (Mkg/m$^3$), and thickness $d$ (mm)

where $K_{23}$ is the plain strain bulk modulus. Combining equations 3.9, 3.10, and 3.11 will lead to the last equation for $C_{44}$,

$$C_{44} = \frac{C_{12}E_{11}E_{22}}{4C_{12}E_{11} - 2E_{11}E_{22}\nu_{12} - 4C_{12}E_{22}\nu_{12}^2}.$$  \hspace{1cm} (3.12)

Using the material properties in Table 3.2, the values for the stiffness components are: $C_{11} = 63.0$, $C_{22} = 7.45$, $C_{44} = 2.85$, $C_{55} = 1.63$, and $C_{12} = 2.57$ GPa. These calculations are generally sufficient for design purposes and provide approximate values for the stiffness components. However, for the theoretical calculations in this paper, we will be using the values in Table 3.3, which were obtained through the experimental work performed by others [7, 17]. We can see the derived stiffness components are relatively similar in magnitude.

**Principles of Ultrasonic Evaluations of Materials**

Employing the use of sound for testing materials is one of oldest methods of nondestructive testing. Ancient techniques of striking a casting with a hammer and listening for its ring or tapping a pottery cup are still used today. However, the frequencies of sound waves monitored in those experiential methods are in the acoustic range and far below ultrasonic frequencies (0.2-25 MHZ).

Ultrasonic evaluation of materials employs stress waves to elucidate mechanical properties of the material being examined. Stress waves consist of the coherent
movement of atoms in the material being tested. Ultrasound induces low amplitude mechanical stresses in the test piece being examined. Mechanical stresses in the specimen are produced by tensile, compressive, or shearing forces, and as long as the material is not stressed beyond its elastic limit, the particles in the test item will oscillate. Although stressing the material beyond its elastic limit is possible under carefully prepared conditions, strains rarely exceed 10 microstrain.

There are numerous ways in which ultrasonic waves can be generated and detected, but the most common one takes advantage of the piezoelectric effect. If a piezoelectric material has an electric field applied to it, it will expand or contract depending on the direction of the field. Conversely, if a piezoelectric material is deformed by the application of pressure, it will cause electrical charge separation that can be sensed as an AC voltage. Transducers are designed to make use of resonant piezoelectric plates and to tailor their bandwidth by suitable mechanical Q spoiling.

The ultrasonic wave from the transducer is coupled to the part by a fluid such as oil or water, or by a rubbery solid. The received signal can be analyzed for indications of flaws by time-of-flight comparisons or, as is the case of through-transmission (TT) tests, by comparing varying amplitudes.

**Fundamental Equations** The dynamic behavior of a linear elastic solid can be described by the following equations

\[
\frac{\partial \sigma_{ij}}{\partial x_j} = \rho \frac{\partial^2 u_i}{\partial t^2} \quad (3.13)
\]

\[
\sigma_{ij} = c_{ijkl} e_{kl} \quad (3.14)
\]

\[
\varepsilon_{kl} = \frac{1}{2} \left( \frac{\partial u_l}{\partial x_k} + \frac{\partial u_k}{\partial x_l} \right) \quad (3.15)
\]

where \( \sigma_{ij}, \varepsilon_{kl}, \) and \( c_{ijkl} \) are the stress, strain, and stiffness component terms respectively. By adopting the contracted index notation the general constitutive relation
\[ \sigma_{ij} = c_{ijkl} \varepsilon_{kl} \] simplifies to

\[
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{23} \\
\sigma_{13} \\
\sigma_{12}
\end{bmatrix} =
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\
C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\
C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\
C_{14} & C_{24} & C_{34} & C_{44} & C_{45} & C_{46} \\
C_{15} & C_{25} & C_{35} & C_{45} & C_{55} & C_{56} \\
C_{16} & C_{26} & C_{36} & C_{46} & C_{56} & C_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{33} \\
\gamma_{23} \\
\gamma_{13} \\
\gamma_{12}
\end{bmatrix}
\] (3.16)

where the engineering shear strain \( \gamma_{ij} = 2\varepsilon_{ij} \). For the isotropic case, equation 3.16 reduces to

\[
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{23} \\
\sigma_{13} \\
\sigma_{12}
\end{bmatrix} =
\begin{bmatrix}
C_{11} & C_{13} & C_{13} & 0 & 0 & 0 \\
C_{13} & C_{11} & C_{13} & 0 & 0 & 0 \\
C_{13} & C_{13} & C_{11} & 0 & 0 & 0 \\
0 & 0 & 0 & C_{66} & 0 & 0 \\
0 & 0 & 0 & 0 & C_{66} & 0 \\
0 & 0 & 0 & 0 & 0 & C_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{33} \\
\gamma_{23} \\
\gamma_{13} \\
\gamma_{12}
\end{bmatrix}.
\] (3.17)

**Wave scattering at interfaces** When a wave is incident on a plane boundary between two different isotropic media, some of the wave energy is transmitted through the interface and some is reflected. In the case of a longitudinal (L) wave traveling through water and approaching a solid interface at an angle, mode conversion will generally occur. The incident L wave will generate separate longitudinal and shear (S) waves in both solid media, as shown in Figure 3.3. If the incident L wave is in a medium that does not support shear waves, only an L wave will be reflected from the interface. The existence of boundary conditions at the interface that must be satisfied for all points on the interface plane and for all time implies the equality of
the propagators at the interface,

$$k_i^A \cdot \epsilon^+ = k_s^A \cdot \epsilon^+ = k_i^B \cdot \epsilon^- = k_s^B \cdot \epsilon^- \equiv \xi \cdot \epsilon, \quad (3.18)$$

where $^+$ and $^-$ denote positions above and below the interface, $\epsilon$ is a unit vector in the interface plane, $l$ and $s$ denote longitudinal and shear, and the materials are $A$ and $B$. This can also be expressed, assuming $k_l = \omega / V_l$ and $k_s = \omega / V_s$, as

$$\frac{\sin \theta_{il}}{V_l \text{ liquid}} = \frac{\sin \theta_{rl}}{V_l \text{ liquid}} = \frac{\sin \theta_{tl}}{V_l \text{ solid}} = \frac{\sin \theta_{ts}}{V_s \text{ solid}}, \quad (3.19)$$

This relation, Snell's law, governs the kinematics of refraction and reflection at a fluid solid interface. Here, $\theta_{il}$ and $\theta_{rl}$ are the incident and reflection angles for the incident longitudinal wave, and $\theta_{tl}$ and $\theta_{ts}$ are the refraction angles for the transmitted longitudinal and shear waves. The $V$ term denotes the velocity of the wave in the medium in which it is traveling, and the subscripts $l$ and $s$ represent longitudinal and shear waves. By increasing the incident angle, the refraction angles increase until
they reach the angle of 90°. This incident angle is known as the critical angle. There are two critical incident angles, the first when $\theta_{il}$ reaches 90° and the second when $\theta_{ts}$ reaches 90°. Beyond the second critical angle total reflection occurs and only evanescent waves are present in the solid.

**Plate Waves**

Plate waves, or Lamb waves [18], involve particle oscillation at right angles to the surface of the plate. Figure 3.4 illustrates the two fundamental types of plate waves, symmetrical and asymmetrical. In the case of the symmetrical wave, the particle displacement along the center line of the plate is in the form of pure longitudinal oscillations. In the case of the asymmetrical wave, the particle displacement along the center line is in the form of pure shear. In both cases the particles beyond the center line of the plate oscillate in an elliptical manner. Transverse resonance is a product of the incident shear and longitudinal waves reconstructing themselves after reflections from the lower and upper faces of the plate (Figure 3.5 [19]).
Incident and reflected vertically polarized shear partial waves

Incident and reflected longitudinal partial waves

Figure 3.5: Partial shear and longitudinal waves reconstructing after reflections

Any vector can be expressed as the sum of irrotational and solenoidal components, according to Helmholtz' theorem. The vector displacement field of a stress wave can be expressed therefore as the gradient of a scalar potential $\phi$ and the curl of a vector potential $\psi$,

$$ u = \nabla \phi + \nabla \times \psi. $$  

(3.20)

This substitution for the particle displacement can be used in the linear elastic wave equation to replace the usual trial solution, $u = U \exp[i(k \cdot r - \omega t)]$. The implication is that the potentials $\phi$ and $\psi$ each satisfy a separate partial differential equation, providing that we also apply the transverse gauge to the vector potential, $\nabla \cdot \psi = 0$. Then,

$$ \frac{\partial^2 \phi}{\partial t^2} = v_i^2 \nabla^2 \phi $$  

(3.21)

$$ \frac{\partial^2 \psi}{\partial t^2} = v_s^2 \nabla^2 \phi, $$  

(3.22)

where $v_{i,s} = k_{i,s}/\omega = \sqrt{C_{11,55}/\rho}$ is a necessary condition for the validity of the above equations.
Figure 3.6: A plate of isotropic material with traction-free surfaces

Solution for Plate Waves in Homogeneous Isotropic Media

**Notation** For the following problems, a brief explanation of the notation is necessary. Consider a wave propagating in an arbitrary direction in the \( x_1 - x_3 \) plane. Plane waves will have a vector wavenumber \( k \) that is related to the phase velocity by

\[
k_{l,s} = \frac{\omega}{v_{l,s}},
\]

where \( \omega \) is the angular frequency, and the subscripts \( l \) and \( s \) denote longitudinal and shear. The common \( x_1 \) wavenumber component is denoted \( \xi \), and the \( x_3 \) components for the longitudinal and shear are \( \alpha_1 \) and \( \alpha_3 \), respectively. The \( x_3 \) wave vector components have the following simple vector relationship with the total wavenumber \( k \)

\[
\alpha_{l,3}^2 = k_{l,s}^2 - \xi^2 = \omega^2 / v_{l,s}^2 - \xi^2
\]

which could also be deduced from a solution of the Christoffel equation.

**Isotropic Plate Waves** Consider the propagation of two-dimensional steady-state waves along an isotropic plate with traction-free surfaces (Figure 3.6). The
displacement fields in the $x_1 - x_3$ plane are described by

$$
\begin{align*}
    u_1 &= u_1(x_1, x_3, t) \\
    u_2 &= 0 \\
    u_3 &= u_3(x_1, x_3, t).
\end{align*}
$$

In terms of the potentials $\phi$ and $\psi$ the displacement terms of equation 3.20 are simplified with the absence of any $x_2$ dependency to

$$
\begin{align*}
    u_1 &= \frac{\partial \phi}{\partial x_1} - \frac{\partial \psi}{\partial x_3} \\
    u_3 &= \frac{\partial \phi}{\partial x_3} + \frac{\partial \psi}{\partial x_1}.
\end{align*}
$$

Trial solutions for $\phi$ and $\psi$ in a two-dimensional geometry are

$$
\begin{align*}
    \phi &= (A \sin \alpha_1 x_3 + B \cos \alpha_1 x_3) e^{i(\xi x_1 - \omega t)}, \\
    \psi &= (D \sin \alpha_3 x_3 + E \cos \alpha_3 x_3) e^{i(\xi x_3 - \omega t)}.
\end{align*}
$$

Substitution of the trial solutions into equations 3.25 and 3.26 yields the displacements component $u_1$ and $u_3$ as

$$
\begin{align*}
    u_1 &= i\xi(A \sin \alpha_1 x_3 + B \cos \alpha_1 x_3) - \alpha_3(D \cos \alpha_3 x_3 - E \sin \alpha_3 x_3) e^{i(\xi x_1 - \omega t)} \\
    u_3 &= i\alpha_1(A \cos \alpha_1 x_3 - B \sin \alpha_1 x_3) - i\xi(D \sin \alpha_3 x_3 + E \cos \alpha_3 x_3) e^{i(\xi x_3 - \omega t)}.
\end{align*}
$$

Stress and strain are related here by Hooke's law, and together with the linearized expressions for strain as displacement gradients, we have

$$
\sigma_{ij} = \lambda \frac{\partial u_k}{\partial x_k} \delta_{ij} + \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right). 
$$

For the traction-free plate the appropriate boundary conditions are

$$
\sigma_{33} = \sigma_{13} = \sigma_{23} = 0 \text{ at } x_3 = \pm h.
$$
The following identity will be useful in our derivation,

$$\alpha_1^2 + \xi^2 = (\alpha_3^2 + \xi^2) \frac{\mu}{\lambda + 2\mu}. \tag{3.33}$$

Substituting the trial solutions into the boundary condition equations (suppressing $e^{i(\xi x - \omega t)}$) yields

$$\sigma_{33}^{(x_3=h)} = -(\alpha_3^2 - \xi^2)S_1A - (\alpha_3^2 - \xi^2)C_1B - 2i\xi\alpha_3C_3D + 2i\xi\alpha_3S_3E = \Psi. \tag{3.34}$$

$$\sigma_{33}^{(x_3=-h)} = (\alpha_3^2 - \xi^2)S_1A - (\alpha_3^2 - \xi^2)C_1B - 2i\xi\alpha_3C_3D - 2i\xi\alpha_3S_3E = 0 \tag{3.35}$$

$$\sigma_{13}^{(x_3=h)} = 2i\xi\alpha_1C_1A - 2i\xi\alpha_1S_1B - (\alpha_3^2 - \xi^2)S_3D - (\alpha_3^2 - \xi^2)C_3E = 0 \tag{3.36}$$

$$\sigma_{13}^{(x_3=-h)} = 2i\xi\alpha_1C_1A + 2i\xi\alpha_1S_1B + (\alpha_3^2 - \xi^2)S_3D - (\alpha_3^2 - \xi^2)C_3E = 0. \tag{3.37}$$

Here, $C_i$ and $S_i$ are the appropriate harmonic functions evaluated at $\alpha_i h$. The boundary condition equations can be collected into matrix format,

$$\begin{bmatrix}
-(\alpha_3^2 - \xi^2)S_1 & -(\alpha_3^2 - \xi^2)C_1 & -2i\xi\alpha_3C_3 & 2i\xi\alpha_3S_3 \\
(\alpha_3^2 - \xi^2)S_1 & -(\alpha_3^2 - \xi^2)C_1 & -2i\xi\alpha_3C_3 & -2i\xi\alpha_3S_3 \\
2i\xi\alpha_1C_1 & -2i\xi\alpha_1S_1 & -(\alpha_3^2 - \xi^2)S_3 & -(\alpha_3^2 - \xi^2)C_3 \\
2i\xi\alpha_1C_1 & 2i\xi\alpha_1S_1 & (\alpha_3^2 - \xi^2)S_3 & -(\alpha_3^2 - \xi^2)C_3
\end{bmatrix} \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} = 0. \tag{3.38}$$

where a nontrivial solution for the four unknown amplitudes requires that the determinant of the coefficient matrix vanish. The symmetry of the above matrix allows it to be reduced by factoring to a product of two $2 \times 2$ determinants. The $2 \times 2$ determinants are comprised of the corner elements of the first, and the interior elements for the second

$$\begin{vmatrix} -(\alpha_3^2 - \xi^2)S_1 & 2i\xi\alpha_3S_3 \\ 2i\xi\alpha_1C_1 & -(\alpha_3^2 - \xi^2)C_3 \end{vmatrix} \times \begin{vmatrix} -(\alpha_3^2 - \xi^2)C_1 & -2i\xi\alpha_3C_3 \\ -2i\xi\alpha_1S_1 & -(\alpha_3^2 - \xi^2)S_3 \end{vmatrix} = 0. \tag{3.39}$$

Setting each of the above determinants to zero, we arrive at two fundamental dispersion relations that provide solution sets for the plate wave problem:

$$4\xi^2\alpha_1\alpha_3 \sin \alpha_3 h \cos \alpha_1 h + (\alpha_3^2 - \xi^2)^2 \sin \alpha_1 h \cos \alpha_3 h = 0$$
Dividing the first equation by \( \sin \alpha_3 h \sin \alpha_1 h \) and the second by \( \cos \alpha_3 h \cos \alpha_1 h \), the two secular equations are obtained in final form,

antisymmetric

\[
4 \xi^2 \alpha_1 \alpha_3 \cot \alpha_1 h + (\alpha_3^2 - \xi^2)^2 \cot \alpha_3 h = 0
\]  

\[(3.40)\]

symmetric

\[
4^2 \xi^2 \alpha_1 \alpha_3 \tan \alpha_1 h + (\alpha_3^2 - \xi^2)^2 \tan \alpha_3 h = 0.
\]  

\[(3.41)\]

Solutions of these equations depend on the plate’s material properties, \((\lambda, \mu, \rho)\), as well as its thickness \(h\). Using numerical methods the solutions of equations 3.41 and 3.41 can be found. The roots can then be plotted in a \(V_L\) versus \(f d\) format (Lamb wave phase velocity \((= \omega/\xi)\) versus frequency times thickness). A typical plot, as shown in Figure 3.7, reveals the numerous antisymmetric and symmetric Lamb wave modes. Varying the material properties will change the profiles of the mode curves. Likewise, varying the thickness of the plate will change the frequencies at which the Lamb waves will propagate. By maintaining a constant Lamb wave velocity in equations 3.41 and 3.41 we can find the roots in terms of \(f d\). These modes will depend on both intrinsic and extrinsic aspects of the plate and their variation will alert us to locally changing elastic properties.

**Wave Propagation in Layered Media**

Although the use of potentials conveniently solves the problem of the isotropic plate waves, it cannot be applied to layered media. Instead, the stress and displacement equations (3.13, 3.14) have to be used. As we will be focusing our attention on the reflected signal from a composite plate, an analytical expression is required for
the reflected field resulting from a wave incident on a fluid-immersed plate. Solutions to the problem of wave propagation in layered media using the transfer matrix are well documented [20-22], and an in-depth explanation is given by Nayfeh [23]. For the procedure in this paper, the problem is simplified since only the cases where the incident wave is either perpendicular or parallel to the fibers will be examined. Therefore, the derivation given by Chimenti et al. [24] is employed.

Consider a layered plate as shown in Figure 3.8. The laminate has a total thickness of

$$d = \sum_{k=1}^{n} d^{(k)}. \quad (3.42)$$

With the surface of the plate parallel to the $x_1 - x_2$ plane, the fibers in the $x_1$ or $x_2$ direction, and the incident wave coming from a fluid in the $x_1 - x_3$ plane,
particle displacement will be restricted to the $x_1 - x_3$. By selecting this coordinate system, and noting that the fluid does not support shear, one only has to deal with $\sigma_{11}$, $\sigma_{13}$, $\sigma_{33}$, $u_1$, and $u_3$. The boundary conditions for the fluid at $x_3 = 0$ and $x_3 = d$ are

$$
\sigma_{13} = 0, \quad \sigma_{33} = \sigma_{33}', \quad u_3 = u_3', \quad u_1 = u_1', \quad (3.43)
$$

and at the laminate interfaces

$$
u^k_1 = u^{k+1}_1, \quad u^k_3 = u^{k+1}_3, \quad 
\sigma^{k}_{33} = \sigma^{k+1}_{33}, \quad \sigma^{k}_{13} = \sigma^{k+1}_{13}. \quad (3.44)
$$

For each layer $k$, equations 3.13 and 3.14 can be combined to form two coupled equations as follows

$$
(u_1, u_3) = (U, W)e^{i\xi(x_1 + \alpha x_2 - ct)}. \quad (3.45)
$$

Where $U$ and $W$ are displacement amplitudes, $\xi$ is the wave number, $c$ is the phase velocity, and $\alpha$ is now an unknown ratio of the wavenumber components along the
Looking to find a characteristic equation for $\alpha$, superposition is used to obtain

$$(u_1, u_3, \sigma_{33}, \sigma_{13}) = \sum_{p=1}^{4} (1, W_p, D_{1p}, D_{2p})_k U_p e^{i(x_1 + \alpha x_3 - \alpha)}$$

(3.46)

where the non-trivial solution for $\alpha$ is found in the polynomial

$$\alpha^4 + A\alpha^2 + B\alpha^2 + C$$

(3.47)

that relates $\alpha$ to $c$. The coefficients $A_1, A_2$ and $A_3$ are given as

$$A = C_{33}C_{55}$$

$$B = (C_{11} - \rho\alpha^2)C_{33} + (C_{55} - \rho\alpha^2) - (C_{13} + C_{55})^2$$

$$C = (C_{11} - \rho\alpha^2)(C_{55} - \rho\alpha^2)$$

(3.48)

where for each $\alpha_p$, we express the displacement ratios by dividing by $U_{1p}$ for $W_p = U_{2p}/U_{1p}$ with

$$W_p = (\rho\alpha^2 - C_{11} - C_{55}\alpha_p^2)/(C_{13} + C_{55})\alpha_p,$$

$$D_{1p} = C_{13} + C_{33}\alpha_p W_p,$$

$$D_{2p} = C_{55}(\alpha_p + W_p), \quad \sigma_{ij} = \sigma_{ij}/i\xi.$$  

(3.49)

The stresses and displacements at the upper and lower surfaces of a ply can now be related via the common amplitude term $U_p$ by

$$[u_1, u_3, e_{33}, e_{13}]_{x_3 = d_k} = [a_{ij}]_k [u_1, u_3, e_{33}, e_{13}]_{x_3 = 0}$$

(3.50)

where the local transfer matrix is now defined as

$$[a_{ij}]_k = \begin{bmatrix}
B_1 & B_2 & B_3 & B_4 & 1 \\
W_1 B_1 & W_2 B_2 & W_3 B_3 & W_4 B_4 & W_1 \\
D_{11} B_1 & D_{12} B_2 & D_{13} B_3 & D_{14} B_4 & D_{11} \\
D_{12} B_1 & D_{22} B_2 & D_{33} B_3 & D_{24} B_3 & D_{21}
\end{bmatrix} \begin{bmatrix}
1 & 1 & 1 & 1 \\
W_1 & W_2 & W_3 & W_4 \\
D_{11} & D_{12} & D_{13} & D_{14} \\
D_{21} & D_{22} & D_{23} & D_{24}
\end{bmatrix},$$

(3.51)
This method can be repeated for all plies until the stresses and displacements at the top of the plate relate to those at the bottom by

\[
[u_1, u_3, \vec{\sigma}_{33}, \vec{\sigma}_{13}]^T_{x_3=d} = [A_{ij}] [u_1, u_3, \vec{\sigma}_{33}, \vec{\sigma}_{13}]^T_{x_3=0},
\]

where the global transfer matrix \([A_{ij}]\) is given by

\[
[A_{ij}] = [a_{ij}]_n[a_{ij}]_{n-1}...[a_{ij}]_1.
\]

The upper and lower fluid displacement and stresses can be given as

\[
\begin{bmatrix}
  u_1^{(u)} \\
  u_3^{(u)} \\
  \vec{\sigma}_{33}^{(u)}
\end{bmatrix}
= \begin{bmatrix}
  1 & 1 & \alpha_f & -\alpha_f \\
  \rho_f c^2 & \rho_f c^2 & \eta_f c^2 & \eta_f c^2
\end{bmatrix}
\begin{bmatrix}
  U_1^{(u)} e^{i\xi \alpha_f(x_3-d)} \\
  U_2^{(u)} e^{-i\xi \alpha_f(x_3-d)}
\end{bmatrix}
\]

and

\[
\begin{bmatrix}
  u_1^{(l)} \\
  u_3^{(l)} \\
  \vec{\sigma}_{33}^{(l)}
\end{bmatrix}
= \begin{bmatrix}
  1 & \alpha_f \\
  \rho_f c^2 & \rho_f c^2
\end{bmatrix}
\begin{bmatrix}
  U_1^{(l)} e^{i\xi (x_1+\alpha_f x_3-ct)}
\end{bmatrix}
\]

where

\[
\alpha_f^2 = (c^2/c_f^2) - 1, \quad \vec{\sigma}_{33} = \sigma^{(u)}/i\xi.
\]

Subjecting the solutions of equations 3.53, 3.55, and 3.56 to the boundary conditions in equation 3.43, the solution to the reflection coefficient can be found as follows

\[
R = \frac{(M_{21} + Q M_{22}) - Q(M_{11} + Q M_{12})}{(M_{21} + Q M_{22}) + Q(M_{11} + Q M_{12})}
\]

where

\[
\begin{bmatrix}
  M_{11} & M_{12} \\
  M_{21} & M_{22}
\end{bmatrix}
= \begin{bmatrix}
  A_{21} & A_{22} & A_{23} \\
  A_{31} & A_{32} & A_{33}
\end{bmatrix}
\begin{bmatrix}
  -A_{42} & -A_{43} \\
  A_{41} & 0 \\
  0 & A_{41}
\end{bmatrix}
\]
Leaky Lamb Wave Field

Figure 3.9: Illustration of an incident beam creating a Lamb wave in the plate, with a null zone in the reflected beam and a weaker trailing field known as the leaky wave field.

and

\[ Q = \frac{\rho f c^2}{\alpha_f}. \quad (3.60) \]

Reflection from Fluid-Coupled Plates

Several phenomena occur when an incident beam is reflected from a liquid-solid interface of a half-space. Bertoni and Tamir [25] found that there is a beam shift and a phase shift in the reflected field when the angle of the incident wave is at or near the Rayleigh angle. Additionally, a null zone was found due to the energy redistribution caused by the Rayleigh, or surface, wave. The same effects are found in the case of a fluid-immersed plate when the incident beam is near the angle which will cause Lamb waves in the plate. An illustration of this phenomenon in the experimental set-up is provided in Figure 3.9.

In the experimental procedure of this paper, we are going to observe the voltage minima of the receiver transducer caused by the null zone created by the Lamb waves.
in the plate. One would like the voltage minima to coincide with the minima of the 
reflection coefficient derived in equation 3.58. This being the case, the beam shape, 
size, near and far field effects, and the relative lateral transducer position have to be 
taken into consideration. The following derivations are taken from Lobkis et al. [26].

To attack the problem a plane wave decomposition of the incident transducer field is done. The incident beam is assumed to have a Gaussian distribution, and both the receiver and transmitter probes are identical. The incident particle velocity \( \Psi_i(x, y) \) can be expressed according the Rayleigh Integral formula as

\[
\Psi_i(x, y) = \frac{1}{2\pi} \int \int \mathcal{V}_T(f, S_T) \frac{\exp[ikr]}{r} \, dS_T. \tag{3.61}
\]

Where \( \mathcal{V}_T(f, S_T) \) is the frequency and position dependent particle velocity on the transmitter surface \( S_T \), \( f \) is the frequency, \( k \) is the wave number in the fluid, \( r \) is the distance between between two points \( (x_T, y_T, z_T) \) and \( (x, y, 0) \) on the transmitter and on the plate, so that \( r = (z_T^2 + (x_T - x)^2 + (y_T - y)^2)^{1/2} \), and the subscript \( T \) refers to the transmitter. The free space Green’s function, \( \exp[ikr]/r \), is the solution to the wave equation for a point source. With equation 3.61, the particle velocity can be determined at a position \( r \) away from the transducer. To compute the reflected field the incident field has to be multiplied with the reflection coefficient. Since the reflection coefficient is derived assuming plane waves, the incident Gaussian shape beam has to be decomposed into plane waves. This can be done by a Fourier transformation or numerically with the Fast Fourier Transform algorithm. Following Lobkis with the plane wave spectral decomposition of a spherical wave, the incident transducer field can be expressed as

\[
\Psi_i(x, y) = \frac{ik}{4\pi^2} \int_0^{2\pi} \int_0^{\pi/2} D_T(\theta, \phi) \exp[-i\kappa \sin \theta \{x \cos \phi + y \sin \phi\}] \sin \theta \, d\theta \, d\phi , \tag{3.62}
\]
where \( \theta \) and \( \phi \) are polar and azimuthal angles for each plane wave direction of propagation, and \( D_T(\theta, \phi) \) is the transmitter directivity function which depends on its position and orientation. The expression for the directivity function is as follows

\[
D_T(\theta, \phi) = \int_{S_T} \mathcal{V}_T(f, S_T) \exp \left[ i\kappa z_T \cos \theta + i\kappa \sin \theta(x_T \cos \phi + y_T \sin \phi) \right] dS_T. \tag{3.63}
\]

For the reflected field each spectral component of the incident beam has to be weighted by the reflection coefficient. Since the wave propagates over a finite path from the plate to the receiver, the propagator of the reflected has to be multiplied with an additional phase term. The reflected field for an arbitrary point on the receiver \((x_R, y_R, z_R)\) is then given by

\[
\Psi_r(x_R, y_R, z_R) = \frac{i\kappa}{4\pi^2} \int_0^{2\pi} \int_0^{\pi/2-i\infty} R(\theta, f) D_T(\theta, \phi) \exp[i\kappa(z_R \cos \theta - \sin \theta \{x_R \cos \phi + y_R \sin \phi\})] \sin \theta \, d\theta \, d\phi. \tag{3.64}
\]

Since we are interested in the voltage on the receiver, we can apply Auld and Kino's [40, 41] reciprocity formulas. This reciprocity formula relates mechanical vibrations to the corresponding voltage, and the resulting output signal can be represented by

\[
V_R = \int_{S_T} \mathcal{V}_R(f, S_R) \Psi_r(x_R, y_R, z_R) \, dS_R, \tag{3.65}
\]

where \( \mathcal{V}_R(f, S_R) \) is the particle velocity on the receiver surface \( S_R \). After combining equations 3.64 and 3.65 the voltage can be written in terms of the directivity function. After assuming a Gaussian beam, and following Lobkis, the voltage on the receiver can be written as

\[
V(x_i, f) = \frac{i\kappa}{4\pi^2} \int_0^{2\pi} \int_0^{\pi/2-i\infty} R(\theta, f) D_T(\theta, \phi) D_R(\theta, \phi) \sin \theta \, d\theta \, d\phi \tag{3.66}
\]

where \( D_R(\theta, \phi) \) is the receiver directivity function, in analogy to \( D_T(\theta, \phi) \), and \( x_i \) is the distance between the intersection of the transducer axis and the plate, as shown.
According to Lobkis, the product of $D_T D_R$ can be replaced with a Gaussian beam approximation for the transducers by

$$|D_T^G(\theta, \phi) D_R^G(\theta, \phi)| = \nu_T(f, S_R) \nu_R(f, S_R) \exp[-(b k \alpha \sin \delta)^2].$$

(3.67)

If a beam is incident on a plate several phenomena occur. The reflected beam is shifted from the position predicted by geometrical acoustics. Within the reflected field a null zone exists, due to interferences. Furthermore, a weaker field accompanies the reflected beam, and extends for a considerable distance to the right. Lobkis et al. pointed out that the relative phase of the specular, leaky wave and the voltage minima are dependent on the beam shift. Therefore only one optimal value for the beam shift $x_i$ shown in Figure 3.10 yields the minimum voltage that coincides with the reflection coefficient zeros. After rigorous experimental work, Lobkis et al. concluded that the closest correspondence of voltage minima with reflection coefficient zeros over a wide
frequency range occurs when the transducers are positioned such that their axes intersect the plate surface with a separation approximately equal to the transducer radius.

**Floquet Theorem**

As the observation of stop bands and pass bands for waves in the laminate is going to be a part of the protocol, an understanding of their formation is necessary.

Consider a material such as the ARALL laminates with alternating plane layers of two materials, as previously shown in Figure 3.8. The first two layers form what is called the unit cell of the composite. With the periodicity of the problem, the Floquet theorem can be used to find solutions for the stresses and displacements as a function of \( x_3 \) by the following equations,

\[
\begin{align*}
    u_i &= U_i(x_3)e^{i(kx_3-\omega t)} \quad \text{and} \\
    \sigma_i &= T_i(x_3)e^{i(kx_3-\omega t)},
\end{align*}
\]

where \( k \) is the wave number through the periodic media and the functions \( U_i(x_3) \) and \( T_i(x_3) \) are continuous across the layer interfaces and do not depend on time, \( U_i(x_3) \) and \( T_i(x_3) \) are periodic functions with the period equal to the unit cell, or \( x_3 = \text{unit cell length} \). The solution for the problem will yield real values for \( k \) within distinct frequency bands, known as pass bands. The solutions with imaginary parts \( k = k_R + ik_I \) will have the equations for the stresses and displacements containing the term \( e^{-k_Ix_3} \). Therefore, the amplitudes for the stresses and displacements will decrease, or attenuate, exponentially with \( x_3 \). The frequencies where \( k \) is complex are known as stop bands. In the stop band what is physically happening is that the partial waves will not reconstruct themselves in contrast to the pass bands where they will.
Figure 3.11: Dispersion curve for a 5/4 ARALL plate

The theoretical dispersion curve in Figure 3.11 illustrates the stop and pass band behavior for a 5/4 ARALL plate [7]. Here, one can see the distinct frequency ranges where the plate waves will propagate for a given phase velocity. For example, following the horizontal dashed line at the phase velocity of 5 km/s, we can see the mode clustering (pass bands) in the 0.5-2.0, 4.0-8.0, and 9.5-10.5 frequency ranges. Outside these bands, plate waves will not propagate in the laminate. It is this information that will be used in designing the protocol. For the experimental case where a compressional wave from a transducer is incident on a fluid-loaded plate, the phase velocity of the plate wave can be found using Snell’s law,

\[
V_p = \frac{V_f}{\sin \theta_i},
\]  

(3.70)
where $V_p$ is the phase velocity, $V_f$ is the fluid wavespeed, and $\theta_i$ is the incident angle. By correlating the observed minima from the reflected signal with the calculated reflection coefficient minima, deviations in the minima groupings will indicate changes in the laminates structural characteristics.
CHAPTER 4. EXPERIMENTAL SETUP

In this chapter we discuss several issues relating to the conduct of the experiments reported herein. The experimental geometry and the procedure used to acquire the data are covered first, and we end with a description of the analysis of the data.

Experimental Geometry

The experimental apparatus employed in these measurements to simulate an industrial test setup is illustrated in Figure 4.1. Starting with the trigger, the path lines step us through the experimental procedure. Upon being triggered, the function generator sends a “chirp” signal to the transmitting probe. The received signal from the other probe is then amplified and sent on to the oscilloscope where the trace of the signal is held in memory for retrieval by the computer. The computer then processes the data all the while controlling the motion of the transducers through the scan. For clarity of explanation, the procedure will be separated into five phases: signal generation, transducer configuration, signal amplification and acquisition, computer control and data transfer, and data manipulation. After all phases have been presented, a description of the pertinent data processing techniques and analysis will be given.
In these experiments we decided to attempt an improvement on the usual industrial practice of excitation with an rf impulse. We chose instead to employ a "chirp" signal, consisting of an rf signal having a time-dependent frequency. In a general sense such a signal can be thought of as frequency-modulated, but with the difference that in a chirp, the frequency varies monotonically, usually from low to high. If expressed as a signal in the audio range, such frequency coding would have a sound...
similar to a songbird, hence the name "chirp". The distinct advantage here over the wide-band impulse is that the signal bandwidth can be specifically tailored to the application at hand. Applications of chirp signals to NDE have been performed by Paul Gammell [17], where an improvement in signal-to-noise ratio equivalent to averaging 100,000 pulsed signals can be found by using a low sweep rate of around 50 ms. For our purposes, this rate of 50 ms is considered to be too long and is beyond the capabilities of the arbitrary wave form function generator.

An example of a short chirp signal is shown in Figure 4.2. In this signal trace, one can see the frequency begin at a low value of 100 kHz and end at 10 MHz. The duration of the signal is 4.5 \(\mu\)sec, purely for illustrative purposes, because a larger period would produce an image of a solid block where the lines in the signal could not
be seen. For this experiment the period of the signal is 100 $\mu$sec. This time span was chosen for two reasons: 1) short enough to avoid disturbing reflections; 2) long enough to transmit substantial energy at all frequencies of interest. The power spectrum of a chirp similar to that shown in Figure 4.2, but with the frequency range of 1-12 MHz over a 100 $\mu$s duration is shown in Figure 4.3. From the power spectrum one can see that significant energy is contained outside our intended bandwidth. This is due to the short transition time in reaching maximum amplitude. The rise and fall times for the chirp signal are also carefully chosen to minimize production of energy outside the bandwidth of interest. The rise and fall times for the final chirp signal used in this experiment are illustrated in Figure 4.4. Again the period is shortened strictly for illustrative purposes. One can see in this example the gentle increase
Figure 4.4: An example of a chirp with its amplitude enveloped by a gentle increase and decrease at the start and end of the signal and decrease in the amplitude of the chirp at the leading and tail ends of the signal, respectively. After the signal has slowly, or gently, increased the amplitude quickly rises to the maximum amplitude, and is mirrored at the end of the signal. Figure 4.5 illustrates the power spectrum of the chirp used in this experiment. The period of this signal is 100 $\mu$s with a frequency range of 1-12 MHz. Compared to Figure 4.3 we can see that the comparative energies outside the power spectrum have significantly decreased.

After an appropriate frequency range has been established for the chirp, a FORTRAN program running on a VaxStation 3100/38 is used to produce the required sampled data points to be sent to an arbitrary function generator which will approx-
imate the desired signal. Prior to voltage generation, the signal points are converted from 16-bit binary words to a voltage level required by the function generator. The duration of the chirp is 100 \( \mu s \) and its frequency increases linearly. Typically, the frequency range varies from 0.5 to 10 MHz. Triggered externally by a 1 kHz square wave, the generator then sends a repeated chirp signal to an immersed transducer which directs the resulting pressure waves at the ARALL plate being scanned.

**Arbitrary Function Generation** The arbitrary function generator is a model DS345 synthesized function generator manufactured by Stanford Research Systems and is ideally suited for this experimental procedure. The generator allows the downloading of arbitrary waveforms in discrete format. The DS345 has a maximum dig-
Figure 4.6: Example of an applied chirp signal while under transducer load

itization rate of 40 MHz, and is therefore capable of reproducing the maximum 10 MHz frequency necessary for this study. Owing to the variation of the output voltage levels at the high frequency end, care must be taken in designing the chirp to compensate for any frequency-dependent impedances. An example is shown in Figure 4.6, where the amplitude decreases with frequency. The difference between this Figure and Figure 4.4 is that the arbitrary function generator is now under the load of the transducer. Figure 4.6 illustrates that the load of the transducer is causing a decrease in the amplitude chirp signal at the higher frequencies. By measuring the variation in synthesized signal amplitude at higher frequencies, a compensation factor can be found and used to modify the original chirp data prior to down loading. This ensures that the voltage level is nearly constant for all frequencies within the
desired bandwidth.

**Transducer Configuration**

For all experiments, two ULTRAN L37-5 9.4 mm diameter broad band piston transducers are used as transmitter and receiver. According to the manufacturer's test, each transducer has a bandwidth of approximately 3.8 MHz at -6 dB from the peak or center frequency. The broad band capabilities of the transducers make them well suited for the large frequency range of the chirp used in the procedure. For consistency, the same transducer is used as the transmitter during all experiments.

The transducers are affixed to search tubes and are set at opposite angles to one another from the normal of the plate. Both transducers are maintained at an equal elevation above the plate. The angles of the search tubes are adjusted using a Newport motion controller capable of fine adjustments to one hundredth of a degree. The transducer orientation is shown in Figure 4.7. Prior to positioning the transducers
to the desired angles, they must be aligned so that the maximum radiation of the transducer is consistent with the angle chosen. To accomplish this, the transducer is positioned normal to a level interface. The probe is then set up for a pulse-echo measurement and excited with an rf signal of ten cycles near its center frequency. The maximum return amplitude is then found by fine micrometer adjustments of the search tube on a gimbal mount. The Newport motion controller is then set to zero, thereby establishing an incident angle of zero degrees consistent with the maximum radiation of the transducer. The zeroing process is repeated for the second transducer.

**Signal Amplification and Acquisition**

The received signal is amplified by a Model BR-640 Ritec Broadband Receiver prior to continuing on to the oscilloscope. Typically a gain of eight dB was found to be sufficient amplification for this experiment. The oscilloscope is triggered externally by the same square wave that triggers the function generator. However, the oscilloscope has its delay set to compensate for the traveling time of the waves in the water. The received signal is averaged for ten sweeps and stored for later retrieval by the computer.

The LeCroy 9304A Digital Oscilloscope used for this procedure can provide a 100 megasamples per second digitizing rate for transient, or single shot, signals. The 9304A has four input channels and four traces. For all measurements, the received signals are sent to channel one on the oscilloscope, with trace A configured to take the average of ten sweeps where it is stored and transferred to the computer in byte format. The 9304A is capable of averaging 1,000 sweeps, but the time required to attain that many averages is excessive and little improvement is seen with regard to the reduction of noise in the captured signal. The signal is digitized using ten
thousand points and the averaged signal is stored in trace A. Each averaged signal is then retrieved by the computer for final data processing and comparison.

Prior to each scan, a reference curve covering the frequency range of the chirp and transducer geometry is acquired. The reference curve is intended to compensate for the frequency response of the transducers and the acoustic attenuation of the water [24]. To achieve this, a thick homogeneous plate is positioned at the same depth below the transducers as where the plate will be for the scanning process. The homogeneous plate is intended to be thick enough to be considered a half-space. The signal of the reflected chirp is then transformed to its power spectrum via a Fast Fourier transform. The reference curve is then saved for the scanning program to be used to normalize the received signals reflected off the plate being tested.

**Computer Control and Data Transfer**

A digital VaxStation 3100/38 computer is used for all aspects of this experimental procedure. The only exception is the image processing, which is performed on a MacIntosh computer using Image 1.55. All programming is done in FORTRAN (f77) language. Data transfer and control commands are passed to and from the computer over a IEEE-488 bus using National Instruments commands. The Vax station receives the data from the oscilloscope in byte format and converts it to integer format. The scanning process is fully automated after the chirp signal is down loaded into the function generator and a reference curve has been acquired.

**Data Manipulation**

Typically, the signal captured by the oscilloscope has 10,000 points. A Fast Fourier Transform program is used to convert the signal into the frequency domain
Figure 4.8: Power spectrum of a reflected signal from a half-space used for normalizing plate signals

[28]. In order to proceed with the Fast Fourier Transform, the signal data points are padded with zeros so that the total number of data points are a power of 2. The transformed data is then used to produce the power spectrum of the received signal by taking the square root of the real and imaginary components squared. It is this spectrum that is normalized with the reference curve so that it can be compared to the theoretical data. An example of the reference curve is shown in Figure 4.8, where we can see the increased amplitude near the center frequency and the subsequent lower amplitudes at frequencies on either side. Using 10,000 points over a period of 100 µs translates to 164 data points per MHz in the power spectrum. Some noise is present in the signal and this becomes evident when normalizing the acquired plate
signal with the reference curve. At the higher and lower frequencies of the normalized data, there appear to be irregularities where the signal to noise ratio is considerably less than that of the frequencies nearer to the center. Nevertheless, a relatively clean signal is acquired thereby simplifying and minimizing the post-processing of the data.

A simple system is used in an attempt to remove the irregularities from the normalized data. The method employed is called moving window averaging [29]. This data processing technique entails taking the average of the forward and rear points of the data point to be adjusted. This method can be described by

\[ g_i = \sum_{n=-n_L}^{n_R} c_n f_i + n, \quad c_n = \left( \frac{1}{n_L + n_R + 1} \right) \]

where \( f_i \) is the old data point, \( n_L \) and \( n_R \) are the number of points to the left and right of \( f_i \), and \( g_i \) is the new data point that replaces \( f_i \). There is some danger in using this method, especially in a spectrometric application where a narrow spectral line will have its height or depth reduced and its width increased. However, for this experiment only a very small window is applied, and as a result of the density of data points, no appreciable difference in the width or depth of narrow spectral lines is found. Examples of a windowed and non-windowed signal are shown in Figure 4.9. For illustrative purposes, the top curve has an amplitude offset of .5. We can see that by maintaining a minimal number of averaging points, \( n_L \) and \( n_R \), the narrow minima at the far left of the spectrum exhibits negligible change in its width or depth. At the same time, we can see that the window averaging effectively reduced some of the irregularities at the higher and lower frequency ranges. The data for the two curves in Figure 4.9 were collected from separate signals indicating that variations in random noise will not affect the final output curve.

Once the normalized signal has been established, it is compared to the theoretical results, already implemented in the scanning program, and assessed for any
Figure 4.9: Normalized power spectrum, top window averaged, bottom raw signal similarities or discrepancies. For each point that is scanned, there is a single value assigned to that position for the final output. The value assigned corresponds to the known condition of the plate. For example, the value “one” may correspond to a signal that has the characteristics of a good plate. If the signal cannot be compared to any theoretical result, it will be assigned a value that will indicate that the characteristics at that point are unknown. Each assigned value is then placed into an array and saved for image processing. The final image is coded with respect to the intensity of the gray scale. Each level of intensity corresponds to a distinct characteristic feature of the plate.

Several variations of the final scanning program and image output are used for explanations in the next chapter. Figure 4.10 illustrates the various methods used.
Single Point Data Collection

Output Data
Receiver Voltage vs Freq.

Used For
Comparison of Theory and Experimental Data

Line Scan

Output Data
Full frequency power spectrum for each point in line scan

Used For
Visual analysis of the change in the frequency power spectrum for each point in line scan

Full Scan

Output Data
A single value assigned to each point in the scan representing the physical characteristics at that point

Used For
A visual image of plate describing the physical characteristics of the plate at each point

Legend

• Single Collection Point

\rightarrow

Multiple Collection Points

Arrow Indicates Scan Direction

Figure 4.10: Variations of the data collecting process

The first method consists of taking the data values from the normalized reflection spectrum at one point on the plate. The data is stored in a paired array with an amplitude voltage for each frequency point. The plotted data produces the spectrum curves similar to those shown in Figure 4.9. This collection procedure permitted the comparison with the theoretical curves. The second method entails making a line scan. Here, the whole reflection spectrum for each point in the scan is stored in an array for image processing at a later time. The final image provides a two-dimensional image for the line scan. The end result produces a visual depiction of the change in the reflection minima by use of a gray scale. Finally, the full plate scan assigns a single value at each point on the plate and is stored in a matrix form. Each value is scaled according to the condition of the plate. After final processing with Image
1.55, a gray scale coded illustration is produced depicting the characteristics of the plate for every point on the plate.
CHAPTER 5. RESULTS AND DISCUSSION

All experiments discussed in this chapter have been performed using the experimental setup detailed in the previous chapter. We will first discuss the strategy used to ultimately select the transducer and fiber angles. A series of line scans that allowed us to observe obvious changes in the frequency spectrum will be presented next, followed by a review of some of the point data collections. An example of a plate scan will be provided and the protocol procedures for ultrasonic testing of ARALL plates follows.

Transducer and Fiber Angles

This experimental procedure relies heavily on the minima location of the reflected signal with respect to the frequency and how it compares to that of the theoretical results. A computer program designed to generate, for a given incident angle, reflection coefficient curves as a function of frequency was used to find the minima corresponding to the plate waves present in the laminate. The program is also capable of generating reflection coefficient curves for a composite with a smooth interface, or “kissing bond”, present within the composite. Numerous curves were constructed in order to find the optimum angle and fiber orientation that would provide distinct changes in the reflection characteristics. Ideally, the angle and fiber orientation chosen should produce a reflection curve with two specific characteristics that will aid in the detection of flaws for the frequency range chosen. First, the reflec-
Figure 5.1: Illustration of the incident beam on a plate and the defined angles: $\theta$ and $\phi$

tion coefficient curve should exhibit mode clustering as discussed previously during the review of Shull’s work [7]. If debonds or smooth interfaces are present in the laminate, changes in the number of minima (or modes) in the monitored reflected signal should occur indicating a change in the composite’s physical make-up. The second desirable characteristic would entail distinct stop bands. Again, if debonds or smooth interfaces are present in the laminate, there could be a change in the area that was once a stop band and now allows a significant amount of wave energy to be transmitted through the plate. These two characteristics will provide the possibility of searching two different areas of the reflected signal for signs of a composite flaw.

Various angles were tried for the case where the horizontal projection of the incident beam runs parallel to the fibers in the aramid-epoxy plies. As shown in Figure 5.1, we will denote the angle between the horizontal projection of the beam and the fibers as $\phi$ and the angle between the beam and the plate normal as $\theta$. Although pronounced changes in the curves could be found in the case of a delamination, the
same could not be said for the presence of a smooth interface within the composite. Sample reflection curves for the case where smooth interfaces are present in the laminate are shown in Figures 5.2 and 5.3. On examining the figures, we can see the desired prominent stop bands and grouping of the minima, but there is little or no change in the reflection curves for smooth interfaces. However, we can see changes in the curve between .5 and 2 MHz, but this is outside the practical range for the transducers being used.

Changing the ply orientation so that the horizontal projection of the incident
Figure 5.3: Reflection curve results for an ARALL 3/2, \( \theta = 20^\circ, \phi = 0^\circ \). The curves are ordered in the same manner as shown in Figure 5.2.

Beam is now perpendicular to the fibers, \( \phi = 90^\circ \), provided positive results. Distinct changes in the location of the minima can now be found in the reflection curves with a smooth interface present in the composite. Sample curves where smooth interfaces are present in the laminate are illustrated in Figures 5.4 and 5.5. If we examine these figures, we can see marked changes in the location of the stop bands and the mode groupings for the top curves which represent a plate that is considered intact. We can also see that for the lower curves, which indicate smooth interfaces at various interfaces, there are significant changes in the mode groupings and the areas where the stop bands exist. These significant changes in the reflection curves will aid us in determining the characteristics of the plate. Compared to the reflection curves for
Figure 5.4: Reflection curve results for an ARALL 3/2, \( \theta = 10^\circ, \phi = 90^\circ \). The curves are ordered in the same manner as shown in Figure 5.2.

\( \phi = 0^\circ \), it becomes quite apparent that the azimuthal angle of \( \phi = 90^\circ \) will provide us with more information towards determining whether or not flaws are present in the composite.

If we pay special attention to the top curve in Figure 5.4, we can see two characteristics which are going to be desirable for our protocol procedure. The top curve represents a good 3/2 laminate. The mode grouping between 6 and 8 MHz has four minima. Since the 3/2 plate has 2 unit cells, this corresponds to two plate modes in that region. The second desirable feature of this curve is the wide stop band prior to the start of the grouping. Other than the frequency range where the mode clustering exists, this is a common trait for all the laminates (2/1 to 5/4) when the incident
angle is set at $\theta = 10^\circ$. The only exception is the 2/1 layup where there are three modes present in this range. As we will see later, any changes in the physical make up of the plate, such as delaminations or smooth interfaces, will change the mode grouping or the stop band. Due to this dependable grouping, and large stop band which proceeds it, the incident angle of ten degrees will be chosen for the protocol procedure. Nevertheless, some sample test results at other incident angles will be presented.

For generating the theoretical curves that represent complete delamination, a model of a laminate separated by two different fluids was used. The fluid that contacts the top layer where the beam is incident has the property values of water. For
Figure 5.6: Complete delamination reflection curves starting at the top with 1 layer through to 8 layers, $\theta = 10^\circ$, $\phi = 90^\circ$

the bottom layer, the point at which the delamination is to be assimilated, the fluid has the properties of air. The reflection curves depicting delaminations for an incident angle of ten degrees are shown in Figure 5.6. The top curve represents a delamination between plies one and two, and each successive curve below denotes an increment of one ply layer before the point of delamination. Upon examination of these curves, we can see an almost direct correlation with respect to the number of unit cells present before the delamination occurs and the number of modes. For example, between 4.5 and 8 MHz, we can see the modes increasing almost proportionately to the number of unit cells before the delamination. It is very apparent that we will be able to find a detectable delamination near the top of the surface for
a 4/3 or 5/4 plate, due to the severe drop in the number of modes present between 4 and 8 MHz. However, for the case of a delamination of a ply near the bottom of the plate the same cannot be said. In this situation, the number of unit cells is approaching the total amount for the entire plate and the reflected spectrum will give the appearance that the plate is intact. As a result, we will have to be careful in our approach to finding delaminations deep within the composite. To attack this problem it is foreseeable that the plate may have to be inspected with a second receiver positioned below the plate to monitor the through transmission signal. If this is done, we can verify our results with the assurance that a detectable delamination deep in the plate has not been overlooked.

With the decision of azimuthal angle in hand, we now move on to the possibility of the changes in the ply thicknesses. We will assume the aluminum plies in the ARALL products are controlled to a high standard and that any variation in thickness will be negligible. Therefore, we now focus our attention on the aramid-epoxy plies. Figures 5.7 and 5.8 show a comparison of the reflection curves for 2/1 and 3/2 plate, respectively. In both cases, the aramid-epoxy layers have been given an added thickness of 5%. This value is chosen as a result of measuring the supplied plates where the aramid-epoxy plies varied from .204 to .215 mm. Visual inspection of the curves reveals that the mode groupings have remained relatively intact in their structure, but with a shift at the higher frequencies. This is a very important feature that we can exploit in an angled incident test procedure. If an increase in the aramid epoxy plies exists, we notice a shift in the mode grouping in contrast to a drop in the received signal amplitude for a normal-incident transmission case. This drop in amplitude may result in the test piece being falsely rejected for a poor bond when in reality there may only be an increase in the thickness of the aramid-epoxy plies.
Figure 5.7: Comparison of reflection curves for ARALL 2/1. Aramid-epoxy plies thickness $d = .204$ mm (top), $d = .214$ mm (bottom), $\theta = 10^\circ$, $\phi = 90^\circ$

**Line Scans**

The line scans used in this experimental procedure provide us with a graphic illustration of the frequency spectrum at each point in the line. It was used as a starting point to observe the changes in the reflection spectrum for the ARALL plates. With the oscilloscope set for continuous trigger, the motion controller keyboard was used to move the transducers about the laminate while monitoring the reflected signal on the oscilloscope screen. If any appreciable changes in the signal were found, the position would be noted to prepare for a line scan through the area in question.

Typically, the line scans are 50 mm in length with stepped intervals of 1 mm.
The image results for a 2/1 plate line scan are shown in Figure A.1. The output of the line scan is represented by the rectangular gray-scale image at the top of the figure. The vertical axis to the left of the image represents the position of each point in the line scan and is measured in mm. The horizontal axis is scaled in MHz and represents the frequency range selected. The intensity of the gray scale corresponds to the normalized voltage at that frequency, where light to dark shades signify low to high voltage amplitudes from the receiver, respectively. The two line graphs below the gray scale image correspond to the two point positions in the line scan as noted by the right angle arrows.

The almost white vertical lines in the gray scale image of Figure A.1 are indica-
tions of where the voltage is at a minimum and, therefore, where plate modes exist for a given frequency. It is visually easy to see that there is a change in the number and frequencies of the modes when scanning from 0 to 50 mm. The lower line graph shows the desired mode grouping and stop bands zones that we are after. We will later show that this reflection spectrum is indicative of a good plate. Comparing the upper and lower line graphs, we can see that the mode grouping has been affected. It will be shown later that this change indicates a debond or a smooth interface after the first ply.

Figure A.2 shows the results from a line scan with the same plate as used previously, but with the incident angle set to twenty degrees ($\theta = 20^\circ$). Again, we can see the changes in the upper and lower line graphs which correlate to a flawed area and good area in the plate, respectively. When comparing the lower line graph to the one in Figure A.1, we can see that the mode groupings have changed and the stop band narrowed. The stop band zone has narrowed from 3 to 6 MHz at $\theta = 10^\circ$ down to 4.5 to 6.5 MHz at $\theta = 20^\circ$. As this is the trait we wish to avoid, an incident angle of 20$^\circ$ would not be chosen for inspecting a 2/1 laminate. The line scans in Figures A.3 and A.4 are through the same flaw in a 3/2 plate, but taken from the opposite sides of the laminate. The line graphs with the greater number of minima, or modes, are consistent in the two figures. The mode groupings are indicative of a good plate. If we look at the number of modes between 6 and 10 MHz for graph one in Figure A.4 and graph two in Figure A.3, we can see that the number of modes has increased. This would suggest that the flaw is in the form of a delamination or smooth interface located further down the laminate for the scan on that particular side.
Single Point Data Collection

The single point results allow for the comparison of the experimental data to the theoretical results. As already shown in the previous sections, the incident angle of $\theta = 10^\circ$ provides good results for producing both the desired mode groupings and stop bands. Therefore, only data for an incident angle of 10 degrees will be presented. The experimental data for all cases is normalized using the methods described in the previous chapter. The distance between the intersecting beam axis on the plate, $x_i$, has been varied from 0 to 4.0. In viewing the up coming figures, we will see that there is very little change in the minima location with respect to the theoretical curves by varying $x_i$.

Figure 5.9 compares theoretical (top) and experimental (bottom) reflection curves for a 2/1 plate. The location of the minima shows good agreement between the two curves. In this case, the theoretical spectrum represents a 2/1 plate with no flaws present. The next three figures represent data collected from a 3/2 plate. In Figure 5.10, good agreement is found with respect to the location of the minima with respect to frequency. Additionally, the desired mode grouping and stop band correlates well to the theoretical curve. It is these two areas that should change significantly if there is to be a change in the bonding at the ply interfaces. The next Figure, 5.11, illustrates this point where the experimental reflection curve (bottom) is compared to the theoretical curves for a delamination after the fourth ply (top) and smooth interface after the fourth ply (middle). The experimental reflection spectrum has now changed in that there are only three minima in the mode clustering range between 6 and 8 MHz. This change in the mode cluster verifies the choice of the swept frequency method for determining the characteristics of an ARALL plate. The same plate and position were measured again, but from the other side of the
Figure 5.9: Comparison of theoretical (top) and experimental (bottom) reflection curves for a 2/1 plate. The data is offset by .5, $\theta = 10^\circ$, $\phi = 90^\circ$, $x_i=0.0$

plate. The experimental results are shown in the bottom curve of Figure 5.12. The theoretical curves represent a debond (top) and smooth interface (middle) after the first ply. Agreement can be found with the minima at 7 MHz, however, it is difficult to interpret the reason for the minima between 2 and 3 MHz. The inclusions of the Teflon tabs in the ARALL samples may account for the extra mode.

The next two figures involve the same experimental signal but compared to two different different theoretical curves. The first, Figure 5.13, illustrates the experimental data (bottom) being compared to the reflection coefficient (top). The deep minima in both the reflection curves show good agreement. However, the shallow minima within the deep minima at 3 MHz in the theoretical curve cannot
Figure 5.10: Comparison of theoretical (top) and experimental (bottom) reflection curves for a 3/2 plate. The data is offset by .5, \( \theta = 10^\circ \), \( \phi = 90^\circ \), \( x_i=3.0 \)

be found in the experimental data. The resolution of the experimental data cannot accurately define these fine changes. The same signal is now compared to the voltage calculations derived in previous experiments by Lobkis et al. [26]. Figure 5.14 shows good agreement between the theoretical voltage curve (top) and the experimental data (bottom). Moreover, the fine fluctuations in the deep minima at 3 MHz are not present in the theoretical voltage curve as compared to the reflection coefficient curve used in Figure 5.13. As a result, the experimental data closely resembles the experimental data in this area.

The 5/4 ARALL samples did not provide the same results with respect to the
mode groupings. Although the frequency range of the mode cluster is the same, the number of modes is different. As illustrated in Figure 5.15 only five minima are present between 6 and 8 MHz for the experimental curve (bottom). However, the theoretical (top) curve shows eight minima in the same location. It is possible that some of the plate modes are so close to one another that the received signal will not provide the resolution required to distinguish the two. Schull et al. [7] noted the same problem in their work. Increasing the incident angle in order to find well defined modes only increased the problem.
After reviewing the theoretical and experimental results, the variable parameters of the protocol have been narrowed. In this section, each step of the protocol will be detailed by subsection, beginning with the general setup.

**General Setup** As discussed earlier, care will have to be taken in finding delaminations deep within a composite plate due to the number of unit cells approaching that of the total composite. However, if a second receiver is positioned under the plate, the amplitude and maxima can be monitored. In the case of a delamination
approaching the size of the beam, the signal will drop significantly. This will add an extra dimension to the test procedure. The setup of the protocol will be similar to the one detailed in previous chapters. The one exception will be the addition of an extra receiver. An illustration of the changed setup is illustrated in Figure 5.16.

**Geometrical Setup** The orientation of the transducers will have to be positioned so that the received signal will vary as a result of changing conditions in the laminate. Additionally the received signals should lend themselves to be compared to the calculated results. The chosen incident and azimuthal angles of $\theta = 10^\circ$ and $\phi = 90^\circ$ provide distinct characteristics for the reflection spectrum that will change
Figure 5.14: Comparison of theoretical voltage curve (top) and experimental reflection curve (bottom) for a 4/3 plate. The data is offset by .5, $\theta = 10^\circ$, $\phi = 90^\circ$, $x_i = 4.0$

 accordingly with different conditions in the ply. They result in providing the user with mode groupings, that correspond to the number of unit cells in the laminate, and wide stop bands. Changes in the makeup of the composite with respect to the interfaces will change the mode groupings or stop bands.

**Signal Interpretation and Comparison** In order to evaluate the status of a plate, the reflected signal must be compared to a theoretical set of minima. A detailed list of the frequencies at which modes will exist in the ARALL plates is given in Appendix B with an example shown in Table 5.1. The theoretical frequencies listed are taken from the derived reflection coefficient minima. For these calculated
Figure 5.15: Comparison of theoretical reflection coefficient curve (top) and experimental reflection curve (bottom) for a 4/3 plate. The data is offset by \( \delta = 0.5 \), \( \theta = 10^\circ \), \( \phi = 90^\circ \), \( x_1 = 3.0 \)

minima, the thickness of the plies were set at .305 mm for the aluminum and .205 mm for the aramid-epoxy.

Changes in thickness of the aramid epoxy plies will cause the mode groupings at the higher frequencies to shift. An increased thickness of 5% will cause a decrease in the location of the minima of approximately .2-4 MHz. This will reverse if the thickness is decreased by 5%. The parentheses around selected frequencies indicates that the minima may not be acquired through the received voltage signal, either due to its close proximity with a minima greater in depth or its own shallow depth. This was previously discussed and illustrated in Figure 5.14. When comparing the
information in the tables to the normalized signal, three approaches can be taken by examining: 1) the mode groupings, 2) total number of modes, and 3) number of modes in the stop band.

In the case of the mode groupings, the information in the tables provides the number of modes for a given frequency range. The ranges provided start with the first minima and end with the last minima. However, this range should be expanded to include the possibility of a change in the ply thicknesses so that the resulting shift in the cluster can be taken into consideration. The number of minima in the mode groupings corresponds to the number of unit cells in the composite. Looking once again at Table 5.1, the number of modes in the grouping (NMIG) shows that there are four modes under the column that represents a good plate (GP). Under the other columns representing bonding flaws at one of the interfaces the NMIG drops to a different total. Using this information, the NMIG in the experimental reflected signal can be compared to the theoretical NMIG to determine if there is a
Table 5.1: Frequencies where plate modes are present for given smooth interfaces and delaminations in an ARALL 3/2 plate. \( \theta = 10^\circ, \phi = 90^\circ \), Frequency Range 2.0-8.0 MHz, Stop Band 2.9-5.6 MHz, Mode Grouping Range 5.6-7.3 MHz

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\(^a\)Good Plate  
\(^b\)Total Number of Modes  
\(^c\)Number of Modes in Grouping  
\(^d\)Number of Modes in Stop Band

delamination or smooth interface in the plate. This method on its own, however, will not provide the location of the flaw.

The total number of modes (TNM) in the entire designated frequency range (2.0 to 8.0 MHz) will change depending on the number of flaws. In the case of 3/2 plate a smooth interface between plies 2 and 3 will cause the TNM to drop from 5(6) modes down to 3. Once again, the location of the flaw will not be known since delaminations or smooth interfaces located at different locations within the laminate produce the same number of modes for the frequency range selected.

Finally, there is the information provided by modes present in the stop band.
However, this situation will only happen for selected depths of delamination or smooth interfaces. For the most part, these types of flaws do not theoretically produce modes in the stop band.

Using the combination of all three of the above mentioned approaches can lead to narrowing down the location of the interface flaw. However, for the laminates with layups of 3/2 to 5/4, this becomes very tedious and may not be necessary if the depth location of the debond or smooth interface is not required. Nevertheless, for the simple case of a 2/1 plate a scanning program has been developed, and the results will be shown later in this chapter.

Standards In order to validate the test procedure samples should be prepared to compare results derived analytically with those acquired through the inspection procedure. As the variations in the ply thickness can change the frequencies at which the plate modes will propagate, the average thickness of the plies should be implemented when deriving the comparison set for the voltage minima.

Plate Scan

With the knowledge gained from the line scans and point gathering procedures, the protocol can now be applied. By analyzing the theoretical curves, we can set out to make a guide line as to what should be expected with regard to the reflected voltage minima and implement these values as a comparison set for the scanning program. For the resulting image shown in Figure 5.17 the comparison set was derived using the data supplied in Table B.1. Several frequency spans in the received signal are monitored for indications that differ the minima structure to that of a good plate. Each delamination and smooth ply column is cross referenced for each spectrum produced by the received signal. By assigning a single value corresponding to the
status of the plate, a gray scale coded image of a scanned plate is produced. The same plate was scanned from the top and the bottom, explaining the mirror image of the two scans. The areas on the outside edges of the plate scale coded as unknown are a result of the tape used to protect the edges of the samples where the aramid-epoxy is exposed. The top image shows that the flaw in the plate is in the form of a delamination after the first ply. The second image of the same plate however, indicates that the flaw is unknown. This may be attributed to the insertion of the Teflon tab.
Figure 5.17: A scan of a 2/1 plate gray scale coded to correspond with known or unknown characteristics in the plate, $\theta = 10^\circ$, $\phi = 90^\circ$, $x_i = 0$
CHAPTER 6. CONCLUSIONS AND FURTHER WORK

The purpose of this thesis was to design a test procedure that is more encompassing than the standard practice through-transmission scan. By employing the use of a broad bandwidth "chirp" signal in combination with guided wave modes that include substantial shear wave energy, more information towards the characterization of the composite could be made. The results of the protocol are based on a comparison between the minima of a theoretical reflection curve and the minima of the normalized power spectrum acquired from the received signal. The theoretical reflection curves used for this test procedure were developed by Chimenti et al. [24].

The choice of the azimuthal angle of the incident beam with respect to the fiber orientation proved to be important in providing a reflection curve that can distinguish itself differently from a curve where a smooth interface or "kissing bond" is present in the laminate. The choice of the incident angle also played a significant role in providing a reflection curve that would change distinctly with different flaws at the interfaces of the plies used in the composite.

The programming of the arbitrary function generator proved to be a frustrating experience due to its decrease in amplitude while under load. A compensation factor had to be derived by measuring the amplitude of the output of the generator while under transducer load over the frequency range selected. The compensation factor was then reintroduced into the designed chirp signal.

The experimental procedure in this paper provided good results with the three,
five, and seven ply ARALL plates, but the same could not be found with the nine ply laminate. Although the frequency range of the mode clustering agreed with the theoretical data, the number of modes did not. This may be attributed to the frequencies of the plate modes being in close proximity to one another. A way to improve this protocol would be to employ the method of calculating the theoretical voltage signal rather than relying on the reflection coefficient minima. Although the reflection coefficient curves did provide good agreement in the tests performed on laminates with fewer plies, it could not be relied upon to do so with the nine layer laminate. Since the reflection coefficient is based on plane waves, not the real structure of a beam generated by an ultrasonic transducer, the voltage calculations based on the work of Lobkis et al. [26] may provide a better reference to compare with the test data.

A second area to be explored entails using lower frequencies. The theoretical reflection curves exhibited considerable changes at the lower frequency ranges with respect to the changing characteristics of the composite plate.

Finally, the use of a third transducer as a receiver below the plate was not explored. With a transducer situated below the plate, the results from the reflected signal can be compared to the transmission signal and serve as a verification device to ensure that a flaw has not been overlooked.
APPENDIX A. LINE SCANS

The following figures provide a visual image of line scans performed on various ARALL plates. The line scans are 50 mm in length with the scan direction shown at the left side of the gray scale image. The gray scale on the frequency axis indicates the voltage values for a given frequency. The vertical light colored lines indicate a drop in the voltage.
Figure A.1: Line scan of a 2/1 plate, $\theta = 10^\circ$, $\phi = 90^\circ$. The bottom line graph displays minima corresponding to a good plate. The top line graph varies significantly, indicating a change in the composite’s properties.
Figure A.2: Line scan of a 2/1 plate, $\theta = 20^\circ$, $\phi = 90^\circ$. The bottom line graph displays minima corresponding to a good plate. The top line graph varies significantly, indicating a change in the composite's properties.
Figure A.3: Line scan of a 3/2 plate, \( \theta = 20^\circ \), \( \phi = 90^\circ \). The top line graph displays minima corresponding to a good plate. The bottom line graph varies significantly, indicating a change in the composite’s properties.
Figure A.4: Line scan of a 3/2 plate, $\theta = 20^\circ$, $\phi = 90^\circ$. The bottom line graph displays minima corresponding to a good plate. The top line graph varies significantly, indicating a change in the composite’s properties.
APPENDIX B. ARALL PLATE WAVE FREQUENCY DATA

The following tables list the frequencies when minima in the reflected signal are anticipated due to plate modes in the test specimen. The incident and azimuthal angles are set at $\theta = 10^\circ$ and $\phi = 90^\circ$ respectively. For these calculated minima, the thickness of the plies were set at .305 mm for the aluminum and .205 mm for the aramid-epoxy. Changes in thickness of the aramid epoxy plies will cause the mode groupings at the higher frequencies to shift. An increased thickness of 5% will cause a decrease in the location of the minima of approximately .2-.4 MHz. This will reverse if the thickness will decrease by 5%. The parentheses around selected frequencies indicates that the minima may not be acquired through the received voltage signal either due to its close proximity to a minima greater in depth, or its shallow depth.
Table B.1: Frequencies where plate modes are present for given smooth interfaces and delaminations in an ARALL 2/1 plate. $\theta = 10^\circ, \phi = 90^\circ$, Frequency Range 2.0-8.0 MHz, Stop Band 2.8-5.9 MHz, Mode Grouping Range 5.9-7.2

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$^a$Good Plate  
$^b$Total Number of Modes  
$^c$Number of Modes in Grouping  
$^d$Number of Modes in Stop Band
Table B.2: Frequencies where plate modes are present for given smooth interfaces and delaminations in an ARALL 3/2 plate. $\theta = 10^\circ, \phi = 90^\circ$, Frequency Range 2.0-8.0 MHz, Stop Band 2.9-5.6 MHz, Mode Grouping Range 5.6-7.3

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*a Good Plate  
*b Total Number of Modes  
*c Number of Modes in Grouping  
*d Number of Modes in Stop Band
Table B.3: Frequencies where plate modes are present for given smooth interfaces in an ARALL 4/3 plate. $\theta = 10^\circ, \phi = 90^\circ$, Frequency Range 2.0-8.0 MHz, Stop Band 2.8-5.5 MHz, Mode Grouping Range 5.5-7.4

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\(^a\)Good Plate
\(^b\)Total Number of Modes
\(^c\)Number of Modes in Grouping
\(^d\)Number of Modes in Stop Band
Table B.4: Frequencies where plate modes are present for given delaminations in an ARALL 4/3 plate. $\theta = 10^\circ, \phi = 90^\circ$, Frequency Range 2.0-8.0 MHz, Stop Band 2.8-5.5 MHz, Mode Grouping Range 5.5-7.4

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<tr>
<td>NMISB(^d)</td>
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</table>

\(^a\)Good Plate  
\(^b\)Total Number of Modes  
\(^c\)Number of Modes in Grouping  
\(^d\)Number of Modes in Stop Band
Table B.5: Frequencies where plate modes are present for given smooth interfaces in an ARALL 5/4 plate. $\theta = 10^\circ, \phi = 90^\circ$, Frequency Range 2.0-8.0 MHz, Stop Band 3.0-5.4 MHz, Mode Grouping Range 5.4-7.5

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<td>6.1</td>
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</table>

| TNMb             | 911 | 23 | 56 | 5 | 46 | 67 | 67 | 79 | 6 |
| NIG              | 8  | 23 | 1 | 4 | 3 | 5 | 5 | 6 | 6 |
| NMISBd           | 0  | 0 | 1 | 0 | (2) | 0 | 0 | 0 | 0 |

*Good Plate
bTotal Number of Modes
aNumber of Modes in Grouping
*Number of Modes in Stop Band
Table B.6: Frequencies where plate modes are present for given delaminations in an ARALL 5/4 plate. $\theta = 10^\circ$, $\phi = 90^\circ$, Frequency Range 2.0-8.0 MHz, Stop Band 3.0-5.4 MHz, Mode Grouping Range 5.4-7.5

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</tr>
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<sup>a</sup>Good Plate  
<sup>b</sup>Total Number of Modes  
<sup>c</sup>Number of Modes in Grouping  
<sup>d</sup>Number of Modes in Stop Band
REFERENCES


[40] B.A. Auld, "General electromechanical reciprocity relations applied to the calculation of elastic wave scattering coefficients," *Wave Motion* 1, 3-10 (1979).