Investigation of Methods to Detect Defects in Thin Layered Materials

Ajaykumar S. Chinthalapudi
Husam M. Hassan

Department of Mechanical Engineering
Blekinge Institute of Technology
Karlskrona, Sweden
2005

Investigation of Methods to Detect Defects in Thin Layered Materials

AJAYKUMAR S CHINTHALAPUDI
HUSAM M. HASSAN

Department of Mechanical Engineering
Blekinge Institute of Technology
Karlskrona, Sweden
2005

Thesis submitted for completion of Master of Science in Mechanical Engineering with emphasis on Structural Mechanics at the Department of Mechanical Engineering, Blekinge Institute of Technology, Karlskrona, Sweden.

Abstract:
Cost effective and reliable damage detection is critical for the utilization of thin layered materials and microstructures. This Thesis presents a brief overview of conventional NDT methods and the usage of unconventional NDT methods applicable to thin layered materials, and the conclusion of applicability of these methods for damage detection in thin layered materials.

Keywords:
Thin layered materials, NDT, Vibration based NDT, Air coupled ultrasonic, Acoustic microscopy, Ultrasonic spectroscopy, Shearography, and Thermography.
Acknowledgements

This work was carried out at the Department of Mechanical Engineering, Blekinge Institute of Technology, Karlskrona, Sweden, under the supervision of Associate Prof. Claes Hedberg and M.Sc. Etienne Mfoumou. We wish to express our sincere appreciation to Associate Prof. Claes Hedberg and M.Sc. Etienne Mfoumou, for their understanding, guidance and encouragement that made our graduate experience memorable one. They have provided us with all sorts of assistance, showing their dedication to our academic and professional growth.

Karlskrona, April 2005

Ajaykumar

Husam
Contents

1 Notation 5
2 Introduction 8

3 Literature review of NDT methods 10
   3.1 Types of damages in composites 10
   3.2 Visual and optical testing 11
      3.2.1 Direct visual testing 11
      3.2.2 Remote visual testing 11
   3.3 Liquid penetrant testing 12
   3.4 Magnetic particle inspection 13
   3.5 Electro magnetic or Eddy current testing 14
   3.6 Radiography 15
   3.7 Ultrasonic testing 16
      3.7.1 Resonance Technique 16
      3.7.2 Pulse Technique 17
      3.7.3 General non-destructive testing using Rayleigh and Lamb waves 19
      3.7.4 Localized non-destructive testing using Rayleigh and Lamb wave 20
      3.7.5 Long range non destructive testing using Lamb wave 20
   3.8 Summary review of conventional NDT methods 21

4 Unconventional NDT methods 22
   4.1 Material characterization by air-coupled Ultrasound 22
      4.1.1 Presentation 22
      4.1.2 Focus slanted transmission mode 23
      4.1.3 Defect imaging using FSTM 24
      4.1.4 Applicability to thin flexible materials 29
   4.2 Shearography 29
      4.2.1 Presentation 29
      4.2.2 Applications 30
   4.3 Thermography 31
      4.3.1 Presentation 31
      4.3.2 Applications 31
      4.3.3 Pulsed thermography 32
      4.3.4 Vibrothermography 33
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3.5 Lock-in thermography</td>
<td>33</td>
</tr>
<tr>
<td>4.3.6 Applicability to material of interest</td>
<td>34</td>
</tr>
<tr>
<td>4.4 Ultrasonic spectroscopy</td>
<td>34</td>
</tr>
<tr>
<td>4.4.1 Presentation</td>
<td>34</td>
</tr>
<tr>
<td>4.4.2 Linear Angle Beam Ultrasonic Spectroscopy</td>
<td>35</td>
</tr>
<tr>
<td>4.4.3 Nonlinear Angle Beam Ultrasonic Spectroscopy</td>
<td>35</td>
</tr>
<tr>
<td>4.5 Acoustic microscopy</td>
<td>40</td>
</tr>
<tr>
<td>4.5.1 Presentation</td>
<td>40</td>
</tr>
<tr>
<td>4.5.2 Application</td>
<td>40</td>
</tr>
<tr>
<td>4.5.3 Scanning acoustic microscopy</td>
<td>40</td>
</tr>
<tr>
<td>4.5.4 Photo Acoustic Spectroscopy</td>
<td>42</td>
</tr>
<tr>
<td>4.5.5 Guided wave techniques</td>
<td>43</td>
</tr>
<tr>
<td>4.5.6 Bulk wave Techniques</td>
<td>43</td>
</tr>
<tr>
<td>4.5.7 Guided Acoustic Waves in Layered Films</td>
<td>44</td>
</tr>
<tr>
<td>4.6 Vibration based methods</td>
<td>45</td>
</tr>
<tr>
<td>4.6.1 Model-based vibration methods</td>
<td>46</td>
</tr>
<tr>
<td>4.6.2 Model independent vibration methods</td>
<td>47</td>
</tr>
<tr>
<td>4.6.3 Base line strain energy mode shapes method</td>
<td>47</td>
</tr>
<tr>
<td>4.6.4 Non-base line strain energy mode shapes method</td>
<td>50</td>
</tr>
<tr>
<td>4.7 Sound transmission methods</td>
<td>52</td>
</tr>
<tr>
<td>4.7.1 Presentation</td>
<td>52</td>
</tr>
<tr>
<td>4.7.2 Transmission loss</td>
<td>53</td>
</tr>
<tr>
<td>4.7.3 Energy loss by air-coupled ultrasound</td>
<td>53</td>
</tr>
<tr>
<td>4.8 Summary review of various unconventional NDT methods</td>
<td>55</td>
</tr>
<tr>
<td>5 Conclusions</td>
<td>56</td>
</tr>
<tr>
<td>6 References</td>
<td>57</td>
</tr>
</tbody>
</table>
1 Notation

$h$ Thickness
$C$ Wave velocity
$f$ Resonance frequency
$Z$ Impedance
$\rho$ Density
$\theta$ Angle of incidence wave
$\lambda$ Wave length
$v$ Velocity of the Lamb wave
$\alpha$ Thermal Diffusivity
$t$ Time
$E$ Elastic stiffness
$D$ Flexural rigidity
$\sigma$ Average residual stress
$U$ Strain energy
$EI$ Flexural stiffness
$\phi$ Displacement mode shape
$U$ Strain energy
$\omega$ Angular frequency
$\nabla$ Laplace operator
$T$ Tension force per unit length
$\mu$ Mass per unit area
<table>
<thead>
<tr>
<th>Indices</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>Integer number</td>
</tr>
<tr>
<td>R</td>
<td>Raleigh wave</td>
</tr>
<tr>
<td>L</td>
<td>Lamb wave</td>
</tr>
<tr>
<td>0</td>
<td>Zero order</td>
</tr>
</tbody>
</table>
**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDT</td>
<td>Non Destructive Testing</td>
</tr>
<tr>
<td>NDE</td>
<td>Non Destructive Evaluation</td>
</tr>
<tr>
<td>NAM</td>
<td>Non-linear Amplitude Modulation</td>
</tr>
<tr>
<td>VT</td>
<td>Visual Testing</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
<tr>
<td>MPI</td>
<td>Magnetic Particle Inspection</td>
</tr>
<tr>
<td>NTM</td>
<td>Normal Transmission Mode</td>
</tr>
<tr>
<td>STM</td>
<td>Slanted Transmission Mode</td>
</tr>
<tr>
<td>FSTM</td>
<td>Focus Slanted Transmission Mode</td>
</tr>
<tr>
<td>LDPE</td>
<td>Low Density Poly Ethylene</td>
</tr>
<tr>
<td>Al-foil</td>
<td>Aluminium Foil</td>
</tr>
<tr>
<td>CT</td>
<td>Computerized Tomography</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon-Fiber Reinforced Plastics</td>
</tr>
<tr>
<td>AI</td>
<td>Acoustic Impedance</td>
</tr>
<tr>
<td>SAM</td>
<td>Scanning Acoustic Microscopy</td>
</tr>
<tr>
<td>PAS</td>
<td>Photo Acoustic Spectroscopy</td>
</tr>
<tr>
<td>PAM</td>
<td>Photo Acoustic Microscopy</td>
</tr>
<tr>
<td>BAM</td>
<td>Bulk Acoustic Wave</td>
</tr>
<tr>
<td>SEMS</td>
<td>Strain Energy Mode Shapes</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>WVU</td>
<td>Western Virginia University</td>
</tr>
<tr>
<td>DSEMS</td>
<td>Difference Strain Energy Mode Shape</td>
</tr>
<tr>
<td>LT</td>
<td>Lockin Thermography</td>
</tr>
<tr>
<td>PE</td>
<td>Poly Ethylene</td>
</tr>
<tr>
<td>Adh</td>
<td>Adhesive</td>
</tr>
</tbody>
</table>
2 Introduction

Thin layered laminates are used in a wide range of industrial applications. However, their use in safety relevant areas such as food packaging requires techniques of non destructive testing for condition monitoring of the material. Meanwhile, damage detection and characterization using non-contact experimental techniques with the aim of obtaining more sensitive techniques are continuously growing, but only few of them satisfy the requirement to be non-contact and non-invasive to food packaging material for example, made of carton, aluminium foil and plastics.

During production, the material goes through different processes such as painting, coating, creasing, laminating, perforation etc. To become complete, the material also needs to be formed, folded, filled, etc. Before reaching to the consumer, the packages have to tolerate loading during transport and distribution. The result is often small defects in form of cracks, delamination, or local weakness. If these defects are enhanced or grow into certain size, the function of the layers become insufficient which may bring the food product in contact with external environment, disqualifying the product as human food. At an earlier stage, it is therefore necessary to investigate such defect detection in laboratory samples.

Damage detection can increase safety, extend serviceability, and extend the operating limits of structures or materials. In the case of composite structures, typical damage may include surface cracks, interfacial cracks, delamination, propagating fatigue cracks, distributed fatigue and others.

Among these, embedded damage such as delamination, local weakness and distributed fatigue are the most difficult to detect using conventional methods.

Several investigations have been reported using vibration-based methods for damage detection. These approaches are more globally sensitive to damage than localized methods mostly on thin layered flexible materials, still not yet widely investigated in the field of NDT.

Most of conventional non-destructive inspection methods are local methods. Meanwhile, because damage signals are always contained in dynamic responses of structures, many of the current structural health monitoring studies concentrate on developing dynamic-based global inspection methods. Although some methods have been shown the ability to detect the existence of small but critical damage, none is really able to locate small damage. The two major problems in dynamic-based global
inspection methods are (1) how to obtain dense and accurate experimental data, and (2) how to extract clear damage signals from the measured data.

Several works have been done in the field of NDT related to vibration-based damage detection. A considerable amount of work is presented on modal properties as indexes of damage; many of them can be found in [1-5]. A more recent work in [6] has expanded the flexibility and application area of Nonlinear Amplitude Modulation (NAM) technique by combining the benefits of noncontact ultrasound excitation (remote locating and imaging of defects) with sensitivity of nonlinear methods in a new air-coupled NAM-version.

In the frame of this thesis work, a brief overview of these existing methods is first done and their applicability to sheet-like materials investigated with focus on layered materials made of aluminium, polymer and cardboard.

This thesis is divided into 5 chapters.

• Chapter 2 Includes introduction and thesis outline.
• Chapter 3 Includes a literature review of conventional Non-destructive testing (NDT) methods used to detect damages.
• Chapter 4 Includes a detailed description of unconventional methods
• Chapter 5 Conclusion
3 Literature review of NDT methods

3.1 Types of damages in composites

Defects and damages in laminated composites reduce the strength, stiffness and also the safe working life in composite structures. Defects may be introduced during manufacturing, in service or in design due to discontinuities during manufacturing, in service or in design due to discontinuities such as cut outs and ply drops.

The defects commonly introduced to composite materials during manufacturing, processing and service operation are.

![Figure 3.1 Typical defects in bonded joints.](image)

Inclusions are the most common bulk defect arises from foreign particles being included in the prime material. These second-phase particles, called inclusions, are seldom wanted because they significantly alter the structural properties.

Voids occur during the heat cycle, the volatiles (including water vapour) in the matrix become gaseous and either remains as a fine dispersion of bubbles to form porosity or join together to form larger voids.

Cracks are the one of the common form of damage occurred in materials due to transverse loading in the cross ply-laminates and is often a precursor to overall failure.

De-lamination is a form of failure which occurs on plane between adjacent layers within a laminate. The plane between two laminae is often a weak layer due to air entrapment during stacking and to excess resin.

Local weakness is caused due to rubbing of the surfaces.
3.2 Visual and optical testing

Visual inspection (VT) is the most common and simplest non-destructive testing method. The test involves a close visual inspection of components surface, the surface may be illuminated or the inspector may use a magnifying glass, mirror or other optical aid in order to gain accurate results. Visual inspection method can be classified, into two types as shown in Figure 3.2.

3.2.1 Direct visual testing

This form of visual testing is defined as a method where mirrors, telescopes or cameras are utilized. Direct examination is conducted if the observer can obtain access to be within 25 inch of the object, and at an angle of no less than 30° to the surface.

3.2.2 Remote visual testing

Remote visual testing can be divided into three categories: borescopes, fiberscopes, and video technology. These tools allow for inspection of surfaces that are not directly accessible to the human eye. Use of flexible glass fibers permits the viewer to inspect images in great detail without causing much interference to the object. The incorporation of digital video cameras through use of solid-state imaging sensors, some of which are known as charge-coupled devices (CCD), allow for the display of images on a monitor.

Figure 3.2 Direct and Remote visual inspection techniques [7].

But for composites the main failure criteria which are of interest, such as micro crack, de-lamination etc cannot be visualized by this technique.
One of the main advantages of visual inspection is the real-time acquisition of data and its instantaneous interpretation. Given the extremely low equipment cost, this inspection technique should be regarded as an indispensable precondition for all further investigations.

Drawbacks of VT are the high susceptibility to human misperception and the requirement for establishing of a baseline for defects in general, especially under varying conditions (i.e. time of day when inspection is performed, lighting conditions, inspector’s past experience, etc.). Moreover, it is limited only to the object surface; subsurface conditions of opaque materials cannot be revealed. This beside the access to and illumination of the object or area of interest is a major restriction of this technique [7].

### 3.3 Liquid penetrant testing

Liquid penetrant testing is a non-destructive method used to detect surface breaking defects in any nonporous material. The surface of the part under evaluation is coated with a penetrant in which a visible or fluorescent dye is dissolved. The penetrant is pulled into surface defects by capillary action. After some time insuring that the dye has penetrated into the narrowest cracks, the excess penetrant is cleaned from the surface of the sample. A white powder, called developer, is then sprayed or dusted over the part. The developer lifts the penetrant out of the defect, and the dye stains the developer. Then by visual inspection under white or ultraviolet light, the visible or fluorescent dye indications are located, thereby defining the defect.

**Advantages**

1) The method has high sensitivity to small surface discontinuities.
2) The method has few material limitations, i.e. metallic and non-metallic, magnetic and nonmagnetic, and conductive and nonconductive materials may be inspected.
3) Large areas and large volumes of parts/materials can be inspected rapidly and at low cost.

**Disadvantages**

1) Only surface breaking defects can be detected. (Figure 3.3)
2) Only materials with a relative nonporous surface can be inspected.
3) Precleaning is critical as contaminants can mask defects.
4) Surface finish and roughness can affect inspection sensitivity.

Figure 3.3 Liquid penetrant inspection [7].

3.4 Magnetic particle inspection

Magnetic particle inspection is a non-destructive testing method used for defect detection. MPI is a fast and relatively easy to apply and part surface preparation is not critical. MPI uses magnetic fields and small magnetic particles, such as iron fillings to detect flaws in components as shown in Figure 3.4 The only requirement from inspectability point of view is that the component to be inspected should be ferromagnetic material such as iron, nickel, cobalt or some of their alloys. Ferromagnetic materials are materials that can be magnetized to a level that will allow the inspection to be effective. MPI is particularly sensitive to surface breaking or near surface cracks even if the crack opening is narrow.

Figure 3.4 Magnetic particle inspection [7].
Advantages

1) Simple and easy to conduct.
2) Will detect surface and near surface flaws.
3) Can detect flaws filled with contaminants.
   e.g. oxide or non-metallic inclusions.
4) Sensitivity of testing can be specified and checked.

Disadvantages

1) Can only be applied to ferromagnetic material.
2) Will not detect deep internal flows.
3) High currents applied to component may cause damage.
4) Components usually have to be demagnetized.

3.5 Electro magnetic or Eddy current testing

Electric currents are generated in conductive material by an induced alternating magnetic field. The electric currents are called eddy currents, because they flow in circles and just below the surface of the material, interruptions in the flow of eddy current caused by imperfections, dimensional changes, or changes in the material conducive and permeability properties, can be detected with the proper equipment. Its application ranges from crack detection, to the rapid sorting of small components for flaws size variations or material variation.

In an eddy current inspection when an energized coil is brought near the surface of a metal component, eddy current are introduced into the specimen. These currents set up a magnetic field that tends to oppose the original magnetic field. The impedance of the coil is close approximation to the specimen is effected by the presence of eddy currents in the specimen are distorted by the presence of the flaws or material. Variation the impedance coil is altered. This change is measured and displayed in a manner that indicates the type of flaws or material condition

Note: that cracks must interrupt the surface eddy current flow to be detected. Cracks lying parallel to the current path will not cause any significant interruptions and may not be detected.
Advantages

1) Crack detection.
2) Material thickness measurements.
3) Coating thickness measurements.
4) Conductivity measurements for
   - material identification
   - heat damage detection
   - Case depth detection.
   - Heat treatment monitoring.

Disadvantages

1) Only conductive materials can be inspected.
2) Surface must be accessible to the probe
3) Skill and training is required than other techniques.
4) Flaws such as delaminations that lie parallel to the probe coil winding and probe scan direction are undetectable.

3.6 Radiography

In general radiography involves the use of penetrating gamma or x-radiation to examine parts and products for imperfections. The radiographic testing is higher energy (shorter wavelength) version of the electromagnetic waves that we see as visible light. A receiving end records the image in the form of radiographs to detect the features and internal structure of the specimen that exhibit a difference in thickness or physical density as compared to the surrounding material. This image is a result of difference in attenuation rates, or absorption, for various types of matter. Radiographic attenuation might be affected by dissimilarities in material properties, which causes some difficulties in the interpretation of radiographs. The other applications of radiography in non-destructive testing are radioscopy (real time radiography), computerized tomography (CT), micro focus radiography, and flash radiography.

Radioscopy produces the image of the specimen on the screen rather than on the film, so that very little time lag occurs between the specimen being exposed to radiation and the resulting image. In this technique the image is produced on the screen when the radiation passing through the specimen interacts with the fluorescent screen. In this technique the resolution of the images are not as good as those for images produced on film.
Advantages

1) Extreme accuracy and sensitivity.
2) Any geometric configuration can be inspected.

Disadvantages

1) High cost.
2) Safety and energy supply.

3.7 Ultrasonic testing

Standard ultrasonics in the range of 0.2-30 MHz use bulk stress waves constituting substantial area of NDT. These waves may be excited in the majority of material used in industrial applications, and system using stress waves are flexible, versatile, cheap and safe. The resulting data may be interpreted in the time or frequency domain and can be stored and processed to operate sorting gates or to give alarms. Standard ultrasonic testing may be separated into two major areas:

1) Resonance techniques in which the excitation is narrow band.
2) Pulse technique.

3.7.1 Resonance Technique

These techniques are principally employed to measure the thickness of the materials and the depth of the delaminated layers. Physically this is achieved by locating the resonant frequencies of the component under investigation, the material thickness being obtained from the relation.

\[ 2.\text{h} = \frac{C}{2.(f_{n+1} - f_n)} \quad n = 1, 2, 3, \ldots n \text{ max} \quad (3.1) \]

Where \( f_n \) is the resonant frequency, \( C \) is the wave velocity, \( 2.\text{h} \) is the material thickness and \( n \) is an integer. Since the wave velocity is material dependent, instrument that using this method must be recalibrated for
different materials, provided that damping or (apparent damping due acoustic transmission) is well defined.

### 3.7.2 Pulse Technique

These methods in which ultrasonic pulses are propagated through the area of interest are used for more extensively in industry. When ultrasonic pulses interact with defect, for example air filed cracks there will be almost total reflection. This enables the relative amplitudes and time of flight of ultrasonic pulses to be use as a measure of integrity of the material under test. The advantage of pulse methods is that the system under test may be decoupled easily from the measuring system. Firestone and Ling probably are the first to recognize the advantage of pulsed methods in NDT applications.

The pulse echo mode, see Figure 3.5.a requires access to only one side of the test piece and a single transducer acts as transmitter and receiver. In pitch-catch mode see Figure 3.5.b two transducers, one acting as transmitter and one acting as receiver are located in the same side of the test piece.

Because of the large impedance mismatch between air and solid materials it is difficult to propagate waves from a transducer through air into the structure. Therefore, a coupling media between the two is generally employed. The normal impedance $Z$, is the ratio of the acoustic pressure to the projection of the particle velocity on the normal of the surface and is given by

$$Z = \frac{\rho.C}{\cos \Theta} \quad (3.2)$$

Where $\rho$ is the density, $\Theta$ is angle of the wave front normal to the surface.

In solid coupling, the transducer is bonded or fixed to the test piece. In dry contact coupling a flexible membrane which is generally filled with oil and will deform to the shape of the test piece surface is attached to the transducer. In thin film coupling a gel is applied to small area where the transducer is to be positioned, and in immersion coupling the whole test piece is immersed in a liquid (generally water). Thin film and immersion coupling are the most popular methods.
The frequency and the wave length of ultrasound are related by

\[ \lambda = \frac{C}{f} \] (3.3)

Where, \( \lambda \) is the wave-length. Hence if the wave velocity is constant the wave length will become smaller with increasing frequency. It is shown that the detectable defect size is related to the wave length the higher the frequency the smaller the detectable defect. However, in real materials the wave amplitudes decrease or attenuate during propagation. Attenuation is a function of frequency; therefore as the frequency of the wave is increased its penetrating power (propagation distance) will be reduced.

The sensitivity of the ultrasonic methods is dependant on the properties of the transducers used. Transducers have near and far fields; in the near fields it is difficult to determine the presence of defects as the amplitude of the reflected wave is affected by the diffraction pattern. Delay lines coupling may be used to alleviate this problem. Focused transducer also may be used to reduce the extend of the near field and increase the intensity of the ultrasound at particular point, there by increasing sensitivity.

Resolution is the ability to distinguish between defects located very close to one another. Resolution and sensitivity are also function of the properties of the test piece.

*Figure 3.5 a Pulse echo mode [8].*
3.7.3 General non-destructive testing using Rayleigh and Lamb waves

Rayleigh and Lamb waves are propagating two dimensional vibrational modes (sometimes called guide waves). The Rayleigh wave exists in the boundary of a free half space and Lamb waves may propagate in free plates. In practice half space do not exist but if the plate thickness is greater $5\lambda_R$, where $\lambda_R$ is the Rayleigh wave length. That the zero order Lamb modes $a_0$ and $S_0$ will combine to form a quasi-Rayleigh wave and hence forth will be referred to as Rayleigh wave.

In the last few decades, Lamb and other guided waves have been used increasingly in ultrasonic NDT applications where standard ultrasonic techniques using bulk wave can not be applied; for example to detect small cracks located near an interface or narrow cracks that run normal to an interface or free surface. As Rayleigh and Lamb wave are two dimensional they may propagate over considerable distances therefore they used long range testing applications. However, more than one mode is usually excited by real transducers and in the case of Lamb wave signals are generally very complicated. Rayleigh and Lamb waves are usually excited using thin film or immersion coupling;

Rayleigh wave inspection is used predominantly to find small defects located near to or at boundary, as the Rayleigh wavelength is always smaller than that of any propagating mode and most of its energy is concentrated close to the surface.
Recently many workers have recognized that there are two distinct applications area of Rayleigh and Lamb waves:

1) Localized short range applications where sensitivity is important.
2) Long range applications where speed is important.

### 3.7.4 Localized non-destructive testing using Rayleigh and Lamb wave

When testing very thin plates or looking for defects very close to the interface the resolution between two echoes, which is inversely proportional to the pulse length is critical because of the finite duration of the pulses from real probes. This is a major importance in industrial NDT where many defects are found near surface or at material interface as in our material.

In localized detailed nondestructive testing application the detectability of particular defect may be optimized when using Lamb wave by choosing the most appropriate mode at the most suitable frequency-thickness product and not necessary by using higher frequencies as in standard ultrasonic NDT using bulk waves.

The major advantage of using Lamb waves in localized detailed NDT applications is that they produce stresses throughout the material thickness (although there may be stress nodes which have to be carefully considered). Therefore the entire thickness of the plate is interrogated. This point of major important as it means that it is possible to detect defects located very near interface, or at other internal location.

### 3.7.5 Long range non destructive testing using Lamb wave

Standard ultrasonic using bulk waves for the non destructive testing for large plates or plate-like structures interrogate discrete points. In order to completely test a structure reliably requires many points’ readings. The use of Lamb wave is very attractive solution to this problem since they can be excited at one point on the structure and propagate over considerable distance; the received signals contain information about the integrity of the line between the transmitting transducer and the receiving transducer.
## 3.8 Summary review of conventional NDT methods

**Table 3.1 Various NDT methods used to detect the defects in composites.**

<table>
<thead>
<tr>
<th>DEFECT TYPE</th>
<th>X-RAY TOMOGRAPHY</th>
<th>ULTRASONICS</th>
<th>EDDY CURRENT</th>
<th>ACOUSTIC EMISSION</th>
<th>VISUAL INSPECTION</th>
<th>DYE PENETRATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void/Porosity</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Only surface porosity</td>
</tr>
<tr>
<td>Debonds</td>
<td>Yes</td>
<td>Some</td>
<td>No</td>
<td>Some</td>
<td>No</td>
<td>Only surface debonding</td>
</tr>
<tr>
<td>Delamination</td>
<td>Yes</td>
<td>Some</td>
<td>No</td>
<td>Some</td>
<td>Only edge delamination</td>
<td>Only edge delamination</td>
</tr>
<tr>
<td>Broken fibers</td>
<td>Yes</td>
<td>Some</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Micro cracks</td>
<td>Yes</td>
<td>Yes</td>
<td>Some</td>
<td>Some</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Matrix cracking</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Only surface matrix cracking</td>
<td>Only surface matrix cracking</td>
</tr>
</tbody>
</table>
4 Unconventional NDT methods

Over the past few years, new trends have been developed within acoustic microscopy, ultrasonic spectroscopy as well as vibration analysis. Below are presented few of them.

4.1 Material characterization by air-coupled Ultrasound

4.1.1 Presentation

The air-coupled ultrasound transmission technique is a challenging methodology for non-contact acoustic inspection. It was shown to be a successful alternative to conventional immersion and dry-contact methods [8]. Generally, it utilises an ultrasound beam incident and transmitted normally to the sample surface (normal transmission mode (NTM)). For this case, only longitudinal acoustic waves are excited in the sample and can provide information on internal defects. Furthermore, the acoustic energy transmitted in air for the NTM is usually extremely small due to a severe impedance mismatch on the boundaries of the sample.

One way to increase the output is to use an oblique incidence of the acoustic wave at an angle of “total” transmission [9] (maximum transmission) corresponding to the “coincidence rule” [10]: the phase velocity of the incident wave along the sample surface coincides with the phase velocity of Lamb modes in the plate-like sample. Besides a drastic increase of the transmitted wave amplitude, one can also easily determine the Lamb mode phase velocity by measuring the angles of maximum transmission [9]. However, the technique is critically dependent on two factors:

a) Precise measurements of the angles of incidence and, therefore, need for a thorough angular positioning of the transducers;

b) A requirement of an incident plane wave that inevitably stipulates for the use of wide-aperture transducers.

The latter deteriorates the spatial resolution and prevents the development of the scanning slanted transmission mode STM-versions for air-coupled NDE systems.
The plate modes obtained from oblique incidence is also source of a significant increase in acoustic scattering by defects inside the sample, especially, by cracks, delaminations and disbonds. Both single- and opposite-sided schemes for non-contact Lamb wave generation and detection are studied in literature [13]. In most of the cases, the incident plane-wave approach is followed based on the use of large-aperture electrostatic transducers[12]. Similar to the above, in this case the information on the elastic properties of the materials can be extracted only by precise angular measurements. The presence of defects is manifested in additional reflection, attenuation or scattering of propagating plane wave modes.

4.1.2 Focus slanted transmission mode

The problem of plane acoustic wave transmission through a solid plate separating two elastic media has been considered previously [9]. If the wave impedance for the surrounding medium is much less than that of the sample, the transmission coefficient was shown to display a singularity, i.e. total transmission is expected at an optimum angle of incidence ($\theta_0$) corresponding to a phase matching between the incident wave and the Lamb mode in the sample:

$$\frac{v_{air}}{\sin \theta_0} = v_L^n$$

(4.1)

Where $v_L^n$ is the phase velocity of the $n$-order Lamb-mode.

Physically, the “coincidence rule” (4.1) means that the sound transmission is achieved when the incident wave on the front surface excites a plate mode, which re-radiates acoustic energy from the rear side of the sample. Such a model, obviously, assumes a good acoustic coupling between the sample surfaces which occurs for reasonably thin plates and, therefore, for the modes with low numbers of $n$.

In an experimental investigation as shown in Figure.4.1, piezoelectric 1-3 composite material transducers were used to radiate and receive a focused ultrasound beam (fundamental frequency 450 kHz, diameter of the transducers 18 mm, full angular transducer aperture $\equiv 20^\circ$, focus distance $\equiv 40$ mm, and focus neck $\equiv 2$ mm) [11]. A 15-cycle burst of $\approx 1400$ V amplitude was applied to the transducer to generate the acoustic wave; the two-step amplification of the receiver provided $\equiv 140$ dB total dynamic range of the PC-operated system. After 8 bit-A/D-conversion at 12.5 MHz
sampling frequency the transmitted pulse can be observed and measured at the PC-display. A scan of the angle of incidence (θ) was implemented by a sample rotation using a line-scan of the PC-operated scanning table. Such an angular B-scan shown in Figure.4.2 for an A4-paper sheet, demonstrates about 20 dB rise of the transmitted wave amplitude under the “resonance” phase matching conditions that allowed for measurements of θ₀ at an accuracy of ± 0.5° and keeping an error of the velocity calculations from (4.1) below 1%.

4.1.3 Defect imaging using FSTM

The plate modes involved in the FSTM can also play an important role in the interference mechanism of image formation and thus affect the imaging of internal defects in the sample [11]. In the studied case, acoustic beams of the full angle aperture (Δθ ≈ 20°; focus neck ≈ 2 mm) were used to obtain a high spatial resolution in the experimental results on imaging obtained for both NTM and FSTM Figures 4.3-4.8 below. In the FSTM-imaging, the optimal angle θ₀ was first measured for the intact part of the sample and then set for the subsequent 2D-scans where the output was averaged to obtain the C-scan images.
In these images the defects are not superposed to the intact structure, they are rather enhanced like in dark-field methods in optics or in defect-selective imaging. The most obvious situation is in the case of cracked defects Figures. 4.3 And 4.4. First, the NTM and FSTM, obviously, demonstrate inverse contrast: lower scattering increases the NTM wave amplitude in the area between the crack faces Figure. 4.3a while the plate modes in the FSTM exhibit much higher scattering (and lower output amplitude) in that area Figure 4.3b. For the NTM through a very thin crack, the transmitted acoustic field is strongly affected by diffraction (similar to light diffraction at a slot). The amplitude of the main diffraction maximum decreases rapidly with crack thickness thus making such defects practically invisible in the NTM Figure 4.4a. On the contrary, the plate modes propagate along the sample plane and therefore the scattering efficiency is expected to be non-zero even for very tight cracks. Comparison of Figures 4.4a and b, demonstrates the much higher sensitivity of the FSTM for small (closed) crack detection: the contrast of the crack image is \( \frac{\Delta u}{u} \approx 80\% \) with FSTM Figure 4.4b while it is \( \frac{\Delta u}{u} \approx 2\% \) with NTM Figure 4.4a.

In the case of delaminations, disbonds or inclusions over the sample thickness, the local velocity of the plate modes within the defect area may change dramatically either due to variations of local thickness (delaminations) or material elasticity (strongly inhomogeneous inclusion). Besides the increase of acoustic scattering in those areas, which takes place for both NTM and FSTM, an additional contrast enhancement is to be expected due to following factors:

a) \( \theta_0 \) -variation (\( \Delta \theta_0 \)) that should cause the “resonance” drop of the transmitted wave amplitude if \( \Delta \theta_0 > \Delta \theta / 2 \);

b) alteration of the interference pattern between the plate modes involved in the FSTM (whose phase changes locally within the defect area) and the acoustic wave transmitted normally to the sample surface (existing for a wide angular aperture beams if \( \Delta \theta / 2 > \theta_0 \)).

Solodov, Stoessel and Busse [11] believe that the former mechanism contributed to the contrast of the STM-image of the piezoelectric actuator imbedded into epoxy-based composite Figure 4.5b. The contrast of the actuator FSTM-image (\( \Delta u/u \equiv 45\% \)) Figure 4.5b is far superior to that of the NTM, which is \( \Delta u/u \equiv 15\% \) Figure 4.5a. A similar conclusion for the delamination defects is obvious from the C-scans of aircraft landing flap shown in Figure 4.6 a, b.

The latter mechanism can manifest even if the variation of material properties within a defect area is not enough to shift \( \theta_0 \) from the transducer
angular aperture. However, in the case of “fast” materials (e.g., in CFR-composites) with small $\theta_0$ and well-focused air-borne beams, the variation of the interference pattern between locally generated plate modes and normally transmitted ultrasonic waves is expected over the defect area. Even small variations in local material properties within the defect areas will result in additional alteration of the FSTM output due to the amplitude and phase variation of the interfering components. In Figure 4.8, the results of NTM-scans are compared to those that were obtained when using the interference version of the FSTM for imaging of the weak inhomogeneities. The inhomogeneities in the CFR-composite plate ($d \cong 4 \text{ mm}$) were simulated by circular insertions fixed into the matrix at various depths and made of the same matrix material but with slightly different (by $22.5^\circ$) orientation of the carbon fibres Figure 4.7 Comparison of the images shows Figure 4.8 that some additional contrast is gained in the FSTM even for such minor structural inhomogeneities.

![Figure 4.3 C-scans of cracks in PMMA plate [11].](image)

a) NTM  b) FSTM
Figure 4.4 C-scans of an impact closed crack in polystyrene plate (Top). Transmitted amplitude distributions across images (Bottom) [11].

a) NTM                              b) FSTM

Figure 4.5 a) NTM      b) FSTM
C-scans of an actuator embedded into epoxy-based composite (Top). Transmitted amplitude distribution across images (bottom) [11].
Figure 4.6 C-scans of delaminations in a CFRP-aircraft landing Flap [11] a) NTM b) FSTM.

Figure 4.7 Comparison of images with slightly different variations [11].

Figure 4.8 C-scans of transmitted amplitude distribution for anisotropic inhomogenities in CFR –composites a) NTM & b) FSTM.
4.1.4 Applicability to thin flexible materials

The “coincidence” scheme of the FSTM results in a substantial increase in the amplitude of air-coupled ultrasound transmitted through a solid plate-like sample and seems to be well suited for thin flexible laminates as well[51]. The “resonance” angle behaviour of the weakly focused FSTM allows determining significant in-plane elastic anisotropy by measuring the angles of maximum transmission. Some results obtained from testing of a LDPE/Al/Adh/LDPE/PPR are shown in Figure 4.9.

![Figure 4.9 FSTM imaging for LDPE/Al/Adh/LDPE/PPR material [51].](image)

The much more sensitive interference version of the FSTM is shown to be a simple and robust technique for non-contact detection of minor anisotropy in crystalline samples. A far superior contrast observed for the FSTM imaging of cracks, delaminations, disbonds and other inhomogeneities is found to be not only due to an additional scattering of the plate modes but also caused by a local alteration of the interference pattern of the FSTM output signal, which may be much significantly expressed in the case of non-rigid bodies such as liquid food packages made of Al foil, PE and PPR.

4.2 Shearography

4.2.1 Presentation

Shearography provides full-field, non-contact nondestructive testing for rapid wide-field inspection of composites, bonded structures and other advanced materials. Shearography is an optical video strain gauge and an appropriately applied stress is used to locate strain concentrations caused by internal defects. During a test, an initial image is stored and the part is stressed to create a strain concentration at the site of the defect. This result
can be displayed in real-time with sub-micron displacement sensitivity see Figure 4.10.

As an example, a composite helicopter blade can be inspected in production with vacuum excitation, while it can be rapidly inspected in the field with thermal excitation from a heat source, such as a heat gun or even a hairdryer. Typically light vacuum, thermal, acoustic or mechanical loading is used.

### 4.2.2 Applications

Typical applications are for rapid, wide area, bond-line NDI (disbonds, delaminations, crushed core), from production to field support. Complex structures can be inspected quite rapidly with this method.

Shearography is an ideal composite repair evaluation tool, as it not effected by the non-homogeneity of the repaired structure. It also is able to detect and easily differentiate between crushed core and disbonding in most cored materials.

Kissing disbonds are a particularly difficult problem with composite structures by using older NDT techniques, such as ultrasonics and thermography. Shearography actually applies real stresses to the bond line, and measures the material carrying the load. Kissing disbonds a readily detected.

*Figure 4.10. Double lobed defect.*
Double lobed defect indication shows precise size shape and location of the anomaly, as rapidly as the material can be stressed.

4.3 Thermography

4.3.1 Presentation

Thermography is a non-contact sensing method concerned with the measurement of radiated electromagnetic energy. Thermographic methods may be divided into two types: passive, in which the response of the test structure to an applied heating or cooling transient is monitored; and active, in which heating is produced by applying cyclic stress to the structure either in a fatigue machine or in resonant vibrations. In both cases, the surface temperature of the structure is monitored, usually with an infra red camera, and anomalies in the temperature distribution reveal the presence of defects.

The passive method has been more widely applied than the active technique and its performance is strongly dependent on the heat source used, a flash gun generally being the most suitable [14]. The conductivity and the anisotropy of the composite are also very important; for example the CFRP the conductivity in the laminate plane is about nine times that in the through–thickness direction, which tends to obscure defects that are not close to the surface.

Work carried out at Harwell [14, 15] has shown that the method is made more convenient by using a video recorder to store the rapidly changing temperature pattern after the structure surface is heated. In this way, defects in conducting materials whose effect on the temperature distribution is very short–lived may be detected. The method can be used with the heat source and camera on the same side of the structure (pulse–echo) or on opposite sides (through transmission). The through–transmission method can detect deeper defects than the pulse-echo technique, but for defects close to the surface pulse echo is superior.

4.3.2 Applications

For NDE applications, involved distances are small and the atmosphere is, in most of the case considered transparent in the spectral bands of interest where absorption is limited 3-5 µm (short waves) or in the 8-12 µm (long waves).
Advantages

1) Fast inspection rate of large areas of structures.
2) Non contact.
3) No harmful radiations involved
4) Results relatively easy to interpret.
5) Detection of disbonds in adhesive joints and delaminations in composites.

Disadvantages

1) Difficulty to deposit a large amount of energy in short period of time over large surface.
2) Effects of thermal losses.
3) Cost of the equipment.
4) Capability to detect only subsurface defects.
5) Limited thickness of material only.
6) Not as sensitive as ultrasonics.
   (In detecting disbonds and delaminations).

The passive scheme tests materials and structures which are naturally at different (often higher) temperatures. While in the case of active scheme an external stimulus is necessary to induce relevant thermal contrasts. To our case of interests active thermography is used since it has numerous applications in NDE. Various models of Active thermography are 1) Pulsed thermography 2) Vibrothermography 3) Lock in thermography.

4.3.3 Pulsed thermography

Pulsed thermography involves heating the specimen and then records the temperature decay curve. The material changed rapidly after the initial thermal pulse because the thermal front propagation by diffusion, under the surface and also because of radiation and conventional losses. The presence of defect reduces the diffusion rate so that when observing the surface temperature defects appear as areas of different with respect to surrounding sound areas. Observation time ‘t’ is a function of the squared of the depth ‘z’ and the loss of thermal contrast c is proportional to the cube of the depth. Where \( \alpha \) is the thermal diffusivity of material.

\[
t \sim Z^2/\alpha \quad \text{and} \quad C \sim 1/Z^3 \quad \text{(4.2)}
\]
4.3.4 Vibrothermography

Vibrothermography is a technique where under the effect of mechanical vibrations induced externally to the structure direct conversion from mechanical to thermal energy occurs and the heat is released by friction precisely at locations where defects such as cracks and delaminations are located.

Advantages

1) Detection of flaws is better than any other infrared thermography schemes.
2) Ability to inspect large structural areas.

Disadvantages

1) Mechanical loading might be sometimes may be difficult.

4.3.5 Lock-in thermography

Lock in thermography (or LT) is based on thermal waves generated inside the specimen under study in the permanent regime [16,17]. Here, the specimen is submitted to a sine-modulation heating at a frequency $\omega$, which introduces highly attenuated and dispersive thermal waves of frequency $\omega$ inside the material (in a close to the surface region). The resulting oscillating temperature field in the stationary regime is remotely recorded through its thermal infrared emission with the infrared camera. The lockin terminology refer to the necessity to monitor the exact time dependence between the recorded temperature signal and the reference signal (i.e. the sine-modulation heating). This can be done with a lock-in amplifier in a point by point laser heating or with a computer in full-field deployment.

In LT, phase and magnitude images become available through simple manipulations of thermograms recorded in the permanent regime. A thermogram is a mapping of the emitted thermal infrared power while a phase image is related to the propagation time and a modulation image is related to the thermal diffusivity. A strong point of LT for NDE is the phase image which is relatively independent of local optical surface features (such as non-uniform heating).

The depth range of magnitude image is roughly given by the thermal diffusion length $\mu$ expressed by
\[ \mu = \frac{2K}{\sqrt{\omega \rho c}} \] (4.3)

With thermal conductivity \( k \), density \( \rho \), specific heat \( c \) and modulation frequency \( \omega \). In the case of phase images the depth range is about twice larger [9]. Eq. (4.3) indicates that higher modulation frequencies will restrict the analysis in a near surface region while lower frequencies will allow to probe deeper under the surface.

One potential difficulty of LT is related to the acquisition time which should cover at least one modulation cycle: 0.12 Hz requires at least 8 s, 0.06 Hz requires at least 16.6 s and 0.03 Hz requires at least 33.3 s. On the other hand, thanks to the relative insensitivity of phase images to non-uniform heating and also to the ease modulated heating is deployed, large areas (~ 2 m²) can be inspected in one experiment provided the spatial resolution of the infrared camera allows detection of the smallest defects of interest [18].

### 4.3.6 Applicability to material of interest

Thermography methods are applicable to our material of interest. But its not preferable due to certain limitations. Main important thing to be considered is the temperature of heating the specimen, since our material of interest is paper which may not able to withstand high temperatures. Its preferable to materials like aluminium foil. One point is in favour of LT is the relatively low temperature increase of the object, which makes it preferable when the testing specimen is very sensitive to temperature variation.

### 4.4 Ultrasonic spectroscopy

#### 4.4.1 Presentation

Ultrasonic spectroscopy utilizes information in the frequency domain obtained due to the constructive and destructive interference of elastic waves for non-destructive evaluation of inspected objects. Ultrasonic spectroscopy has been used for the inspection of aerospace structures and its application field is expected to increase rapidly with the growing application of layered structures.
4.4.2 Linear Angle Beam Ultrasonic Spectroscopy

The linear approach, obliquely and normally incident ultrasonic beam spectroscopy is used. The two angle measurements allow decoupling of elastic moduli and thickness of the interfacial layer and the determination of the effective bulk properties of embedded layers (thickness, moduli, attenuation and density). At each point of the scan, the normal and angle beam time domain signals reflected from the layer are recorded, analyzed in the Fourier domain. The transducer frequency bandwidth is selected such that the reflected spectra exhibit one or two resonance minima in the adhesive layer. The final results are obtained in the form of images of the bond line parameters.

In this way the linear method allows us to discriminate an environmentally degraded bond; however the contrast in the linear ultrasonic method is small, i.e. the difference in linear ultrasonic signature between the degraded and undegraded bond areas is small. This makes the linear ultrasonic bond line reconstruction method susceptible to error due to substrate property variations and misalignment errors. Under static compressive stress a small amplitude high frequency ultrasonic signal reflected from an imperfect bond may possess in some cases the same characteristics as one reflected from a good bond. This is because the ultrasonic stress amplitude is too small to overcome the compressive residual stress which results in the continuity of ultrasonic stresses and displacements across the interface. As a result in this case an imperfect interface is indistinguishable by the linear method from a perfect interface.

4.4.3 Nonlinear Angle Beam Ultrasonic Spectroscopy

Nonlinear Angle beam ultrasonic spectroscopy method combine low frequency vibrations of the layered structure with overlapped linear pulse echo beam ultrasonic reflection measurements to enhance interfacial property measurement and to relate the measurement to local layered material integrity stress modulation is used at the interface. For a good layered structure the interfacial stiffness is independent of low frequency stress under experimental conditions (assuming that the modulation stress is below the threshold where the nonlinear behavior of the good bond sets in). In the case of a poor bond, the interfacial stiffness decreases under the vibration tension. As a result the interfacial stiffness changes during compression and tension periods of the low frequency cycles leading to a low frequency modulation of the spectral minima of reflected ultrasonic signals. Experiments indicate that the frequency modulation due to the
modulation-induced adhesive layer thickness change is negligible [25]. Figure 4.11 illustrates the approach schematically. A tension or compression cycle is applied to the bond. The low frequency stress applied on the bondline is alternately in compression or tension. As illustrated in Figure 4.11 (on the right), for an imperfect bond the spectral minimum of the ultrasonic signal reflected from the adhesive layer shifts under the loading. The bond layer properties are evaluated during cycling using angle beam ultrasonic spectroscopy for different states of the stress of the bondline. This is achieved by synchronizing the low frequency continuous excitation of the structure with the high frequency ultrasonic pulse triggering used for the spectroscopic measurement.

Modulation concept for characterization of adhesive bonds was applied by Rokhlin et al [25], modulated ultrasonic spectroscopy measurements on environmentally degraded joints is used. The bonded sample is excited by the shaker and the vibration amplitude on the sample is measured by an accelerometer. Three different types of low frequency shakers were used for vibration excitation: piezoelectric, magnetostrictive and electrodynamic transducers covering the frequency range 50 Hz-30 kHz. For perfect bonds no mixing of vibrations with pulsed ultrasonic signals is expected; for weak interfaces the boundary springs change under load leading to amplitude and frequency modulation of ultrasonic signals by low frequency vibrations. The angle beam ultrasonic head includes three 10 MHz wide band transducers. The recorded high frequency signals were digitized with a 12 bit 125 MHz digitizer followed by signal gating and FFT.

The adhesive joint samples were exposed to the environment until moisture penetration. Then they were attached rigidly to the shaker. For this experiment the selected modulation frequency 50Hz. 50 modulation cycles were used at each measurement point on the joint. For each cycle at 40 different time points of the cycle synchronized reflected pulses were acquired. Therefore in total 2000 ultrasonic reflections from the interfaces are measured at one location on the bonded area. The modulation resonance spectra for three positions with different bond conditions are shown in Figure 4.12. The solid lines present the modulation spectra for normal incidence and the dashed lines for oblique.
Figure 4.11: Angle beam ultrasonic spectroscopy of adhesive joints under thickness resonance parametric excitation [25].

![Figure 4.11: Angle beam ultrasonic spectroscopy of adhesive joints under thickness resonance parametric excitation](image)

Figure 4.12: Experimental resonance modulation spectra for three transducer positions with different bond properties [25].

![Figure 4.12: Experimental resonance modulation spectra for three transducer positions with different bond properties](image)

The scanning was performed in the dual beam reflection mode over a 20×50mm area. The scanning results for the modulation index are displayed as grey level images in Figure 4.13 (a, b). The grey level images
represent the first harmonic modulation amplitude at 50Hz. The dark grey levels correspond to high levels of the frequency modulation index. Figure 4.13(a) presents the frequency modulation scanning results at normal incidence and Figure 4.13(b) for oblique incidence. Both images indicate the transition from a highly degraded area (right bottom corner marked by ‘D’) to a good bond area (left top corner marked by ‘G’). The images have very high contrast with modulation index varying from 1% to nearly 0.01%. The images show that the damage is propagating inward from the edge area marked by ‘D’. The area marked by ‘G’ exhibits no visible damage. The grey-level image of the averaged peak amplitude is shown in Figure 4.13(c). The two bright areas marked by arrows are artificial marks for the scanning area location. As shown in Figure 4.13(c), the C-scan image has very low contrast and exhibits only the severely degraded area at the right bottom corner ‘D’. The modulation method has much higher contrast providing nearly zero modulation level for a good bond. This is a significant advantage of the modulation method since one judges the existence of bond imperfections by comparing with zero (noise floor) corresponding to the good bond areas [19-25].
Figure 4.13: Comparison of C-scan and modulated angle beam measurements. (a) Gray level image of the resonance frequency modulation at normal incidence. (b) Gray level image of resonance frequency modulation at oblique measurement. (c) C-scan image with 2000 pulse averages. The two bright areas marked by arrows are artificial marks for the scanning area location [25].
4.5 Acoustic microscopy

4.5.1 Presentation

This method is newly developed, low cost alternate ultrasonic methodology that is superior to contact transducer methods for non-tactile underwater identification of material type, orientation, velocity, roughness, stress and attenuation. A transmitted high frequency ultrasound is used to produce images of structures with a resolution approaching that of light microscopy. Ultrasound high frequencies in the order of 10 MHZ -2 GHz are used. The so called acoustic microscope has a transmitting and receiving ultrasound transducer. The specimen is placed between the two transducers Specimen areas of approximately 250 µm are scanned in about 1 second with highly focused ultrasound. The pixel size in the final image is approximately 1µm and the image contrast i.e. the pixel intensity (grey level) is determined by ultrasound attenuation, which is at gigahertz frequencies if mainly determined by the elasticity of the specimen components.

4.5.2 Application

Acoustic microscopy is generally applied to

- Package crack detection.
- Electronic plastic package evaluation.
- Evaluation of the physical integrity (cracking) of materials after stress.

Two types of acoustic microscopy exist: Scanning acoustic microscopy, and Photo acoustic microscopy.

4.5.3 Scanning acoustic microscopy

Scanning Acoustic Microscopy (SAM) works on the principle of propagation and reflection of acoustic waves at interfaces where a change of acoustic impedance (AI = density x velocity) occurs. The specimen is scanned line by line using a very fine ultrasonic beam. There are two kinds of acoustic wave modes being used in a SAM: the burst-wave mode and the pulse-wave mode.
The burst-wave mode uses a group of 30–40 waves with frequency in the range 100 MHz to 1.5 GHz. This mode is designed for inspection of defects on or near the surface.

The pulse-wave mode uses a single pulse wave of frequency in the range 10–100 MHz and is designed for detection of internal defects. In the pulse-wave mode, a lens having good focusing properties on an axis is used to focus the ultrasonic waves onto a spot on the specimen and to receive the reflected waves back from the spot, typically in less than 100 ns. The acoustic beam can be focused to a sufficiently small spot at a depth up to 2–3 mm to resolve typical inter-laminar cracks and other critical crack geometries. The received echoes are analyzed and stored for each point to build up an image of the entire scanned area. The reflected signal is monitored and sent to a synchronous display to develop a complete image, as in a scanning electron microscope. Images can be generated from specific depths (C-scan), cross-sections (B-scan) or through the entire specimen thickness (multiple C-scans). Figure 4.11 below illustrates the principle.

Figure 4.11. Scanning acoustic microscopy.
This technique is suitable for detection of cracks, delamination, and mostly voids which are easily detected.

### 4.5.4 Photo Acoustic Spectroscopy

The techniques of Photo acoustic spectroscopy see figure 4.12 can be applied for non-destructive testing (NDT) of thin films. The Photo acoustic signal shows a change in magnitude and phase wherever the crack or void or the defect is present in thin films. The photo acoustics (PA) technique has been effectively used to characterize materials, because of its great versatility as a non-destructive and non-invasive method for evaluation of materials. Here photo acoustic spectroscopy (PAS) is used in the form of Photo acoustic microscopy (PAM), which offers minimal or no sample preparation, the ability to look at opaque and scattering samples and the capability to detect the defects on the surface of thin film.

There is limited information on the application of photo acoustic spectroscopy as a non-destructive method, even though it provides optical properties as well as the defect states associated with semiconductors effectively. Figure 4.13 show the set-up and the kind of waves for characterizing thin films.

![Figure 4.12. Photo acoustic spectroscopy [26].](image)
4.5.5 Guided wave techniques

This inspection technique has been recognized as a powerful NDE method that can potentially compensate technical limitations of a conventional bulk wave technique for plate-like structures. The guided waves can be generated as various modes with respect to frequency, thickness, and incident angle and they can propagate a large distance along the geometry of a structure [26]. Predicting mode conversion caused by defects, using dispersion theory and experiments, is one of the important parts in guided wave application studies [29-31]. If these characteristics of guided waves are used in NDT we can get improvement of sensitivity using the various modes and reduce inspection time and cost [27-31]. Guided wave techniques are especially useful in NDT of thin plate-like and tubular structures that are hard to test, resulting in signal overlap from the bulk wave technique. Since the 1980s, guided wave application studies have been carried out by numerous researchers such as Rose and Cawley and it was demonstrated that guided waves can be applied to safety insurance of nuclear power station and aircraft successfully [29-31, 34-35].

4.5.6 Bulk wave Techniques

Thin-film bulk acoustic wave (BAW) devices first appeared two decades ago [26], [27], but only recently their large-scale commercial applications have been introduced [28]. This is because of the considerable technical
difficulties in obtaining consistently high-quality, thin-film piezoelectric layers with uniform thickness and the problems in the suppression of the side resonances that may contaminate the frequency response close to the main resonance. For the behavior of the side resonances, the dispersion characteristics of the Lamb-wave modes propagating along a layered structure are important. In addition, many modeling techniques for thin-film BAW devices, such as the mode-matching method [29], require knowledge of the dispersive behavior. This may be computed numerically or, alternatively, the measured dispersion curves can be used in the model. Another major limitation with the current bulk wave inspection techniques is that they can be blind to surface defects such as gauge corner cracking where a shallow, tolerable crack can block the ultrasound from penetrating down to a much deeper crack behind it. Current systems can potentially miss serious defects and cannot be used with high regularity due to their speed limitations. The intensification of the measured effects along the path of the wave propagation, the possibility of testing very thin adhesive layers, only one dimensional scanning is necessary and they are less sensitive to the variations in the properties of the adherends relative to the method of ordinary bulk ultrasonic wave.

4.5.7 Guided Acoustic Waves in Layered Films

Guided wave scattering has different mode conversion phenomena with respect to frequency, thickness, and reflector shape. This means that the variation of plate shape could cause unique scattering at a certain frequency. If plate thickness is fixed, mode conversion occurs only in the vertical direction at the unique $fd$ value as indicated in Figure 4.14. At this time, the transmitting and receiving of each mode is available by control of the wedge angle.

Thickness of plate-like structures can be varied by partial coating, corrosion, and joints in the plate. This variation controls not only the vertical direction mode conversion but also horizontal direction mode conversion on the dispersion curve. The complex mode conversion phenomena are the reason that guided wave scattering analysis for reflector classification is difficult. Komsky and Achenbach [36] were concerned with the scattering characteristics of incident mode but in this study the scattering characteristics of different modes after multi-mode conversion is also proposed.
Asymptotically as \( kh \rightarrow 0 \), the phase velocity for the two lowest order modes become

\[
v_{so} = \frac{\omega}{k} = \sqrt{\frac{c^*}{\rho^*}}
\]  

\[
v_{ao} = \frac{\omega}{k} = \sqrt{\frac{D^*}{\rho^*} (kh)^2 + \frac{\sigma_s}{\rho^*}}
\]  

Where \( C^*, D^* \) and \( \rho^* \) are the elastic stiffness, flexural rigidity and density of composite respectively, \( \sigma_s \) is the average residual stress in the film.

This method is applicable for detection and analysis of subsurface heterogeneities defects like cracks, inclusion, delamination etc.

Advantages

1) Non-contact.
2) Non-destructive.
3) Film support conditions need not be known.

### 4.6 Vibration based methods

Several techniques have been researched for detecting damage in materials, many of them focusing on modal response. These methods are among the earliest and most common, principally because they are simple to
implement on any size structure. Structures can be excited by ambient energy, an external shaker or embedded actuators, and embedded strain gauges or accelerometers can be used to monitor the structural dynamic responses. Changes in normal vibrational modes can be correlated to loss of stiffness in a structure, and usually analytical models or experimentally determined response-history tables are used to predict the corresponding location of damage. The difficulty, however, comes in the interpretation of the data collected by this type of system. There are also detection limitations imposed by the resolution and range of the individual sensors chosen, and the density with which they are distributed over the structure. There have been many different approaches described in the literature that use modal evaluation techniques to locate damage in everything from small specimens to full components. The two major categories that will be described in detail in the following sections are model-dependent and model-independent methods.

4.6.1 Model-based vibration methods

The model-dependent methods are capable of providing both global and local damage information, as well as being cost-effective and easily operated.

Modal analysis-based methods utilize input from several modal parameters including frequency, mode shape and damping ratio to detect damage. Frequency domain techniques attempt to detect damage by only using the frequency response of the structure. In using time domain methods, damage is estimated by using time histories of inputs and their vibration responses. Lastly, impedance domain techniques use changes in electrical impedance to measure damage in the structure. The modal analysis methods recommended on account of their global nature, low cost, and flexibility to select measurement points, however they lack the ability to localize damage and require large data storage capacity for comparisons. The frequency domain methods alone were incapable of detecting the location of damage, however when combined with time domain methods they can detect damage events both globally and locally. Lastly, the impedance domain techniques were described as suitable for detecting most delaminations reliably, unless the layers above the defect are very thin compared to the remaining laminate.

The most thorough reports on frequency response methods can be found in a recently published paper by Zou et al. [37], which presents a review of vibration-based techniques that rely on models for identification of
delamination in composite structures. All of the methods they assessed use piezoelectric sensor and actuators along with finite element analysis results to locate and estimate damage events by comparing changes in dynamic responses. Several other papers [38-40] have documented the use of a combination of the modal analysis and frequency domain methods to detect various damage types with piezoelectric actuators and sensors coupled with finite element or analytical models.

4.6.2 Model independent vibration methods

Model independent vibration based techniques do not require the use of analytical models. The responses were recorded for the healthy structure to be later compared to a potentially damaged structure.

The most thorough reports on frequency response methods can be found in a recently published paper by Zhang et al. [41] investigated the use of transmittance functions for a system of piezoelectric patches were placed on a structure, where some were used as sensors and others as actuators, and changes in curvature were used in this case to detect, locate and assess damage to the structure. One significant finding was that the optimal frequency range to actuate their structure was between 10-20 kHz, however they found that only frequencies less than 5 kHz (200-1800 Hz in most cases) were practical to collect experimental data. Lastly Valdes and Soutis [42] detected delamination in composite laminates using piezoceramic patches and piezoelectric film sensors, again without the use of models. Frequency sweeps between 8-14 kHz were used to induce vibrations on the structure, and clear reductions in modal frequencies were found as the delamination area in the test specimen was increased.

The present research investigates the feasibility of modal evaluation techniques in detecting damage of composite structures. Characteristics examined include these methods’ ability to detect various types of damage, their precision in determining the damage location, and their sensitivity to sensor density. Conformability, or the ability of a sensing system to be integrated easily into an existing structures and infrastructure, is also assessed. A similar procedure is followed by several of the papers presented above to evaluate these methods.

4.6.3 Base line strain energy mode shapes method

In the recent past, several methods for detecting and locating damage (usually cracks) from changes in Strain Energy Mode Shapes (SEMS) have
been developed. All these methods attempt to detect and locate damage that produces local changes in elastic modulus without significant changes in mass. Such damage can be observed as localized changes (damage peaks) on strain energy mode shapes.

The majority of these methods requires knowing strain energy distribution (mode shapes) for the structure without any damage or the so-called baseline SEMS. The comparison to the baseline is used to enhance appearance of damage peaks that sometimes may not be observed otherwise. The need for baseline SEMS is especially obvious for identifying small damages that produce very subtle changes in SEMS.

Unfortunately, such an approach often is not feasible for class of structures where undamaged state is unknown but the need for the non-destructive testing is usually greater. Conventional methods, such as building Finite Element (FE) model of a structure may present a tedious, expensive and time consuming task. Beside it is difficult or sometimes impossible to reach required accuracy of mode shape approximation by a FE model.

Consider some of the recent work in this area. Shi et.al. [43] suggested using change in strain energy distribution to detect and localize damage. The recommended method monitors changes in modal strain energy in each structural element comparing the state before and after it was damaged.

Farrar and Jauregui [44] conducted a comparative study of different damage identification algorithms on bridge. The strain energy methods performed very well compared to other methods tested in the experiments, occupying the top two places by the accuracy of detection. Osegueda, Carrasco and Meza [45] investigated strain energy method on aluminum cantilever beams and honeycomb composite plates. The authors received positive damage detection results in experiments with beams and negative results in experiments with composite plates. They also claimed that strain energy methods not only can identify damage but also quantify it by accounting the energy relations between damaged and undamaged states.

Yoo, Kwak and Kim [46] used difference in strain energy mode shapes between damaged and undamaged cases to detect and locate damage in a plate. Napolitano [47] investigated quality of damage detection using reduced measurement and the strain energy algorithm. The author concluded that the strain energy method perform well when many points are measured. Cornwell, Doebling and Farrar [48] provided a detailed theoretical explanation on application of strain energy method to plate-like structures. They reported that the method was effective enough to detect areas with 10% reduction in stiffness.
A method based on strain energy mode shapes was developed at West Virginia University (WVU) [49]. Strain energy for interval \([a, b]\) was computed the following formula:

\[
U_{[a,b]} = \frac{1}{2} \int_{b}^{a} E.I. (\Phi'')^2 \, dx
\]

(4.6)

Where \(E.I\) is the flexural stiffness of the cross-section; \(\Phi\) is the shape vector (displacement mode shape). Subtracting the baseline SEMS from the SEMS acquired from the structure under test produce so called Difference Strain Energy Mode Shapes (DSEMS) where crack location is identified as damage peaks. Again this method require baseline to extract and enhance appearance of damage peaks. An extension of the WVU method is described in [50]. The suggested procedure performs extraction and enhancement of damage peaks appearance through the separation of damage information in frequency domain rather than traditional spatial domain. It was shown that the damage introduced into a beam creates additional harmonics can extracted by filtering and restored to produce enhanced damage peaks.
4.6.4 Non-base line strain energy mode shapes method

The amplitude spectrum of strain energy mode shapes for pinned-pinned boundary conditions is limited to the first $k+1$ harmonics (as the most general case) in the Fourier series representation. It can also be shown [62] that the amplitude spectrum of damage peak on the strain energy mode shapes is significantly wider than the amplitude spectrum of an undamaged strain energy mode shape. Additionally, all damage peaks of the same shape and amplitude have the same amplitude spectrum but different phase spectrum. Therefore, it is possible to separate mode shape information from damage information in the frequency domain and avoid using a baseline by removing the first $k+1$ harmonics in the frequency spectrum of a strain energy mode shape. The procedure is illustrated in figure 3.16. The non-baseline method has been successfully tested both on finite element models of a free-free beam and experimental data.
The displacement mode shape for pinned-pinned beam for mode $k$ are given by the following equation

$$\phi_k(x) = Q_k \sin\left(\frac{\pi k}{L} x\right) = Q_k \sin\left(\frac{w_k}{L} x\right)$$

(4.7)

Where $Q_k$ the amplitude of mode $k$ is, $w_k = \frac{2\pi k}{L}$ is the angular frequency for mode $k$.

Figure 4.16 Non-baseline strain energy method [50].
4.7 Sound transmission methods

4.7.1 Presentation

In some applications ultrasonic data such as velocity can be directly used to calculate properties such as elastic modulus. In other cases, ultrasonic testing is a comparative technique, where in order to establish a test protocol in a given application it will be necessary to experimentally evaluate reference standards representing the range of material conditions being quantified. From such standards it will be possible to record how sound transmission parameters vary with changes in specific material properties, and then from this baseline information it will be possible to identify or predict similar changes in test samples.

The relevant measurement parameters will typically be one or more of the following:

1. Sound velocity or pulse transit time: Sound velocity is usually the easiest ultrasonic parameter to measure. The speed of sound in a homogenous medium is directly related to both elastic modulus and density; thus changes in either elasticity or density will affect pulse transit time through a sample of a given thickness. Additionally, varying degrees of nonhomogeneity may have an effect on sound velocity.

2. Attenuation: Sound energy is absorbed or attenuated at different rates in different materials, governed in a complex fashion by interactive effects of density, hardness, viscosity, and molecular structure. Attenuation normally increases with frequency in a given material.

3. Scattering: Sound waves reflect from boundaries between dissimilar materials. Changes in grain structure, fibre orientation, porosity, particle concentration, and other microstructural variations can affect the amplitude, direction, and frequency content of scattered signals. Scatter effects can also be monitored indirectly by looking at changes in the amplitude of a backwall echo or a through-transmission signal.

4. Frequency (Spectrum) content: All materials tend to act to some degree as a low pass filter, attenuating or scattering the higher frequency components of a broadband sound wave more than the lower frequency components. Thus, analysis of changes in the remaining frequency content of a selected broadband pulse that has passed through the test material can track the combined effects of attenuation and scattering as described above.
4.7.2 Transmission loss

When a sound wave impacts upon the surface of a solid body, some portion of its energy will be reflected, some absorbed and the rest transmitted through the body. The relative proportion of each depends on the nature of the material impacted.

Transmission loss can be determined by measuring the sound energy on both the source side \( w_{\text{src}} \) and the receiving side \( w_{\text{rec}} \). we can thus determine the transmission coefficient \( \tau \) as follows.

\[
\tau = \left( \frac{w_{\text{rec}}}{w_{\text{src}}} \right)
\]  

(4.8)

The sound reduction index (SRI) are used to describe the reduction in sound level resulting from the transmission through a material,

\[
\text{SRI}=10\log\left( \frac{w_{\text{src}}}{w_{\text{rec}}} \right)
\]  

(4.9)

The SRI of nearly all materials varies with frequency; the main effect is the mass law, with the effect of resonance and coincidence also contributing.

The mass law, obviously the greater the mass of the material the greater the sound energy required to set it in motion.

\[
R = 20\log\left( \frac{2\pi fm}{pc} \right) \text{ dB}
\]  

(4.10)

Where F is the frequency, m is the mass per unit area, and \( pc \) is the characteristic impedance of air, Mass law applies strictly to temp, non-rigid partitions.

4.7.3 Energy loss by air-coupled ultrasound

An easy way to initially visualize what's happening ultrasonically and why flaws are detectable is to follow the trajectory of an ultrasonic tone burst (longitudinal wave mode) as it travels from the transmitter probe, through
air to the material being inspected, through the material and eventually through air again to the receiver probe.

Tone bursts are generated pulsed ultrasonic energy in the form of rapidly reoccurring cycle packets at a given test frequency which possess the necessary duration (pulse length) and amplitude to deliver the desired "penetration power", yet eliminate or minimize standing wave interference.

Low frequency tests can readily be used (less than 100 kHz) with this method, because the frequency is low enough so ultrasonic attenuation (scatter and absorption) is greatly reduced to levels which permit ultrasound to readily propagate through both air and the categories of materials targeted for inspection.

Transmission into Air: Initially, a portion of ultrasonic energy is lost (due to the transmitter probe and air impedance mismatch) as the tone burst is initially launched into the air.

Airpath to Material: Once launched, the tone burst travels through the air and loses further energy due to attenuation (absorption) and beamspread (diffraction).

Entry into Material: A large amount of the incident tone burst energy is lost due to reflection at the material surface, with only a small amount of the ultrasound actually entering the material. This reflection loss is caused by the extremely large acoustic impedance mismatch at the air-material interface.

Travel through Material: As this weakened tone burst travels through the flawless material, it experiences further energy loss caused by attenuation, as well as by additional beamspreading.

Exit from Material: The remaining burst now experiences another huge energy reflection loss due to the same excessive material-air acoustic impedance mismatch as was experienced at the above-mentioned entry surface. At this point, the tone burst has lost most of its energy due to only the two surface reflections.

Airpath to Receiver Probe: After exiting the material, the now extremely low energy tone burst experiences further attenuation and beamspread loss as it travels along the airpath to the receiver probe.
Reception from Air: Finally, when this low-level tone burst impinges on the receiver probe, an additional energy loss is experienced during its ultrasonic transfer to (ultrasonic activation of) the probe.

Impact of Material Flaw: Impedance mismatches at the two material surfaces can be considered energy-stealing enemies, the large air-material mismatch caused by a flaw (delamination, split or cavity) becomes a great ally. Basically, the tone burst experiences another similar energy loss when it impinges on a flaw (assuming the flaw is large enough to intersect the complete beam). Even pressed together delaminations at this test frequency (50 KHz) will still reflect the signal energy (because there is a microscopically thin layer of air still present at the flaw site). Thus, the flaw blocks a huge percentage of the control (flawless) tone burst energy - making the flaw readily detectable.

4.8 Summary review of various unconventional NDT methods

Table 4.1 various unconventional NDT methods used to detect the defects.

<table>
<thead>
<tr>
<th>DEFECT TYPE</th>
<th>ACoustIC MICROSCOPY</th>
<th>SHEAROGRAPHY</th>
<th>THERMOGRAPHY</th>
<th>ULTRASONIC SPECTROSCOPY</th>
<th>VIBRATION BASED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void/Perfora</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Delamination</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Micro cracks</td>
<td>Yes</td>
<td>No</td>
<td>Some</td>
<td>Some</td>
<td>----</td>
</tr>
<tr>
<td>Weak bonding</td>
<td>No</td>
<td>No</td>
<td>----</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

The above Table 4.1. Summarizes the applicability of the methods mention above to different defect types. Acoustic microscopy and ultrasonic spectroscopy are preferred because their capabilities to detect different type of damages like voids, delamination, micro cracks, and weak adhesion with satisfactory precession.
5 Conclusions

In this work, a literature survey of the applicable methods to detect defect of thin layered materials is done.

Most of the unconventional NDT methods are suitable for voids or porosity, delamination in layered materials. Matters relating to weak bonding are still difficult to detect in thin layered materials.

The best technique to initially detect a defect depends on the defect size which must be found, the size of the structure to be inspected, and the environment in which the tests are to be carried out. Ultrasonic methods are very sensitive, but have the disadvantage of requiring a couplant between the transducer and the test structure. Coupling is most reliably achieved either by immersing the component or by using a jet probe system, both of which add to the expense and inconvenience of testing. Manual inspection using a gel couplant is often used, but the reliability and speed of the test is reduced. Passive thermography may rapidly inspect large areas, but the capital costs are high and the sensitivity of the test may not be adequate in all cases.

In damage detection and characterization, the non-contact measurement techniques are gaining an increasing interest, as they offer large potentials, particularly to perform test not only in laboratory, but also in operative conditions.

Among the different techniques, the suitable methods seem to be based on the ultrasonic spectroscopy, and vibration based methods. In fact, these measurement techniques allow the extraction of integrity of the specimen.
6 References


59


[47] Napolitano K.,(1997).“Damage detection using reduced measurements”.


energy mode shapes, to appear in Non-Destructive Testing and Evaluation”.
