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MODAL CONTENT BASED DAMAGE INDICATORS AND PHASED ARRAY TRANSDUCERS FOR STRUCTURAL HEALTH MONITORING OF AIRCRAFT STRUCTURES USING ULTRASONIC GUIDED WAVES

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ABSTRACT

Composite materials, especially carbon fiber reinforced polymers (CFRP), have been widely used in the aircraft industry because of their high specific strength and stiffness, resistance to corrosion and good fatigue life. Due to their highly anisotropic material properties and laminated structures, joining methods like bolting and riveting are no longer appropriate for joining CFRP since they initiate defects during the assembly and severely compromise the integrity of the structure; thus new techniques for joining CFRP are highly demanded. Adhesive bonding is a promising method because it relieves stress concentration, reduces weight and provides smooth surfaces. Additionally, it is a low-cost alternative to the co-cured method which is currently used to manufacture components of aircraft fuselage. Adhesive defects, disbonds at the interface between adherend and adhesive layer, are focused on in this thesis because they can be initialized by either poor surface preparation during the manufacturing or fatigue loads during service.

Aircraft need structural health monitoring (SHM) systems to increase safety and reduce loss, and adhesive bonds usually represent the hotspots of the assembled structure. There are many nondestructive evaluation (NDE) methods for bond inspection. However, these methods cannot be readily integrated into an SHM system because of the bulk size and weight of the equipment and requirement of accessibility to one side of the bonded joint. The first objective of this work is to develop instruments, actuators, sensors and a data acquisition system for SHM of bond lines using ultrasonic guided waves which are well known to be able to cover large volume of the structure and inaccessible regions. Different from widely used guided wave sensors like PZT disks, the new actuators, piezoelectric fiber composite (PFC) phased array transducers (PAT), can control the modal content of the excited waves and the new sensors, polyvinylidene fluoride (PVDF) arrays, which can extract modal information from the received waves. Also, the
PATs and array sensors have broad frequency bandwidth and can easily excite and receive high
order guided wave modes which are not possible using PZT disks.

Currently, many guided wave SHM techniques employ the fundamental guided wave
modes below the first cut-off frequency because of their low dispersion in this frequency range.
Such a practice ignores the possibility of using higher order modes which sometimes have much
better sensitivity to defects. A frequency domain finite element model is created in this work to
study the behavior of the interaction between guided waves and a disbond. The sensitivities of
modes are classified into three levels, namely, good sensitivity, intermediate sensitivity and no
sensitivity. The novel damage indicators, wave modal amplitude and wave modal composition,
are proposed to increase the sensitivity to disbonds.

The effects of environmental operational conditions (EOC) are presenting great
challenges to reliable SHM practice because they may influence the wave amplitude and time of
flight. The use of fundamental modes shows poor sensitivity to the disbond; but the use of higher
order modes shows good sensitivity. The experiments demonstrate that the new damage
indicators have excellent sensitivity to disbonds even with elevated temperatures and have the
capability to characterize the size of a disbond. Additionally, the detection of other types of
defects like notches on aluminum plates and disbonds in adhesively bonded aluminum plate are
also demonstrated using the proposed damage indicators. The use of the new damage indicators
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Chapter 1

Introduction

Aircraft structural materials have seen revolutions from wood and fabrics to aluminum alloys and recently to carbon fiber composites. Carbon fiber reinforced polymer (CFRP), which is referred to as “black aluminum” sometimes, has higher specific stiffness and strength and better corrosion resistance compared with aluminum alloys. Some of the latest commercial airplanes, Boeing Dreamliner [1] and Airbus A350 XWB [2, 3], are famous for having a great portion of their airframes, more than 50 percent, made of composite materials. Rotorcraft like V-22 Osprey [4] uses composite to make all its airframe and CH-53K [5] also employ composite to make its key components like rotor blades.

However, the highly anisotropic and multi-layer nature of CFRP enables special failure modes of composite structures, and the knowledge of the fatigue life of CFRP is still not as well established as that for aluminum alloys, which has been studied for many decades. Fiber breaking, matrix cracking, delamination, debonding and adhesive disbonding are defects that are unique to CFRP. Being able to detect, locate, and characterize damage as well as predict remaining life of structures are of great value to reduce the risk of catastrophic failure and life cycle cost.

Currently in the aircraft industry, a paradigm shift from schedule-based maintenance to condition-based maintenance is taking place [6]. Knowledge of the usage of structures and distribution and severity of defects are the prerequisites to make appropriate maintenance decisions. To obtain this information, sensors need to be permanently embedded onto structures and particular physical quantities, e.g. acceleration and strain, need to be measured continuously
or at intermittent time intervals to provide real-time health conditions of the structure. Such practice is usually regarded as structural health monitoring (SHM).

The initial cost could be high and an increased number of parts need maintenance due to additional instrumentation. However, for safety and reliability critical structures, the improved reliability, decreased maintenance costs and reduction in downtime will outweigh those disadvantages.

This thesis focuses on the development of the instrumentation, i.e. actuators, sensors and data acquisition (DAQ) system, and methodologies for a SHM system to monitor adhesively bonded composite structures. The method utilizes ultrasonic guided waves, which have proved to be a valuable tool for both nondestructive testing (NDT) and SHM, to effectively cover a large volume of the structure with sensors distributed across the structure as sparsely as possible. Efforts are also made to reduce the mass and profile of the actuators and sensors to make them compatible with aircraft structures.

1.1. Problem Statement

Composite materials usually demand different joining techniques than metal alloys. Traditional joining techniques like riveting and bolting are no longer favorable because they will initialize inter-lamina damage, increase stress concentration and accelerate the damage growth. Adhesive bonding is a promising alternative because it does not introduce damage to adherends, mitigates stress concentration, provides a smooth finish and minimizes the weight added by assembly. The most common defect of an adhesive bond is a disbond which could be initialized by poor surface preparation during the bonding process or initialized at the location where stress concentrates under fatigue loading. Unlike fatigue cracks developed near fastener holes, a disbond is usually invisible, which poses challenges to its detection and maintenance.
Nondestructive evaluation (NDE) of adhesive bonds has been studied extensively in the literature. Many methods have been used at one time or another in an attempt to adequately evaluate bond quality. These methods include ultrasonics, thermography, acoustic emission, shearography and radiography. Most of these methods require the bonded region to be accessible such that one side of the bonded joint could be inspected point by point. However, disassembling the aircraft to provide accessibility is not always feasible for some complex structures and it could significantly increase the downtime and maintenance cost. Additionally, a defect could grow rapidly during the interval between maintenance and cause catastrophic failure. For either reason, a technique that could continuously monitor or do the inspection on demand without disassembling the structure is highly preferable.

Using ultrasonic guided waves to monitor disbonds in composite structures has been reported by many researchers in the literature. Fundamental guided wave modes are usually employed in current SHM methods because these modes are less dispersive and easily excited with simple transducers, like PZT disks. However, due to the limited choices of fundamental modes below the first cut-off frequency, it is not guaranteed that there is at least one mode that is sensitive to a particular defect, e.g. disbond. Also, a wave with poor sensitivity to the disbond could work in the lab but may not work in real structures because of changing environmental operation conditions (EOC). It has been reported in the literature that an elevated temperature [7], 60°C, could overwhelm the sensitivity to a defect completely. Additionally, the real structure may have different material and geometry properties due to errors in manufacturing. A robust SHM method should have good tolerance to such variations.
1.2 Literature Review

Recently, much research for inspection of adhesive bonds focuses on ultrasonic methods. Generally speaking, ultrasonic methods have two categories: bulk waves and guided waves. Bulk waves are generally used in NDE applications since it requires point-by-point inspection while guided waves can be used in both NDE and SHM applications because of their long propagation distances.

1.2.1 NDE of adhesive bonds with bulk waves

The application of adhesive bonding to join materials is a promising alternative to bolting and riveting. However, lack of techniques to decisively and nondestructively test the quality of a processed bond hinders wide spread application. Extensive study has been performed to develop methods to test and evaluate the quality of adhesively bonded joints.

Schliekelmann [8, 9] gave an overview of different techniques that can be used in nondestructive tests of adhesive bonds. Use of both through-transmission and pulse-echo techniques were introduced. Chernobelskays et al. [10] employed a very high resolution ultrasonic probe to resolve the reflected waves from each side of an adhesive layer. Biggiero et al. [11, 12] applied high-focusing probes to detect micro-porosity and non-homogeneity of adhesive bonds. Areas with poor bond quality can be nondestructively detected as C-scan images. The C-scan images agreed well with the photos of destructed bonds by showing good contrast between well bonded regions and regions with voids within them. Rokhlin and Marom [13] considered the difference between slip and rigid boundary conditions at the interface of adhesive layer and adherend and proposed to use obliquely incident ultrasonic waves. The amplitude of the reflected ultrasonic wave changed simultaneously with changes of ultrasonic velocity in the adhesive and
thus could be used for monitoring of curing conditions. Guyott and Cawley [14] showed the use of ultrasonic spectroscopy to measure adhesive modulus and thickness. Pilarski and Rose [15] were the first to employ transverse waves having oblique incidences. A numerical model was created to calculate transmission and reflection coefficients for incidences with different incident angles and frequencies. It was found that oblique incidences had better sensitivity to bond conditions than normal incidences and an optimal incident angle and frequency exist. Hanneman et al. [16, 17] studied the transfer function of a time-harmonic wave transmitting through a multi-layer structure. The frequency response could be used as the transfer function and to evaluate the condition of adhesive joints. Cawley and Pialucha [18] utilized oblique incidence as well and studied the effects of different surface preparations on the conditions of bonds. Dickstein et al. [19] studied interfacial condition in composite adhesive joints using feature-based classification. Features were obtained from both time and frequency domain signals. Normal incidence was used for both pulse-echo and through-transmission modes. Moidu et al. [20] applied focused oblique incidence to study the interference pattern in the frequency spectrum. The pattern depended on the relative distance of the transmitter and receiver and shows better sensitivity to the interfacial conditions. Brotherhood et al. [21] studied two distinct types of kissing bond, dry contacting interface and joint with a thin layer of various liquids. Normal incidence of 10 MHz ultrasound was used for both cases. It was found that compressive loading had a significant effect on the reflection coefficient. Furthermore, Brotherhood et al. [22] compared three techniques, normal incidence, oblique incidence using standard ultrasonic transducers and electro-magnetic acoustic transducers. It was suggested that a combination of two or more ultrasonic techniques could enhance the sensitivity for different circumstances. Yan [23, 24] studied the ultrasonic nonlinearity of kissing bonds in adhesive joints. When an ultrasonic wave with high power impinged on a kissing bond, the two interfaces of the kissing bond would either contact or separate and thus generate nonlinear ultrasound.
1.2.2 SHM of composite structures with electromechanical impedance

The electromechanical impedance (EMI) technique usually uses piezoelectric wafer active sensors (PWAS) to study the electromechanical response of the sensor that is bonded to a structure. Giurgiutiu et al. [25] employed PWAS to monitor the disbond between a concrete and fiber reinforced polymer reinforcement. The presence of a disbond severely changed the EMI spectrum. Experiments were also conducted on a concrete beam strengthened with CFRP overlay. Three-point bending fatigue load was applied to the beam and the PWAS was able to detect disbonding before it could be visually seen. Park et al. [26, 27] assessed both degradation of the mechanical/electrical properties of a PZT transducer and the bonding defects between a PZT patch and a host structure. It was observed that the functionality of piezoelectric sensors deteriorated continuously due to the degradation of its bonding and could significantly influence the EMI response.

EMI method is usually sensitive to the defects close to the sensor and thus requires a large number of sensors to cover the whole structure. For this reasons, using EMI for aircraft structure SHM is still challenging.

1.2.3 NDE and SHM of adhesive bonds with guided waves

Besides bulk wave methods, great attention has also been paid to guided wave methods. One benefit of using guided wave methods is that they cover a large volume of the structure with only one measurement and thus guided wave methods outcompete bulk wave methods by considerable time savings.
Rokhlin et al. [28] utilized an interface-wave method for predicting the strength of adhesive bonds. It was observed that phase velocity of the interface wave was related to the strength of the adhesive bonds. Also, Lamb wave interaction with a lap-shear adhesive bond was studied by Rokhlin [29]. Joint quality was determined based on the phase delay and transmission losses of the ultrasonic signals. Mode selection criteria were suggested considering mode conversions at geometry transitions of a lap joint. Rose and Ditri [30] used both pulse-echo and through-transmission Lamb wave to inspect adhesive bond. It was pointed out that the incident angle and frequency should be chosen properly for inspection and a map of the amplitude of transmitted or reflected Lamb wave can serve to locate the disbond regions. Lowe and Cawley [31] carried out theoretical study on the applicability of plate waves and interlayer waves on measurement of properties of adhesive layer and suggested that interlayer waves could be more sensitive to the interlayer itself while Lamb waves are subject to influences from unrelated factors like adherend thickness. To characterize the degradation of the adhesive bond, dispersion curves of Lamb waves for bonds before and after aging were obtained through applying 2D-FFT to time signals received at different locations. Lanza di Scalea [32] excited A0 Lamb wave in a lap-shear adhesive joint to inspect three different bond conditions. Mode conversion at the geometry transition had been studied theoretically and overall transmission coefficient for A0 incidence had been studied experimentally. Matt [33] excited S0 mode with PZT disks bonded to the surface of a composite plate. The composite plate has a spar bonded to it with both poorly cured adhesive and disbanded interfaces. Large sensitivity to the bond conditions was found at mode coupling points where large amount of energy was concentrated at the interlayer.

Puthillath et al. [34] conducted a parametric study on the inspection of a step-lap joint. The effect of adhesive bond geometry, material properties and the presence of a defect on the transmission coefficient of guided wave mode was studied. Kannajosyula et al. [35, 36] studied the interface wave in an isotropic adhesive layer embedded between two half spaces or two plates
with finite thickness. Mode selection criteria for the bond inspection were suggested. Puthillath and Rose [37] proposed a method of mode selection for the inspection of a titanium repair patch bonded to an aluminum aircraft skin. Modes with large in-plane displacement at the interfaces of adhesive layer had better sensitivity. Ren and Lissenden [38] carried out theoretical analysis of wave transmission through a skin-stringer joint and selected modes that were sensitive to disbond. Experiments verified the prediction of both sensitive and insensitive modes. Bostron et al. [39] utilized interface waves traveling along the boundary to inspect the disbond between a stiff material and a soft viscoelastic material. Gardner et al. [40] studied the interface wave between a anisotropic layer and a metallic half space. Philtron et al. [41] demonstrated the mode perturbation method for mode selection. Phased array transducers are used to find optimal excitations with best sensitivity to disbond or penetration power.

To summarize, in the NDE domain, guided waves prove to be effective in detecting disbonds as long as the guided wave modes are well controlled by using proper excitation methods, e.g. angle beam wedges and phased array transducers. However, these transducers are not ready to integrate with an SHM system because of their size and weight. On the other hand, the current actuators for SHM applications do not have the ability to control the modal content of excited waves over a wide frequency bandwidth and sometimes lack the capability to excite the modes that have the best sensitivity to defects. Thus, light weight and small size actuators and sensors with modal control capability will be good enables for aircraft SHM.

1.3 Objectives

The main objective of this work is to develop methodologies for SHM of composite adhesive bonds using ultrasonic guided waves. The idea is to exploit the full potential of ultrasonic guided waves in disbond monitoring by studying the effectiveness of as many modes as
possible in damage detection and characterization. To fulfill such a goal, the following three tasks need to be completed.

1.3.1 Model of wave-defect interaction

To construct guidelines and a theoretical foundation for experiments, a numerical model to study the wave-defect interaction will be created using finite element analysis. The model should provide information on the sensitivity of wave modes and the behavior of wave-defect interaction.

1.3.2 Instrumentation for multimodal excitation and reception in SHM

Good tools are a prerequisite to the successful execution of a job. Transducers that are capable of selectively exciting different guided wave modes are not commercially available for SHM applications. In this work, both actuators and sensors will be designed and fabricated to excite and receive guided waves. The actuator should be able to excite one guided wave mode at one frequency preferentially. The sensor should be able to provide enough information for mode content extraction in post processing. Meanwhile, a DAQ system to meet these requirements will be used.

1.3.3 Experimental verification

Experiments will be conducted by using the newly developed actuators and sensors to verify the predictions from the finite element model and demonstrate the overall performance of the proposed method in detection and characterization of the disbond.
1.4 Overview

The thesis is organized to fulfill the objectives outlined in the last section. A brief description of each chapter is stated below.

Fundamental knowledge of guided wave propagation in multilayer anisotropic plate-like structures is introduced in Chapter 2. Governing equations, boundary conditions and solution methods are also introduced. A sample problem of doing dispersion analysis of a quasi-isotropic CFRP plate is given; dispersion curves and wave structures are calculated as eigenvalues and eigenvectors respectively.

In Chapter 3, an overview of currently used DAQ systems is given as prerequisite knowledge for the experiments carried out in following chapters. Also, to obtain the modal content, the method of post processing is detailed and will be used for all the data processing in following experiments.

Chapter 4 is focused on the design of the actuator for guided wave excitation in a SHM system. The actuator is one of the key components of the hardware of a SHM system. Its performance is verified in experiments.

Another key component of the hardware of a SHM system is the sensor, which is the subject of Chapter 5. PVDF array sensor is designed to fulfill the requirement of modal content extraction and low profile. Also, its capability of suppressing cross talk and extracting wave modal content are both verified in experiments.

In Chapter 6, the concept of using modal content based damage indicators to improve sensitivity is introduced and demonstrated in experiments. Firstly, a finite element model is created to study the behavior of wave-defect interaction. The prediction by finite element analysis provides a good library for mode selection in experiments. Experiments are carried out using the mode selected beforehand and good agreements with predictions are observed. The detection of
disbond under different temperatures and characterization of disbond size are demonstrated experimentally for composite adhesive bonds. Additionally, detection of a notch in aluminum plates and disbond in aluminum adhesive bonds are also demonstrated using modal content based damage indicators.

A summary of the thesis work is given in Chapter 7. The contributions of the work to current SHM system for composite structures are highlighted as well. Directions for future research are also suggested.
Chapter 2

Guided Waves in Multilayer Anisotropic Plate Structures

Guided waves are stress waves that travel along a waveguide, a structure with constant cross-section, while confined by its boundary. The plate structure is one of the most common load-bearing structures used in an aircraft assembly. The plate structure is considered as a waveguide when stress waves are traveling along its in-plane directions and constrained by the two stress-free surfaces. For the simple case that the plate is made of one layer of isotropic material, the guided waves in the plate can be divided into two categories, Lamb waves and shear-horizontal waves [42]. Lamb waves have particle motions only in two directions, out-of-plane and longitudinal in-plane. Shear-horizontal waves have only one direction of particle motion which is the transverse in-plane direction. The characteristics of guided wave propagation can be represented by dispersion curves, which are plots of phase and group velocity verses frequency. Dispersion curves are a function of waveguide geometry and material. For a more general case where the structure is multilayer anisotropic plate, e.g. carbon fiber reinforced polymer, all the guided wave modes usually have particle motions in all the three directions; pure Lamb waves and shear horizontal waves no longer exist. In this section, the fundamental dispersion analysis of guided waves is provided. The plate considered is multilayered and each layer is anisotropic.
2.1 Governing Equations and Boundary Conditions

Guided wave propagation is an eigenvalue problem. To solve the eigenvalue problem for linear elastic solid media, the governing differential equations are the balance of linear momentum, constitutive law and linear strain-displacement relationship:

\[ \tau_{ji,j} + \rho b_i = \rho \ddot{u}_i \]  \hspace{1cm} (1)

\[ \tau_{ij} = C_{ijkl} \varepsilon_{kl} \]  \hspace{1cm} (2)

\[ \varepsilon_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i}) \]  \hspace{1cm} (3)

where \( \rho \), \( u \), \( \varepsilon \), \( \tau \), \( b \), and \( C \) are mass density, displacement, strain, stress, body force, and stiffness, respectively. Indices \( i, j \) and \( k \) are associated with the \( x, y \) and \( z \) Cartesian coordinate system. These governing equations are satisfied within each layer shown in Figure 2-1.

For the top and bottom layers, traction free boundary conditions are applied to their free surfaces; for the interface between two layers, continuity of displacement and stress are satisfied.

\[ \tau_{zi} = 0 \text{ @ free surfaces} \]  \hspace{1cm} (4)

\[
\begin{cases}
  u^j_i = u^{j+1}_i @ interfaces \\
  \tau^j_z = \tau^{j+1}_z @ interfaces
\end{cases}
\]  \hspace{1cm} (5)

where \( i = x, y, z \) indicates coordinate direction, \( j \) is from 1 to \( n - 1 \) indicating the layer number and \( n \) is the total number of layers.
Figure 2-1. Cross-section of a general multilayer anisotropic plate structure with n layers.

2.2 Dispersion Curves and Wave Structures

There are several methods available to solve the eigen problem. Global matrix method and semi-analytical finite element methods both give good precision in solving the eigen problem [42]. In this work, semi-analytical finite element (SAFE) [43] is chosen for all the following analysis because of its accuracy and efficiency.

It is assumed that a plane wave is propagating along the x direction with the assumption that $\frac{\partial}{\partial y} = 0$. Thus, the wave field is a function of $x$, $z$ and $t$, and independent of the $y$ direction.

$$u_i(x, z, t) = U_i(z) \exp(i(kx - \omega t)) \quad (6)$$

where $u_i$ is the displacement field as a function of $t$ and $x$, $U_i$ is the amplitude of the harmonic wave, $k$ is the wave number in the wave propagation direction, $x$ is the coordinate in the wave propagation direction, $\omega$ is the angular frequency and $t$ is the time.
To apply the SAFE method, the plate is discretized along the thickness direction as shown in Figure 2-2. Each physical layer in the multilayer structure may have more than one element; each element has three nodes which makes it a quadratic element. The natural coordinates for the three nodes in the isoperimetric element are shown in Figure 2-2. The corresponding shape functions are

\[
\begin{align*}
N_1 &= \frac{1}{2} (\xi^2 - \xi) \\
N_2 &= (1 - \xi^2) \\
N_3 &= \frac{1}{2} (\xi^2 + \xi)
\end{align*}
\]  

(7)

where \( \xi \) is the local coordinate of an isoparametric finite element. For waves in general anisotropic materials, all the three degrees of freedom are coupled. Each node has displacements in \( x, y \) and \( z \) directions.
Figure 2-2. A sketch showing the plate structure discretized in thickness direction.

Given displacements of three nodes in an element, by substituting Eqn (6), the displacement field in terms of natural coordinate, $\xi$, can be written as follows:
\[\mathbf{u} = \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} = N(\xi)\mathbf{u}_e\]

\[
\begin{bmatrix}
N_1 & 0 & 0 & N_2 & 0 & 0 & N_3 & 0 & 0 \\
0 & N_1 & 0 & 0 & N_2 & 0 & 0 & N_3 & 0 \\
0 & 0 & N_1 & 0 & 0 & N_2 & 0 & 0 & N_3 \\
\end{bmatrix}
\begin{bmatrix}
u_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \nu_6 \\ \nu_7 \\ \nu_8 \\ \nu_9 \\ \nu_{10} \\ \nu_{11} \\ \nu_{12} \\ \nu_{13} \\ \nu_{14} \\ \nu_{15} \\ \nu_{16} \\ \nu_{17} \\ \nu_{18} \\ \nu_{19} \\ \nu_{20} \\ \nu_{21} \\ \nu_{22} \\ \nu_{23} \\ \nu_{24} \\ \nu_{25} \\ \nu_{26} \\ \nu_{27} \\ \nu_{28} \\ \nu_{29} \\ \nu_{30} \\ \nu_{31} \\ \nu_{32} \\ \nu_{33} \\ \nu_{34} \\ \nu_{35} \\ \nu_{36} \\ \nu_{37} \\ \nu_{38} \\ \nu_{39} \\ \nu_{40} \\ \nu_{41} \\ \nu_{42} \\ \nu_{43} \\ \nu_{44} \\ \nu_{45} \\ \nu_{46} \\ \nu_{47} \\ \nu_{48} \\ \nu_{49} \\ \nu_{50} \\ \nu_{51} \\ \nu_{52} \\ \nu_{53} \\ \nu_{54} \\ \nu_{55} \\ \nu_{56} \\ \nu_{57} \\ \nu_{58} \\ \nu_{59} \\ \nu_{60} \\ \nu_{61} \\ \nu_{62} \\ \nu_{63} \\ \nu_{64} \\ \nu_{65} \\ \nu_{66} \\ \nu_{67} \\ \nu_{68} \\ \nu_{69} \\ \nu_{70} \\ \nu_{71} \\ \nu_{72} \\ \nu_{73} \\ \nu_{74} \\ \nu_{75} \\ \nu_{76} \\ \nu_{77} \\ \nu_{78} \\ \nu_{79} \\ \nu_{80} \\ \nu_{81} \\ \nu_{82} \\ \nu_{83} \\ \nu_{84} \\ \nu_{85} \\ \nu_{86} \\ \nu_{87} \\ \nu_{88} \\ \nu_{89} \\ \nu_{90} \\ \nu_{91} \\ \nu_{92} \\ \nu_{93} \\ \nu_{94} \\ \nu_{95} \\ \nu_{96} \\ \nu_{97} \\ \nu_{98} \\ \nu_{99} \\ \nu_{100} \\
\end{bmatrix}\]

\[= N(\xi)\mathbf{u}_e e^{i(kx-\omega t)}\] 

With given linear strain-displacement relationship (3) and (9), dropping the partial derivative respect to \( y \) direction according to the plane wave assumption, the expression of strain can be written as (11).

\[\mathbf{\epsilon} = \left[ L_x \frac{\partial}{\partial x} + L_y \frac{\partial}{\partial y} + L_z \frac{\partial}{\partial z} \right] \mathbf{u} \]

\[(9)\]

\[
L_x = \begin{bmatrix}
1 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1 \\
0 & 1 & 0 \\
\end{bmatrix},
L_y = \begin{bmatrix}
0 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1 \\
1 & 0 & 0 \\
\end{bmatrix},
L_z = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1 \\
0 & 1 & 0 \\
1 & 0 & 0 \\
0 & 0 & 0 \\
\end{bmatrix}\]

\[(10)\]
\[ \mathbf{e} = L_x N_x \mathbf{u}_e + L_x N u_e, x = (b_1 + ik b_2) U_e e^{i(kx - \omega t)} \]  

(11)

The derivative of shape function respect to \( z \), \( N_z \), can be obtained by using Jacobian and its expression is as follows:

\[ N_z = \frac{d\xi}{dz} N_\xi = \frac{1}{J} N_\xi \]  

(12)

\[ J = \frac{dz}{d\xi} = \begin{bmatrix} 1 - \frac{1}{2} & -2\xi & 1 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \]  

(13)

At this point, stress can be easily expressed as a function of node displacements by using (2) and (11). The next step is to construct the governing equation for finite element use. In the finite element method, the theoretical momentum equilibrium equation (1), is not satisfied at every point within the domain but satisfied in an integrated form which is a weak form of the governing equation,

\[ \int_\Gamma \delta \mathbf{u}^T \mathbf{t} d\Gamma = \int_V \delta \mathbf{u}^T (\rho \ddot{\mathbf{u}}) dV + \int_V \delta \mathbf{e}^T \mathbf{C} \mathbf{e} dV \]  

(14)

where the term \( \int_V \delta \mathbf{u}^T (\rho \ddot{\mathbf{u}}) dV \) corresponds to the kinetic energy and \( \int_V \delta \mathbf{e}^T \mathbf{C} \mathbf{e} dV \) corresponds to the strain energy. To obtain the solution for eigenvalue problem, the external force term \( \int_\Gamma \delta \mathbf{u}^T \mathbf{t} d\Gamma \) is assumed to be zero such that the differential equation is homogeneous.

Substitute Eqns (6), (8) and (11), and eliminate the redundant term \( e^{i(kx - \omega t)} \),

\[ \begin{bmatrix} k_{11} + ik(k_{12} - k_{21}) + k^2 k_{22} \end{bmatrix} U_e - \omega^2 m U_e = 0 \]  

(15)

\[ k_{11} = \iiint b_1^T C b_1 dx dy dz = \int_{-1}^{1} b_1^T C b_1 J d\xi \]  

(16)

\[ k_{12} = k_{21}^T = \iiint b_1^T C b_2 dx dy dz = \int_{-1}^{1} b_1^T C b_2 J d\xi \]  

(17)
\[ k_{22} = \iiint b_{\xi}^2 C b_{\xi} dxdydz = \int_{-1}^{1} b_{\xi}^2 C b_{\xi} d\xi \quad (18) \]

\[ m = \iiint N^T \rho N dxdydz = \int_{-1}^{1} N^T \rho N d\xi \quad (19) \]

Eqn (15) is satisfied for each element and thus is valid for the whole domain. The whole domain will produce n set of equations similar to Eqn (15) where n equals the number of elements. These equations can be easily combined by replacing the displacement vector of nodes in one element, \( U_e \), by a displacement vector of all the nodes, \( U \). The combined equation will have the similar form as Eqn (15) but the stiffness matrices, \( k_{11}, k_{12}, k_{12} \), and \( k_{22} \), and mass matrix, \( m \), for all the elements are used to construct the stiffness matrix for the whole domain.

\[(K_{11} + ik(K_{12} - K_{21}) + k^2K_{22})U - \omega^2MU = 0 \quad (20)\]

The \( K_{11}, K_{12}, K_{21} \), and \( K_{22} \) are simply the summation of \( k_{11}, k_{12}, k_{21} \), and \( k_{22} \) of all the elements along the thickness.

Rearrange the above equation

\[(A - kB)\hat{U} = 0 \quad (21)\]

\[A = \begin{bmatrix} 0 & K_{11} - \omega^2M \\ K_{11} - \omega^2M & i(K_{12} - K_{21}) \end{bmatrix} \quad (22)\]

\[B = \begin{bmatrix} K_{11} - \omega^2M & 0 \\ 0 & -K_{22} \end{bmatrix} \quad (23)\]

\[\hat{U} = \begin{bmatrix} U \\ kU \end{bmatrix} \quad (24)\]

For each given angular frequency, \( \omega \), wavenumbers, \( k \), are calculated. Generally, wavenumbers are complex valued. For real valued wavenumbers, the waves are propagating waves; for imaginary valued wavenumbers, the waves are evanescent waves which decay rapidly and will not propagate. Wavenumbers are the eigenvalues and displacement profiles \( U \) are eigenvectors.
The phase velocity can be calculated by $C_p = \frac{\omega}{k}$. The displacement profile in guided wave analysis is usually called wave structure.

### 2.3 Sample Problems

In this section, dispersion curves and selected wave structures for a 16-ply quasi-isotropic carbon fiber reinforced polymer (CFRP) are calculated using the SAFE method. The thickness of the laminate is 3.2mm and the thickness of each ply is 0.2mm. The stacking sequence of the laminate is [0/45/90/-45]$_{s2}$. The material property for 0° ply is listed in Table 2-1. Each ply has one quadratic element and there are totally 16 elements through the thickness.

<table>
<thead>
<tr>
<th>E1</th>
<th>E2</th>
<th>E3</th>
<th>G12</th>
<th>G23</th>
<th>G13</th>
<th>v12</th>
<th>v13</th>
<th>v23</th>
<th>ρ</th>
</tr>
</thead>
<tbody>
<tr>
<td>135GPa</td>
<td>9.5GPa</td>
<td>9.5GPa</td>
<td>4.9GPa</td>
<td>4.9GPa</td>
<td>4.9GPa</td>
<td>0.3</td>
<td>0.3</td>
<td>0.45</td>
<td>1580kg/m$^3$</td>
</tr>
</tbody>
</table>

The dispersion curves of the laminate are shown in Figure 2-3 (a) & (b) as phase velocity and group velocity dispersion curves. Here the mode is not labeled as antisymmetric and symmetric modes as usually used for Lamb waves in isotropic materials. The reason is, as stated in the beginning of this chapter, that all three displacement components are coupled for anisotropic materials and there is no pure Lamb waves. Wave structures for mode 1 and mode 3 at 390 kHz are shown in Figure 2-3 (c) & (d). The two wave structures show that wave structure for different modes at the same frequency could have totally different vibrating patterns indicating that they will have different interactions with defects. The difference in wave-defect interaction will result in different sensitivity to a particular defect. To explore the full potential of defect detection and increase the reliability of defect detection, it is preferable to be able to excite all these mode-frequency combinations rather than rely on just one.
Figure 2-3. CFRP Phase velocity (a), group velocity (b) dispersion curves and wave structures for mode 1 (c) and mode 3 (d) at 390 kHz. The numbers in (a) and (b) indicate the mode number.
Chapter 3
Phased Array DAQ System and Modal Content Extraction

3.1 Phased array DAQ system

A 16-channel phased array DAQ system is developed to conduct all experiments in the following chapters.

3.1.1 Hardware

The phased array DAQ system is mainly composed of a 16-channel Pulser/Receiver card (PHA-16T by US Ultratek), a 16-channel A/D converter card (PCIAD1650 by US Ultratek), a 7-slot Magma box which carries two Ultratek cards mentioned above, and a computer which is connected to the Magma box to control the two cards. The two Ultratek cards both require PCI slots to operate. However, PCI slots are not popular nowadays and most desktop computer has only one or two PCI slots. This limited the capability to upgrade the system with more channels. A Magma box is a PCI-extension box which will use one PCI slot of the computer and provide 7 extension slots. It functions just like the computer itself has 7 PCI slots. The system has the capability to fire 16 channels simultaneously and collect data in either pulse-echo or through-transmission mode simultaneously as well. The maximum peak-to-peak voltage is 350V and a toneburst with up to 16 cycles as square waves can be excited in each channel. Time delay and frequency can be controlled independently on each channel but the voltage cannot. In this thesis, all the mode control is done through time delay control.
3.1.2 Software

The US Ultratek provides software development kits in both C++ and Labview languages. Considering the ease of visualization as well as future modification and upgrades, Labview is chosen as the platform to develop the program. The author looked at a similar program developed by Jason Bostron [44] for an 8-channel phased array DAQ system. However, the previous program has control parameters such as voltage, frequency, on/off etc. as independent variables for all the 8 channels. This may work fine for an 8-channel system but it would be difficult to manage so many parameters for a 16-channel system. Also, it induces difficulties for future upgrades. The author changed the data structure of the all the variables such that the system will detect the number of channels on the card in initialization step and create an array of size of number of channels for each control parameters. The program will adapt to cards with either 8 or 16 channel automatically. Only minor changes are needed for the front panel.

Since the major application of the DAQ system, Phased Array Software for Ultrasonic Guided Waves (PSUGW), is for guided wave research, the function of the program is tailored to focus more on the frequency and modal content of multi-channel-received signals. The program could show the time signal, Hilbert transform, Fourier Transform, short time Fourier transform, 2D Fourier transform and short time 2D Fourier transform in real time. The real time 2D Fourier transform is a useful tool in experiments because it resolves mode content of the wave package with multiple modes in real time.

A screenshot of the main user interface of the PSUGW program is shown in Figure 3-1. The waveforms of the 16 channels are displayed with different colors. Box A controls which channel is currently displayed on the waveform graph. Box B provides control of each pulsor channel by specify frequency, time delay and the on/off status. Box C shows all hardware A/D settings such as hardware filter and sampling rate and Box D provides a control of the software
filter (digital filter). The digital filter is set to be a band pass filter. Box E is also a control of the pulsor channels. It is different from Box B in that the parameters shown in Box E are global parameter which is the same for every channel. It should be noted that the frequency, pulse delay and channel on/off could also be controlled both Boxes B and E. When a parameter is changed in Box B which is a single-channel control, the corresponding parameter in box E will be disabled (turn to grey color) and cannot be changed until the “All_Ch_Ctrl” button (above Box E) is reset. This guarantees the synchronism on the control panel.

Figure 3-1. The screenshot of the main user interface of the PSUGW program showing multi-channel time signals.
A useful feature of the software is it provides real-time 2D Fourier Transform results as shown in Figure 3-2. The spectra are displayed as an intensity plot in the frequency-phase-velocity domain, which can be compared with phase velocity dispersion curves easily. This helps one identify the modal content in received signals without waiting until the post processing step and the modal information is a valuable feedback during the experiment because it makes the interpretation of the signal more straightforward.
3.2 Modal content extraction

There are several ways to check the mode content. One widely used method is to apply the 2D Fourier transform to the time signal received along a line of locations with constant intervals. The 2D Fourier transform was originally used to extract guided wave mode information by Alleyne and Cawley [45].

Assume there are N locations and at each location, M time samples are received. All the received signals can be put into an M*N matrix such that each column is the received signal from one location. The received signal matrix is named $f(m, n)$, where $0 \leq m \leq M - 1$ and $0 \leq n \leq N - 1$. The 2D discrete Fourier transform of $f(x, y)$ is

$$F(\omega, k) = \frac{1}{\sqrt{MN}} \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} f(m, n)e^{-i2\pi\left(\frac{m\omega}{M} + \frac{nk}{N}\right)}$$

which gives the spectrum in the frequency and wavenumber domain. The phase velocity is obtained from the well-known relation, $C_p = \omega/k$.

The 2D fast Fourier Transform will be used for all the experiments demonstrated in the following chapters.
Chapter 4

Phased Array Transducer for Guided Wave Excitation in Structural Health Monitoring*

Phased array ultrasonic transducers are widely used in medical imaging and nondestructive evaluation (NDE). For both medical and industrial applications, the structure of the transducer and method for inspection are similar. A phased array transducer (PAT) is a probe with multiple active elements integrated in it. Each element can be excited independently with a computer controlled time delay or phase delay. By applying different delays to different elements, the transducer can send a wave beam in a predefined direction and focus at a particular distance. Since the probe does not need to be moved manually and all the focusing and sweeping are controlled electronically by the computer, the inspection speed of PAT is much faster than a single element transducer which needs to be moved manually from one point to the other.

Beam steering and focusing methods are originally developed for inspection of bulk structure whose dimensions are considered much larger than the wave length, and can be migrated to inspect a plate structure. The only difference is the wave used for plate structures is an ultrasonic guided wave rather than ultrasonic bulk wave. Bulk waves are non-dispersive, thus the wave speed is independent of frequency. The width of the pulse will keep constant no matter how long it travels. However, most guided waves are dispersive. The width of the excited pulse will spread when propagating and cause difficulties in focusing and steering. As a result, only a few low dispersive guided wave modes are useful for beam forming on plate structure.

* Portions of this chapter are based substantially on B. Ren and C.J. Lissenden, Phased Array Transducers for Ultrasonic Guided Wave Mode Control and Identification for Aircraft Structural Health Monitoring, Materials Evaluation, In press
Besides beam forming, a PAT can also be used to control the excitation of guided wave modes [46]. With a proper control of the excited waves, one mode could be preferentially excited and thus maximize the sensitivity to defects. This section is focused on the design, fabrication and testing of a PAT for preferential mode excitation in SHM applications.

### 4.1 PAT for Guided Wave Excitation

In Chapter 2, the theoretical analysis of guided waves is based on the assumption the wave is an infinite plane wave with particular phase velocity and frequency. But in reality, a finite-size transducer will excite multiple modes. The effect of the transducer configuration on its excitation of guided waves is referred as the source influence [42]. A detailed analysis of the source influence for comb PAT is given by Borigo et al [47] and Kannajosyula [48].

![Diagram](image)

**Figure 4-1.** Piston-type loading profile of a linear PAT with element width $w$ and spacing $s$.

For a PAT coupled to the structure by a thin layer of water or gel couplant, the loading exerted on the structure surface by one active element can be simplified as a piston-type loading. Assume the width of the element is $w=2a$, a rectangular function with unit value between $-a$ and $a$ can represent the piston-type loading:

$$
\Pi_a(x) = \begin{cases} 
1, & -a \leq x \leq a \\
0, & x < -a \text{ or } x > a 
\end{cases}
$$

(26)

The spatial loading function for a linear PAT can be expressed as
where \( w \) is the width of each element, \( N \) is the number of elements and \( s \) is the spacing between center lines of two adjacent elements as shown in Figure 4-1. Then, the spatial spectrum function is obtained by taking the Fourier transform of the spatial loading function \( f_c \) \[47\],

\[
F_c(k) = \frac{w}{\sqrt{2\pi}} \sum_{n=0}^{N-1} \text{sinc} \left( \frac{k w}{2} \right) e^{i k n s} \tag{28}
\]

where \( k \) is the wave number. \( F_c \) actually represents the wavenumber spectrum of guided waves excited by a comb array transducer where all active elements are excited simultaneously without time delays. If a linear time delay, i.e., \( n \Delta t \), is applied to \( n \)th element in the PAT, the spatial spectrum becomes a function of \( k \), \( \omega \) and \( \Delta t \).

\[
F_c(k, \omega, \Delta t) = \frac{w}{\sqrt{2\pi}} \sum_{n=0}^{N-1} \text{sinc} \left( \frac{k w}{2} \right) e^{i n (ks - \omega \Delta t)} \tag{29}
\]

where \( \omega \) is the angular frequency of the time signal. By choosing a proper \( \Delta t \) for a particular \( \omega \), the spectrum function \( F_c \) can be changed and thus chosen to excite a wavenumber preferentially. To determine \( \Delta t \) for a particular phase velocity \( C_p \), the following equation is used,

\[
\Delta t = s / C_p \tag{30}
\]

Besides the wavenumber spectrum, another important component of the source influence is the frequency content, \( Y(\omega) \), of the input time signal. The resultant excitation spectrum \( E(k, \omega, \Delta t) \) is \[42\]

\[
E(k, \omega, \Delta t) = F_c(k, \omega, \Delta t) * Y(\omega) \tag{31}
\]

By calculating \( E \) for all the \((k, \omega, \Delta t)\) combinations, the excitation spectrum for a PAT with spacing \( s \) and time delay \( \Delta t \) can be predicted.
4.2 PAT Design for SHM

As stated in Chapter 2, each point on a dispersion curve is a propagating mode with a unique wave structure that provides this mode-frequency combination with its own excitability/receivability and defect sensitivity characteristics. To examine all of these points for effective SHM, it is desirable to have a transducer that can excite as many points as possible. Thus, in this section the design variables of the PAT are described. The materials for the active elements, the geometry configuration and the assembly method will be discussed below.

4.2.1 Material selection

There are several ways to increase the frequency bandwidth of the transducer: (1) use a backing material, (2) use a matching layer, and (3) minimize the acoustic impedance mismatch between the transducer and the structure. Adding backing and matching materials would considerably increase the weight and size of the transducer, which is not desirable for aircraft SHM. So the design of the transducer will focus on minimizing the acoustic impedance mismatch. The acoustic impedances for a longitudinal wave propagating in the thickness direction of a CFRP and aluminum (and steel) plate are 4.37 MRayls and 17 MRayls respectively. The acoustic impedance of commonly used piezoceramics is relatively high. For example, PZT-5A has the acoustic impedance of 33 MRayls. So piezoceramic elements match poorly with CFRP or aluminum. In order to decrease the acoustic impedance of the active element, PZT-5A piezoelectric fiber composites (PFC) with a 35% fiber volume fraction are used. Its acoustic impedance is about 11-12 MRayls which is much closer to that of CFRP and aluminum. The frequency bandwidth information provided by the manufacturer, Smart Materials Corp., is shown in Figure 4-2. It is observed that the load impedance, electrical impedance of the piezoelectric
element, is greater than 1000 ohms for the whole frequency range shown in Figure 4-2 which is much larger than the source impedance of the pulsor system which is 50 ohms. The smaller the mismatch between the source impedance and load impedance, the higher the power is delivered to the piezoelectric element. Thus, the two valleys shown in Figure 4-2 correspond to the two resonance frequencies of the piezoelectric element.

![Figure 4-2. Measured impedance and phase spectra for one PFC element.](image)

The material properties of PZT-5A and the epoxy in the piezoelectric fiber composite are shown in Table 4-1 and Table 4-2, where $s$ is the compliance, $d$ is the piezoelectric coupling coefficient and $\varepsilon$ is the relative permittivity. The superscripts of $s_E$ and the subscripts of $d$ and $\varepsilon$ define the three directions in material coordinate system which are shown in Figure 4-4(a).

**Table 4-1. The material properties of PZT-5A**

The mechanical properties of PZT-5A (unit: $10^{-12}$ Pa$^{-1}$)

<table>
<thead>
<tr>
<th>$s_{E11}$</th>
<th>$s_{E12}$</th>
<th>$s_{E13}$</th>
<th>$s_{E22}$</th>
<th>$s_{E23}$</th>
<th>$s_{E33}$</th>
<th>$s_{E44}$</th>
<th>$s_{E55}$</th>
<th>$s_{E66}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.4</td>
<td>-5.74</td>
<td>-7.22</td>
<td>16.4</td>
<td>-7.22</td>
<td>18.8</td>
<td>47.5</td>
<td>47.5</td>
<td>44.3</td>
</tr>
</tbody>
</table>
The piezoelectric coupling coefficients of PZT-5A (unit: $10^{-12}$ CN$^{-1}$)

<table>
<thead>
<tr>
<th>$d_{31}$</th>
<th>$d_{32}$</th>
<th>$d_{33}$</th>
<th>$d_{24}$</th>
<th>$d_{15}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-171</td>
<td>-171</td>
<td>374</td>
<td>584</td>
<td>584</td>
</tr>
</tbody>
</table>

The relative permittivities and mass density of PZT-5A

<table>
<thead>
<tr>
<th>$\varepsilon_{11}$</th>
<th>$\varepsilon_{22}$</th>
<th>$\varepsilon_{33}$</th>
<th>$\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1730</td>
<td>1730</td>
<td>1700</td>
<td>7750kg/m$^3$</td>
</tr>
</tbody>
</table>

Table 4-2. The material properties of the epoxy in the piezoelectric fiber composite

<table>
<thead>
<tr>
<th>E</th>
<th>$\nu$</th>
<th>$\rho$</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.9GPa</td>
<td>0.36</td>
<td>1170kg/m$^3$</td>
<td>8.9</td>
</tr>
</tbody>
</table>

To determine the effective material properties of the piezoelectric fiber composite, the micromechanical generalized method of cell method [49] is employed. The overall material properties of the 35% PZT5A piezoelectric fiber composite are shown in Table 4-3.

Table 4-3. The material properties of the piezoelectric fiber composite

The mechanical properties of PFC (unit: $10^{-12}$ Pa$^{-1}$)

<table>
<thead>
<tr>
<th>$s_{E}^{11}$</th>
<th>$s_{E}^{12}$</th>
<th>$s_{E}^{13}$</th>
<th>$s_{E}^{22}$</th>
<th>$s_{E}^{23}$</th>
<th>$s_{E}^{33}$</th>
<th>$s_{E}^{44}$</th>
<th>$s_{E}^{55}$</th>
<th>$s_{E}^{66}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>317</td>
<td>-198</td>
<td>-20</td>
<td>317</td>
<td>-20</td>
<td>51</td>
<td>1032</td>
<td>1032</td>
<td>1031</td>
</tr>
</tbody>
</table>

The piezoelectric coupling coefficients of PFC (unit: $10^{-12}$ CN$^{-1}$)

<table>
<thead>
<tr>
<th>$d_{31}$</th>
<th>$d_{32}$</th>
<th>$d_{33}$</th>
<th>$d_{24}$</th>
<th>$d_{15}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-148</td>
<td>-148</td>
<td>352</td>
<td>204</td>
<td>204</td>
</tr>
</tbody>
</table>

The relative permittivities and mass density of PFC

<table>
<thead>
<tr>
<th>$\varepsilon_{11}$</th>
<th>$\varepsilon_{22}$</th>
<th>$\varepsilon_{33}$</th>
<th>$\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>611</td>
<td>611</td>
<td>583</td>
<td>7750kg/m$^3$</td>
</tr>
</tbody>
</table>
4.2.2 Spacing

According to the spectrum analysis by Borigo [50], PATs usually cannot excite wave modes with a wavelength much smaller than the PAT element spacing. However, they can excite wavelengths larger than its spacing. From this point of view, the smaller the spacing, the more values of wavenumber can be covered by the PAT. However, smaller spacing requires narrower element widths of the PFC element. A PFC element with too small a width will no longer vibrate like a plate structure due to the change of aspect ratio. To take a balance, the spacing is selected to be 4mm and the element width is 2mm.

4.2.3 Fabrication

To fabricate the PFC PAT, a printed circuit board (PCB), shown in Figure 4-3, is designed such that the electrodes on the PCB have the same element width and spacing as the PFC elements as shown in Figure 4-3(b). Then, the PCB and PFC elements are bonded by a layer of double-sided z-axis conductive tape (3M-9707). Since the tape is only conductive in the thickness direction, the PFC element will only be electronically connected to the electrode that faces directly to it. A holder made of plexiglass is used to hold the PFC elements with constant spacing during the bonding, Figure 4-4(a). Finally, a copper foil is bonded to the other surfaces of the PFC elements to make a ground as shown in Figure 4-4(b). There are some alternative ways to make a ground such that the PAT can be easily and permanently bonded to a structure, like using lead wires or small pieces of conductive tape. If the structure to be bonded is metal, no ground layer is needed because the structure itself can function as the ground. However, since the PAT will be used for different experimental setups, another layer of kapton tape is bonded outside the copper foil as a protection from wearing.
Figure 4-3. Photos of the PCB designed for an 8 channel PAT. (a) top layer. (b) bottom layer.

Figure 4-4. (a) An incomplete assembly of the PFC PAT showing the PFC elements arranged as a linear array. (b) A complete assembly of the PFC PAT.

4.3 Electrical impedance matching

It has been shown in Section 4.2.1 that a piezoelectric fiber composite element has electric impedance that is much larger than the source impedance, which could result in low
power delivery from the source to the load. A common circuit of a pulsor system connected to a transducer is shown in Figure 4-5. The average power dissipated in the load can be defined using the following equation,

\[
P_L = \frac{1}{2} \frac{R_L}{(|Z_S + Z_L|)^2} |V_S|^2 \tag{32}
\]

where \(P_L\) is the power delivered to the load, \(R_L\) is the resistance of the load, real part of the complex impedance, \(Z_S\) and \(Z_L\) are the impedance of source and load respectively, and \(V_S\) is the voltage of the source. \(P_L\) will reach the maximum value only when \(Z_S = Z_L^*\) such that the load impedance is the complex conjugate of the source impedance which is 50 ohms in this case.

Figure 4-5. A sketch of the circuit of a pulsor system connected to a transducer.

In SHM applications, it is desirable to increase the power of the wave excited by the actuator such that a larger volume of the structure could be covered. To satisfy the equation, \(Z_S = Z_L^*\), an electrical impedance matching (EIM) network is needed between the \(Z_S\) and \(Z_L\) such that the effective impedance of EIM combined with \(Z_L\) is 50 ohms [51]. Usually, an EIM network has shunt and series inductors and capacitors and their impedance depend on the frequency. Thus, it is impossible to match the load impedance to the source impedance for every frequency.
The design of an EIM network is essentially to determine the EIM circuit and then optimize the values of inductors and capacitors. To achieve a broadband impedance matching, An et al. [52] showed that a genetic algorithm can be used to optimize the value of inductors and capacitors. Huang et al. [51] modeled the transducer with an equivalent circuit and designed the EIM using the Smith Chart.

Figure 4-6. A sketch of the circuit shows the design parameters of the initial guess.

In this work, an EIM network is first designed to match the impedance at one arbitrary frequency, 0.4 MHz for this design, to the source using the Smith Chart. It should be noted that the design parameter of such an EIM is not unique. Usually, the total number of capacitors and inductors depends on the quality factor, Q, specified by the designer. The quality factor is the ratio of a resonator’s center frequency over its frequency bandwidth [53]. For this case, since a broad bandwidth is needed, the quality factor is controlled to be smaller than 2. This results in an initial guess of the design parameters shown in Figure 4-6. The EIM network has 3 series inductors and 3 shunt capacitors designed as a T-network. Such a network is also a lowpass filter [54]. Then the design parameters are optimized using the optimization toolbox in MATLAB 2013b. The objective is to minimize the mean value of absolute value of reflection coefficients over the frequency range of 0.2 MHz to 0.7 MHz. The reflection coefficient is defined as
\[
\Gamma = \frac{Z_S - Z_L}{Z_S + Z_L}
\]  

(33)

where \( \Gamma \) is the reflection coefficient. The optimized values calculated using MATLAB are shown in Figure 4-7(a). However, these values are not readily available in the market. For the actual fabrication, the values shown in Figure 4-7(b) are used.

![Circuit Diagrams](image)

Figure 4-7. Circuits show the design parameters of the EIM networks for (a) optimization using MATLAB and (b) actual values for fabrication.

The EIM network is fabricated using printed circuit board and surface mount devices. Since there are 8 channels in the PAT, 8 identical EIM networks are fabricated on the printed circuit board. The inductors are from CoilCraft, Inc. and the capacitors are from Johanson Dielectrics.
An experiment is carried to test the performance of the EIM network. Two PFC PATs are used as the actuator and the receiver to excite and receive mode 1, 3 and 5 on the 3.2mm CFRP plates. The time signals are first recorded for no-EIM-network case and another set of time signals are recorded with the EIM network connected between the DAQ system and the actuator. It is observed that the amplitude of time signal increases significantly when the EIM network is connected. Figure 4-9 shows the maximum amplitudes in the time signals from 4 channels of the PAT receiver. The amplitudes are plotted versus the frequency of excitation. With the EIM network connected, the amplitudes are roughly more than 5 times stronger than those without EIM network.
Figure 4-9. The comparisons of maximum amplitudes in time signals received in 4 channels of the PATs with (solid line) and without (dash line) the EIM network. Excitation of (a) Mode 1, (b) Mode 3 and (c) Mode 5 on the 3.2mm CFRP plate are shown.
Figure 4-10 shows the power gain plots for 4 channels. The power of a time signal is defined as

\[ P = \sum (s[n])^2 \]  

(34)

where \( P \) is the power of a time signal and \( s[n] \) is the discrete time signal. The power gain is defined as

\[ \text{Power gain} = 10 \log_{10} \frac{P_2}{P_1} \]  

(35)

where \( P_2 \) is the power of a time signal for with-EIM case and \( P_1 \) is the one for without-EIM case.

It is observed that the average power gain is 15 dB which is about 30 times in power. This is a significant improvement and verifies the excellent performance of EIM network in maximizing the power delivered from the DAQ system to the actuator. It should be noted that with the help of EIM network, the usable frequency bandwidth is increased from 0.2-0.6 MHz to 0.2-0.7 MHz. Additionally, since the EIM network is also a lowpass filter, the excitation pulse transforms from square waves to sine waves because the high frequency components are filtered out.
Figure 4-10. The comparisons of power gain after using the EIM network. Excitation of (a) Mode 1, (b) Mode 3 and (c) Mode 5 on the 3.2mm CFRP plate are shown.
4.4 Preferential mode excitation

Single mode excitation is important for successful monitoring because the mode with best sensitivity to the defects should be excited preferentially. The FPC PAT is used to excite guided wave modes in both a 5 mm aluminum plate and the 3.2mm AS4/8552 CFRP plate introduced in Section 2.3. For aircraft structures, aluminum plates with thinner thickness, e.g. 2mm, are more commonly used. A 5mm aluminum plate is chosen here mainly to demonstrate operation when more modes are present, which is the case for thicker plates. These two materials are chosen simply because they are widely used in aircraft structures. The material properties for aluminum are in Table 4-4. Using these material properties, the dispersion curves for the aluminum and CFRP plates can be computed.

Two 8-element PFC PATs are used as transmitter and receiver. The time delays are calculated using equation (30). In the experiment, a tone burst with the calculated time delay is fired into each PFC element. Gel couplant is used to couple the wave from the transducer to the plate. Two PATs are separated by 70mm from center to center. The gel couplant is used for the convenience of reusing the PATs but the PATs can be bonded to the substrate if necessary which is usually the case for SHM applications.

Table 4-4. The material properties of aluminum alloy

<table>
<thead>
<tr>
<th>E</th>
<th>v</th>
<th>ρ</th>
</tr>
</thead>
<tbody>
<tr>
<td>70GPa</td>
<td>0.34</td>
<td>2700kg/m³</td>
</tr>
</tbody>
</table>

The PFC elements are manufactured to have a center frequency of 0.5 MHz. By actually doing the guided wave excitation test, the transducer works reasonably well between 0.2 and 0.6 MHz. It does not mean the bandwidth of the PFC element is from 0.2 to 0.6 MHz. But the
excitations of the PFC elements are powerful enough to effectively excite guided waves in this frequency range. Thus, guided wave modes that exist in this range have been chosen for preferential excitation. This could be explained by the impedance plot in Figure 4-2 where two peaks exist around 0.5 MHz and give a relatively wider working frequency range than just one peak.

Figure 4-11 and Figure 4-12 compare the predicted excitation spectra and the experimentally measured spectra for the aluminum and CFRP plates respectively. The intensity in each plot is normalized by the maximum value on this plot, thus the intensity range for every plot is from 0 to 1. A 16 cycle tone burst is excited to make sure the time signal has narrow frequency bandwidth. For the aluminum plate it should be noted that modes 2 and 4 are shear horizontal modes, which are not excitable with this type of transducer because they have particle motion only in the y-direction (see Figure 2-1).

For the CFRP plate, notice that there are 6 modes in the frequency range from 0.2-0.6 MHz. However, the wave structures of modes 2 and 4 have dominant displacement components in the y-direction and very small components in the x- and z-directions indicating that these modes are very difficult to excite with piston-like transducers. Thus, for this experiment only modes 1, 3 and 5 are tested for preferential mode-frequency excitation.
Figure 4-11: Comparison between predicted (a, b and c) and measured (d, e and f) excitation fields for modes 1, 3 and 5 at 0.39 MHz, 0.39 MHz and 0.54 MHz respectively for 5-mm aluminum plate. Red arrows indicate the target excitation regions. The intensity in each plot is normalized by the maximum value on this plot.
Figure 4-12: Comparison between predicted (a, b and c) and measured (d, e and f) excitation fields overlaid on dispersion curves of modes 1, 3 and 5 at 0.39 MHz, 0.39 MHz and 0.54 MHz respectively for 3.2 mm thick CFRP plate with a layup sequence of [0/45/90/-45]_{s2}. The intensity in each plot is normalized by the maximum value on this plot.
Figure 4-11, for the 5mm aluminum plate, shows modes 1, 3, and 5 being excited at 0.39, 0.39, and 0.54 MHz overlaid on the dispersion curves. (a), (b) and (c) show the spectra predicted by Eqn (30), while (d), (e) and (f) show the measured spectra computed from Eqn (25). For modes 1 and 3, even though the excitation frequencies are the same, the spectra are quite different due to the time delays applied to the transmitter elements. All the measured spectra agree very well with the predicted spectra. The results demonstrate the ability of the PAT to preferentially excite one guided wave mode at a particular frequency.

Similarly Figure 4-12, for the CFRP plate, shows modes 1, 3, and 5 being excited at 0.39, 0.39, and 0.54 MHz. The predicted and measured spectra agree well for each of the three mode-frequency combinations. The modes 2 and 4 here are not pure shear horizontal modes because they still have components in x and z direction. However, the dominant displacements of modes 2 and 4 are in y direction, which is similar to that for aluminum plate. So modes 2 and 4 will not be excited even though the excitation spectra show high intensity on them. The excitation for mode 5 at 0.54 MHz also includes mode 6 because it is in close proximity to mode 5 at 0.54 MHz. It is not possible to tell from Figure 4-12 which mode gets excited, but if a sufficiently long propagation distance is used then the issue can be resolved by examining the group velocity.

In summary, this experiment shows the capability of the PAT to preferentially excite a preselected single mode for both aluminum and CFRP plates. The PAT receiver also has the ability to identify which modes are propagating. Thus, one PAT can be used to preferentially excite a wave mode that has been selected to interact with a defect in such a way that the interaction clearly identifies the defect. Furthermore, different time delays can be applied to preferentially excite different modes with the same PAT.
4.5 Dispersion curve scanning

Being able to inspect structures with unknown material properties is a valuable solution when: (1) the material properties are not known to a sufficient degree or (2) are not what they were expected to be. Scanning a subdomain of the dispersion curve space is a valuable solution in such a circumstance. To verify this idea, a single dispersion curve is scanned to provide a baseline; then blindly scanning a subdomain of the dispersion curve space is performed.

4.5.1 Single mode scanning

Before scanning all the dispersion curves in the subdomain of 0.2 to 0.6 MHz, a single mode scanning is performed to demonstrate how a dispersion curve can be scanned out by exciting a series points on the curve. In this experiment, with the pre-knowledge of the dispersion curves of the 5mm aluminum and 3.2mm CFRP plates. Different time delays are applied to the PAT to excite mode 1 over a range of frequencies. The central frequency of a 16 cycle tone burst excitation is incremented by 10kHz to enable the PAT to scan frequencies from 0.2-0.6 MHz. The received signals are processed using 2DFFT to obtain the spectrum and summed over all of the scans.

The results for mode 1 scanning are shown in Figure 4-13 for both aluminum and CFRP plates. For the case of aluminum, the measured spectrum agrees with the mode 1 dispersion curve very well. However, for the CFRP plate, only the range of 0.2-0.4 MHz agrees with the theoretical dispersion curve very well. For the 0.4-0.6 MHz range, modes 5 and 6 were excited instead of mode. This issue can be explained by regarding the excitation and reception of modes with wavelengths smaller than the PAT element spacing. The PAT has a spacing of 4 mm, which is smaller than the wave length of mode 1 under 0.6 MHz. It should be noted that a PAT can
effectively excite the modes with wavelengths that are larger than the spacing of the PAT; but when trying to excite a wave mode with a wavelength much smaller than the spacing of the PAT, unintended modes with much larger wavelengths are often also excited. Further details are provided by Borigo [50].

Figure 4-13: Excitation spectra for scanned mode 1 for (a) a 5mm thick aluminum and (b) a 3.2mm thick CFRP plate. The intensity in each plot is normalized by the maximum value on this plot. The frequency sweeping is carried out from 0.2 to 0.6 MHz; thus the intensity plot has nonzero values in this range.
4.5.2 Subdomain scanning

Blindly scanning a subdomain of the dispersion curve space is the next step. Without a priori knowledge of where the dispersion curves are located, the scan is performed over a grid from 0.2 to 0.6 MHz in 10 kHz frequency increments and from 1 to 10 mm/μs in 1 mm/μs phase velocity increments. The scanned points are shown in Figure 4-14. Again, scanned spectra are produced by summing the spectra obtained from exciting each grid point mentioned above for the aluminum and CFRP plates. For the aluminum plate, modes 1, 3 and 5 are primarily excited; these three modes are all Lamb modes whose particle displacement matches well with the vibrating directions of wave excitation by piezoelectric elements. Modes 2 and 4 are not actually being excited due to their particle displacements being predominantly in the y-direction. For CFRP plate, the mode 1 is still problematic at high frequency due to the same reason stated in Section 4.4.1 that the element spacing is too large. Mode 3 is excited well at 0.3-0.4 MHz frequency range but very weakly in the 0.2-0.3 MHz range. For 0.4-0.6 MHz in CFRP plate, modes 5 and 6 are preferentially excited even though it is hard to differentiate one from the other. The reason that mode 3, for both plates, are not excited quite well could be the dominated $u_x$ and lacking in the $u_z$ displacement in wave structures of mode 3 while the PAT more effectively excites $u_z$. The wavestructures for mode 3 at 0.2 MHz in aluminum and CFRP plates are shown in Figure 4-16. The strong in-plane polarization of mode 3 makes it challenging for PFC elements with poling in the thickness direction to excite these modes effectively. Similarly, mode 5 is not efficiently excited below 0.5 MHz because the displacement $u_z$ at top surface is too small.
Figure 4.14: Scanned points on the subdomain of dispersion curve plots for the (a) aluminum plate and (b) CFRP plate.

Figure 4.15: A comparison between theoretically predicted and blindly scanned dispersion curves for the (a) aluminum plate and (b) CFRP plate.
4.6 Discussion and conclusion

Dispersion curve scanning capability could be a useful tool when dealing with materials having unknown properties. Usually, we know something about the structure to be inspected. For example, if dealing with CFRP, we may know if the layup is uni-direction, cross-ply or quasi-
isotropic. For such a case, the general shapes of the dispersion curves are known and scanning the phase velocity-frequency space provides key values that enable estimation of material properties. Therefore, the wave structure for a mode at a particular frequency can be estimated. For rare situations where no information about the structure is available, scanning is still valuable because it enables maximization of the mode excitability.

The dispersion curves of a CFRP laminate can be affected by the total thickness, the material properties of each lamina, the layup sequence of the laminate and the wave propagation direction. The influence of the wave propagation direction is studied here for different layup sequences, which are [0/45/90/-45]_{32}, [0/90]_{45} and [0]_{16}. Figure 4-18 shows the dispersion curves for four different propagation directions: 0, 45, 90, and -45 degrees. It is observed that for this quasi-isotropic CFRP laminate, the propagation direction does not affect the dispersion curves of lower order, i.e. mode 1 to 6 and at the low frequency range, below 0.6 MHz. When it comes to the high frequency range, above 0.6 MHz, the difference in propagation direction has a more significant effect on the dispersion curves. Figure 4-19 and Figure 4-20 show the dispersion curves of different wave propagation directions for a cross-ply, [0/90]_{45} and uni-directional, [0]_{16} laminate. These two layup sequences are not quasi-isotropic and thus are more anisotropic, so that the dispersion curves are much more direction-dependent. It is observed that the dispersion curves for the whole frequency range are highly dependent on the wave propagation direction, which is a result of highly anisotropic laminate. These results indicate that when dealing with a laminate with anisotropic material property, the dispersion curve needs to be swept out first to determine the optimal excitation of a guided wave mode and the PAT introduced in this chapter can be used to determine the actual dispersion curves of a laminate for a specified wave propagation direction.
Figure 4-18: Dispersion curves of waves propagating on a 16-ply quasi-isotropic CFRP laminate ([0/45/90/-45]_{s2}) with four different propagation directions: 0°, 45°, 90° and -45°.
Figure 4-19: Dispersion curves of waves propagating on a 16-ply cross-ply CFRP laminate ([0/90]_{4s}) with four different propagation directions: 0°, 45°, 90° and -45°.
In this chapter, a phased array transducer for structural health monitoring (SHM) has been designed, fabricated and tested experimentally. It has a low profile making it suitable for aircraft SHM applications. The experimental results show that the transducer can successfully excite a predominant single mode in aluminum plates and composite laminates. The preferential mode excitation isolates the interaction between the defect and one dominant mode, and thus helps us understand the wave scattering mechanism and find sensitive defect indicators. This capability makes the PAT a good tool in exploring the full potential of damage detection and characterization. Additionally, the transducer can be readily adapted to structures with unknown material properties by scanning out the dispersion curves.
Chapter 5

PVDF Array Sensor for Lamb Wave Reception*

The multi-modal and dispersive characteristics are common in most types of guided waves, but are not the case for bulk waves; they provide both challenges and opportunities for NDT and SHM. Guided waves are dispersive, so the wave speed depends on frequency and the wave spreads out as it propagates. Also, because a finite frequency bandwidth is excited by an actuator, it is common to have multiple modes generated. Additionally, the geometric complexity of real structures introduces reflections into the received signal. These effects jointly result in the received waveform being very complex, making the detection and monitoring of damage challenging. Selecting a feature that is sensitive to damage, but not to varying environmental and operational condition, is challenging.

In the domain of NDT, Lamb waves have been studied extensively; methods for NDT using Lamb waves are well established. To take advantage of the multi-modal characteristic, modal content information becomes very useful because at every frequency each mode has a unique wavestructure, which is largely responsible for its sensitivity to material damage. Furthermore, mode conversion occurs when the waves interact with damage, making modal content an excellent damage detection feature. Modal content can be determined by moving a sensor to different positions and then transforming the spatial-temporal data into the wavenumber-frequency domain. Within the domain of NDT, movable sensors such as laser vibrometers and air-coupled transducers are popular for visualizing the wave field either along the propagation path or across the whole wave field. Dispersion, multiple wave modes, and edge reflections can be identified by 2D Fourier transformation when time signals at grid points on a

* Portions of this chapter are based substantially on B. Ren and C.J. Lissenden, PVDF Multi-Element Lamb Wave Sensor for Structural Health Monitoring, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Submitted
structure are obtained. Alleyne and Cawley [45] applied the 2D Fourier transform to the signals received by a sensor moved to multiple locations to analyze multimodal propagation. Costley et al. [55] carried out a similar analysis using laser generated signals. El youbi et al. [56], Rquit et al. [57] and Minonzio et al. [58] employed multi-emitter and multi-receiver arrays to sweep out the dispersion curves. Additionally, Alleyne and Cawley [59] showed that the interaction between a Lamb wave and a notch defect can quantitatively characterize the notch depth. Safaeinili et al. [60] used the wave mode spectrum to characterize viscoelastic material parameters for aluminum aramid and graphite-epoxy plates. Besides its role in damage detection and material characterization, the 2D Fourier transform is also a powerful tool in the study of mode conversion at geometry transitions: e.g., free edges [61], beveled edges [62] and lap-shear adhesive joints [63]. Nevertheless, these methods have not migrated to the domain of SHM because of the requirement for movable parts or the large size and heavy mass of the transducers.

In the domain of SHM the transducers are typically at fixed locations and are immovable. This poses a challenge to develop proper instruments for Lamb wave reception in SHM applications. In this chapter, an affixed polyvinylidene fluoride (PVDF) multi-element sensor is developed and its capability of mode extraction is demonstrated.

5.1 Lamb wave reception

In bulk wave applications, e.g. medical ultrasonic imaging, phased array transducers are widely used to receive waves at multiple locations. However, the difference in scenarios of receiving bulk wave and Lamb wave receiving, as shown in Figure 5-1, makes the use of phased array transducer for Lamb wave receiving problematic. One of the biggest problems is cross talk. Cross talk between elements in a multi-element sensor can corrupt the received signal. While this often is not an issue when receiving bulk waves because the wave impinges on all elements with
very small time differences, it is a significant issue for Lamb waves (and Rayleigh waves) as illustrated in Figure 5-1. The cross talk often occurs after the bulk wave front has arrived at all elements, making it possible to eliminate the cross talk by windowing the signal before it occurs. However, Lamb waves are sensed in a progressive manner by the individual elements, so that the cross talk occurs while the wave front is moving from the first receiving element to the last. The Lamb wave causes wave motion in element 1 for example, that leaks into the backing material and housing and then into adjacent elements. Likewise, the wave motion of an element can interact with the Lamb wave and alter it. An important goal of the multi-element sensor design for Lamb wave reception is to minimize both of these types of cross talk. To demonstrate the effectiveness of the new sensor in suppressing cross talk, the comparison of the waveforms of a commercial phased array and the new sensor will be shown in Sec. 5.3.1. Sensors made of a monolithic piezoceramic material having individual electrodes to form multiple elements are especially susceptible to cross talk because the piezoceramic material itself serves as a waveguide. Such a design is often the case for commercial phased array transducers because it is easy to manufacture. Even if the piezoceramic elements are separate, the waves can propagate through kerf filling materials and the housing. Moreover, the vibration of the piezoceramic will interact and thus interfere with the wave motion to be measured in the plate.

Figure 5-1: Bulk wave reception occurs at similar times for all elements (a), while Lamb waves are received progressively element by element (b).
The other feature a good receiver should have is a broad frequency bandwidth. Characteristics of Lamb waves are usually a function of frequency. To detect different defects in structures, excitations with different frequencies may be needed. An all-around sensor could significantly reduce the number of sensors needed and thus the weight of the whole SHM system. Also, real structures have complex geometries including curvature, thus a flexible sensor is highly desired.

5.2 Design and fabrication

5.2.1 Materials selection

PVDF (Polyvinylidene Fluoride) is selected as the active material for the sensor because it has a very high piezoelectric coefficient for a polymer and it is readily available. It is selected over piezoceramics that have higher piezoelectric coefficients because it is flexible, broadband, and can be configured to suppress cross talk.

Usually, PVDF is purchased as a clear film with or without metalized coatings on the top and bottom surfaces. The thickness is generally less than 110 μm, which in conjunction with its low Young’s modulus gives it good flexibility. It can be coupled to flat or curved surfaces by a thin bondline of cyanoacrylate adhesive.

PVDF has much lower stiffness and mass density than piezoceramics. PVDF can be made into very thin film (a thickness of 9 μm to 110 μm is commercially available). Thus, the film bends easily with the surface of the substrate and its effect on the wave field is minimized. It deforms easily with the surface of the substrate and the large acoustic impedance mismatch with the substrate keeps the wave energy in the substrate. The typical acoustic impedances for PVDF,
PZT5A and aluminum are 4, 33 and 17 MRayls, respectively. Thus cross talk between elements is minimized, as will be verified in experiments shown in section 5.3.

Monkhouse et al. [64], Hay and Rose [65], and others have used PVDF in interdigital and comb transducers to excite and receive ultrasonic guided waves in plates and pipelines. The broad operational frequency bandwidth (0.5-4 MHz reported in [64]) is a big advantage for sensors. We have found PVDF to function well in the 0.2-0.5 MHz range as well; and the lower limit was dictated by the actuator, not the PVDF sensor.

### 5.2.2 Electrical connectivity

To achieve good resolution, the sensor array has 16 independent receiving elements/channels and a fine pitch, \( p \), of 2 mm. The pitch is center-to-center distance between two adjacent elements. Each element is a rectangle with the dimension of 24mm x 1.2 mm. The smaller the pitch, the better the wavelength resolution it has. This fine pitch makes soldering wires difficult, but by using a flexible printed circuit (FPC) board, no lead wires or soldering are needed and the element size is kept small. To have 16 independent channels, a FPC board with 16 independent circuits is designed as shown in Figure 5-2.

Sixteen 1.2 mm wide copper filled regions are printed on the bottom surface of the FPC board with 0.8 mm gaps as shown in Figure 5-2 to serve as the top electrodes for PVDF film. The PVDF film has an electrode only on the bottom surface. Between the FPC board and PVDF film, a layer of anisotropic, z-axis conductive tape is inserted to make connection between the top surface of the PVDF film and the bottom surface of the FPC board. The completed sensor assembly is a 3-layer patch, which from top to bottom comprises FPC board, z-axis conductive tape, and PVDF film (Figure 5-3).
Figure 5-2: Photographs of the FPC board (a) and the sensor bonded to an aluminum plate (b).

Figure 5-3: Sketch of the 3-layer structure of the sensor.

### 5.2.3 Sensor fabrication

The FPC board, z-axis conductive tape, and PVDF film are each 50 mm square. The FPC board is 0.15 mm thick polyimide film. Two 18-channel FPC connectors are soldered onto the top surface of the FPC board. Two channels of each FPC connector are used as ground, leaving 16 active channels.

The PVDF film comes with silver ink electrodes on both surfaces. The electrode on one side of PVDF film is washed off by acetone and a layer of double-sided z-axis conductive tape is adhered to the side of the PVDF with no electrode. Then the FPC board is adhered to the other
side of the conductive tape. The total thickness of the assembled sensor is 0.3 mm (except for the
PFC connectors) and it has a mass of 3 g. The cost of a PVDF sensor is about $25, which is much
lower than commercial phased arrays. Finally, the PVDF sensor is bonded to the substrate surface
with cyanoacrylate. A PVDF sensor bonded to an aluminum plate is shown in Figure 5-2 (b).

5.3 Experimental Test

A sequence of experiments was conducted to demonstrate the capabilities of the PVDF
sensor. A phased array transducer [66] and angle beam actuators with central frequencies of 0.5,
1.0, and 2.25 MHz were used to excite different Lamb modes with 5-cycle tonebursts. The angle
beam actuator has a 50 mm by 43 mm footprint and a mass of 127 g. The substrates are aluminum
alloy plates (mass density, \( \rho = 2700 \text{ kg/m}^3 \); Young’s modulus, \( E = 70 \text{ GPa} \); and Poisson’s
ratio, \( \nu = 0.34 \)).

5.3.1 Cross talk

As introduced in Sec. 5.2, being able to collect signals at equally spaced locations along
the propagation path with minimal interference of the sensor on the wave field is very important
for Lamb wave reception and analysis. Here, we compare a commercial phased array (GE
Krautkramer Benchmark, 0.5 MHz, \( p=5.2 \text{ mm, footprint=110 mm x 45 mm, mass=470 g} \)) with
the PVDF sensor described in Sec.5.2.

A phased array transducer developed for SHM applications [66] is used to preferentially
excite the A0 mode at frequencies from 0.25 to 0.33 MHz with an increment of 0.01 MHz. Both
sensors have 16 elements, which are numbered 1-16 from left to right. The Hilbert transform of
each received signal normalized with respect to the maximum value is shown in Figure 5-4 for
both sensors. Our first observation from Figure 5-4 is that all 16 elements in the PVDF sensor have peak envelope values greater than 0.75, while the commercial sensor has only four peak envelope values greater than 0.75 (i.e., elements 1-4). The very significant amplitude drop observed for the commercial sensor can be viewed as power loss and is associated with wave energy leaking into the sensor. Our second observation from Figure 5-4 is that the envelopes from the PVDF sensor are self-consistent with respect to shape, while those from the commercial sensor are not. The large variations in envelope shapes for the commercial sensor are apparently due to cross talk, as described in Sec. 5.1. Our third observation from Figure 5-4 is that the envelope peak values for element $i$ (where $i = 1, 2, \ldots, 16$) occur at significantly different times for the commercial sensor and the PVDF sensor. This is simply because the sensors have different pitches. The smaller pitch could have an effect on the ability of the PVDF sensor to determine the group velocity, but as will be discussed subsequently it does not.

The rather minimal wave energy leakage into the PVDF sensor has multiple benefits: cross talk is small, as is interference of the sensor on the passing wave, multiple PVDF sensors could receive the wave energy at different positions on the substrate, and group velocity can be measured by a single PVDF sensor. The group velocity can be computed based on the difference in the time of arrival at element 16 relative to element 1 and a travel distance of $15p$ [67]. The group velocities computed from the PVDF sensor are shown in Figure 5-5 for the A0 mode between 0.25-0.33 MHz. The group velocities predicted from the dispersion relations are also shown for a bare aluminum plate and for an aluminum plate with a PVDF sensor bonded to its top surface. Notice that the presence of the sensor does have an effect on the group velocity. The PVDF sensor reduces the group velocity by 9% here, but this will vary from plate to plate based on material properties and thickness. Above 0.33 MHz the S0 and A0 modes are not separated for this sensor location relative to the actuator. While it is not done here, filtering could be used to separate the modes and compute group velocities from multimodal signals. The results from the
PVDF sensor are in good agreement with the predicted group velocity. Even though the pitch of the commercial sensor was larger than that of the PVDF sensor, it was not possible to measure the group velocity due to the power loss and cross talk. For example, the received signals from the commercial sensor elements 1 and 16 are shown in Figure 5-6.
Figure 5-4: Envelopes of the received signals (A0 mode at 0.3 MHz) from each channel from (a) a commercial sensor and (b) the PVDF sensor.
Figure 5-5: Mode A0 group velocities over a range of frequencies for the PVDF sensor.

Figure 5-6: Envelopes of the received signals (A0 mode at 0.3 MHz) from 1st and 16th channels from commercial sensor.
5.3.2 Wave mode extraction

The broadband nature of the PVDF sensor is very useful for wave mode extraction over a broad frequency range [64]. Wave mode extraction is demonstrated on a 2 mm thick plate since the thicker plate has more propagating modes over a prescribed frequency range. Three actuators are used in order to investigate a broad frequency spectrum. The actuator center frequencies and frequency ranges that were used are: 0.5 MHz and 0.2-0.5 MHz, 1.0 MHz and 0.5-1.5 MHz, and 2.25 MHz and 1.5-3.0 MHz. Incident angles of 20° and 30° were used to activate phase velocities of 7.98 and 5.46 mm/µs based on Snell’s law in order to demonstrate that the PVDF sensor can resolve different modal content from different wave excitation inputs. A-scans were acquired in the frequency range of 0.2-3.0 MHz in increments of 0.01 MHz. The wave mode content for each excitation is calculated using the 2D fast Fourier transform (FFT) given in equation (25) [45]. The spectra for all frequencies in the 0.2-3.0 MHz range are summed up and overlaid on the dispersion curves as an intensity plot (Figure 5-7). As emphasized by Rose [42], actuators do not excite a specific point on a dispersion curve, but rather, due to the finite size of the actuator and the frequency bandwidth (i.e., source influence) there are zones of excitation. It is observed that for the 20° incidence angle (Figure 5-7(a)), the spectra are in a high phase velocity range, which corresponds to the activation line at 7.98 mm/µs. In Figure 5-7(b), the excited spectra follow the activation line at 5.46 mm/µs associated with the 30° incidence angle. It is quite clear that a single PVDF sensor is capable of resolving modal content over a broad frequency range.

The PVDF sensor is also used for CFRP composites. Its capabilities of calculating group velocity and extracting mode content will be demonstrated in Sec. 6.3.1.
Figure 5-7: Lamb wave energy spectra determined by the PVDF sensor. The blue lines are predicted dispersion curves and the dashed red line indicates the activation line corresponding to the prescribed incidence angle: (a) 20°, (b) 30°. The color bar shows amplitudes with arbitrary unit calculated from the summation of 2D Fourier transforms.
5.4 Discussion and Conclusion

This chapter introduces another useful tool in guided wave SHM. The PVDF array sensor is light, thin and flexible which provides a good option for monitoring complex aircraft structures. Additionally, compared with commonly used PZT disks, the PVDF array sensor has a much wider frequency bandwidth and is more versatile because it could measure the modal content of a wave package which is not an option for PZT disks. On the other hand, PVDF cannot be used to excite ultrasonic waves because of its low piezoelectric coupling coefficients. This is a drawback compared with using PZT disks, which can both send and receive ultrasonic waves. However, if a phased array transducer which possesses multiple excitation elements is used to excite guided waves, the excited wave could be much stronger than that from a single PZT disk. In this case, one transmitter could be used to send waves to multiple PVDF receivers and thus provide a good coverage of the structure even though the PVDF sensor only receives the waves.
Chapter 6

Modal Content Based Damage Indicators

It has been widely proven in NDT domain that modal content can be used to detect and characterize defects [59, 68-70]. The physical nature behind the change of mode content is defect induced mode conversion. A study of the nature of the wave-defect interaction will reveal the features expected to see when a particular defect is present in the structure. In this chapter, the wave-defect interaction is studied in both theoretical analysis and experiments; afterwards, mode content based damage indicators are proposed and tested to demonstrate their effectiveness in detection and characterization of defects. The theoretical analysis mainly relies on finite element analysis in the frequency domain [71]; the experiments employ the PAT transducers and PVDF array sensors introduced in previous chapters to preferentially excite a mode of interest and thus isolate the interaction of a wave mode and a defect. Even though the thesis is focusing on the monitoring of disbonds in an adhesively bonded composite structures, other types of defects, e.g. notches on aluminum plates, are also studied to demonstrate the versatility of the proposed mode content based damage indicators.

6.1 Literature review on wave-damage interaction

Wave-damage interactions have been studied extensively by researchers in literature. Both theoretical and experimental methods are applied to different types of defects.

Abduljabbar et al. [72] studied the diffraction of shear horizontal waves by normal edge cracks in a plate. A hybrid method was used such that that the finite region containing the crack was discretized by finite elements and the field in the exterior regions was written as a modal sum. Koshiba et al. [73] employed a similar method to analyze the scattering of Lamb waves due
to the defect. The relationship of reflection coefficient versus size and shape of the defect was calculated. However, only the fundamental symmetric mode, \( S_0 \), was studied. Al-Nassar et al. [74] studied scattering of Lamb waves by a normal rectangular strip weldment. Transmission and reflection coefficients for \( A_0 \) and \( S_1 \) mode incidences were calculated over a range of frequency-thickness product. Karunasena et al. [68, 75] extend this method to model cracks in laminated composite plates. Cho and Rose [76] employed the boundary element method to study the mode conversion of Lamb waves on the edge. The region of interest, i.e. the neighborhood of the edge, was discretized only at the boundary rather than over the whole domain. Five modes, \( A_0 \), \( A_1 \), \( S_0 \), \( S_1 \) and \( S_2 \) were studied for their reflections at the edge of a plate. Hayashi and Kawashima [77] used semi-analytical-finite-element (SAFE) method to study the mode conversions and multiple reflection of Lamb waves at a delamination. Since in a 2D plane strain model, constant waveguides were present between the two tips of the delamination, it was not necessary to use finite element method to discretize the surroundings of the delamination. Doing normal mode expansion at the tips of the delamination utilizing wavestructures obtained by SAFE method was sufficient to function. The method has also been applied to model cracks in elastic cylinders, e.g. pipelines, by Benmeddour [78].

6.2 The modal content based damage indicator

6.2.1 The concept of modal content based damage indicator

The multimodal nature of Lamb waves results in diverse behaviors of wave-defect interactions and thus provides abundant information for detecting, characterizing and sizing defects. The behavior is regarded as mode conversion, and it occurs for both reflected and transmitted waves. Such behavior is a function of three factors, mode, frequency and defect
configuration. Any combination of the three could give a quantitatively unique behavior of the wave-defect interaction. With the employment of the PFC PATs and PVDF array sensors introduced in Chapters 4 and 5, for a given defect, the mode conversion information could be acquired for multiple mode-frequency combinations and thus helps determine the type and size of the defect.

It has been studied and discussed extensively in the literature that changing environmental operational conditions (EOC) is a big challenge to reliable SHM. For example, changing temperature \([7, 79]\) could affect the amplitude of the received signal by influencing both coupling conditions between transducer and substrate and wave propagations; loading \([80]\) can influence the time of flight of signals. In this sense, amplitude and time of flight of Lamb wave signals may not function as reliable damage indicators for SHM. An ideal damage indicator should be sensitive only to defects but be blind to changing EOCs.

It should be noted that the EOCs usually globally affect the whole domain being monitored and will not induce mode conversion because they are not essentially discontinuities in the waveguide. On the contrary, most defects are local discontinuities that will scatter and reflect incident wave energy. This distinction will help find reliable damage indicators for variable EOCs.

In this chapter, modal-content based damage indicators are proposed and used experimentally to demonstrate its capability of detecting, characterizing defects and its reliability under different temperatures.

**6.2.2 The prediction of insensitive and sensitive modes**

As stated above, the sensitivity to a given defect is a function of both mode and frequency because it is the wavestructure that primarily determines defect sensitivity and
wave structure depends on both mode and frequency. It is thus beneficial to build a model to study the sensitivity of each point on dispersion curves. In this chapter, each point on dispersion curves will be called as an incidence point, which specifies both mode and frequency. A 2D plane strain frequency domain finite element model is created in COMSOL. The frequency domain finite element model simulates a steady state where a continuous wave is traveling in the waveguide. The benefit of using a frequency domain model is that the frequency content can be specified precisely and thus the propagation of one mode at a frequency can be isolated. For the time domain model, the excitation signals, e.g. a toneburst, has multiple frequency components. With the help of a perfectly matched layer which absorbs incident waves with no reflections, a small size model is sufficient to simulate the interaction of an incidence wave and defect without worrying about interference by reflections from edges. Since a frequency domain model indicates a steady state problem and the number of degrees of freedom is relative low for a 2D model, the model can be solved in just a few seconds for one point on a dispersion curve which makes it feasible to examine all the points on dispersion curves.
Figure 6-1: A sketch of the 2D plane strain model of two adhesively bonded composite plates with an adhesive defect at the interface between adhesive layer and lower composite laminate.

Figure 6-2: A zoom-in view of the meshed domain near the tip of the disbond

Take a disbond between two adhesively bonded composite laminates as an example. A sketch of the model is shown in Figure 6-1 and the meshed domain near the tip of the disbond is
shown in Figure 6-2. At the loading region, wavestructure-type loading will be applied to that region such that only one mode at one frequency is excited. The wavestructure-type loading is a body force applied to the loading region whose distribution through the thickness is the nodal force wave structure calculated using SAFE method and the distribution along the wave propagation direction follows $e^{ikx}$ where $k$ is the wavenumber. The wave is propagating from the left to the right. At the incident region, the mode content can be extracted by applying a FFT to field parameters, e.g. displacements or power flux. The selection of the field parameters is case-by-case considering that a particular mode may have dominant in-plane or out-of-plane displacement components. The mode content is checked at the incident region to verify the excited mode is as expected and get quantitatively evaluation of the power of incident wave. Then, the wave will interact with the defect at the disbond region where both reflected and transmitted waves are generated. The reflected waves can be identified at the incident region because its wavenumber has the opposite sign to the incident wave. At the output region, the mode content of transmitted waves can be calculated using 2DFFT as well. At the ends of the model, two perfectly matched layers are attached. It could be expected that some incidence of some modes will result in no scattering and that no reflection or mode conversion is possible. These mode-frequency combinations are insensitive to the disbond. On the other hand, incidences have energy that gets reflected, mode converted or both are sensitive to the disbond. Its sensitivity depends on how much energy is reflected or converted to other mode.
Figure 6-3: A sketch of the composite adhesive bond showing the geometry and materials

![Composite Adhesive Bond Diagram]

Figure 6-4: The dispersion curves of the composite adhesive bond. (a) is phase velocity dispersion curve plot and (b) is group velocity dispersion curve plot.

![Dispersion Curves]

Table 6-1. The material properties of the adhesive layer in composite adhesive bond

<table>
<thead>
<tr>
<th>E</th>
<th>v</th>
<th>ρ</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.56GPa</td>
<td>0.4</td>
<td>1104kg/m³</td>
</tr>
</tbody>
</table>

Both sensitive and insensitive incidences can be identified by finite element analysis. A thorough analysis has been carried out for every point on the dispersion curves. The geometry of the composite adhesive bond is shown in Figure 6-3. The two CFRP laminates have the same thickness and layup sequence which is [90/-45/0/45]_{S2}. The material of CFRP laminates is AS4/8552 whose material properties are shown in Table 2-1. The material property of the
adhesive layer is shown in Table 6-1. The theoretical dispersion curves of this composite adhesive bond are shown in Figure 6-4. According to the behavior of wave-defect interaction, sensitivities of different incidences are categorized into three groups:

(1). No sensitivity: the incident wave is blind to the defect, no reflection or mode conversion is observed.

(2). Good sensitivity: the incident wave is very sensitive to the defect, the amplitude reduction of the primary mode is about 50%.

(3). Intermediate sensitivity: clear mode conversion or reflection is observed while the amplitude reduction of the primary mode is usually less than 20%.

For each category, the simulation results of a couple of representative incidences will be shown.

6.2.2.1 Incidences with no sensitivity

Three examples will be shown as incidences with no sensitivity, which are mode 3 at 200 kHz, mode 5 at 310 kHz and mode 6 at 310 kHz. Figure 6-5 shows an example of insensitive incidence, which is mode 3 at 200 kHz. The top two plots in Figure 6-5 are displacement fields for $u_x$ and $u_z$ in the xz plane. The z-component is used instead of y-component to keep consistent with the coordinate system used across the whole thesis. For the plane of the multilayer plate, $u_x$ is the in-plane displacement and $u_z$ is the out-of-plane displacement. Figure 6-5 (c) and (e) show modal content at the incident and output region as spectra in the phase velocity domain and Figure 6-5 (d) and (f) show the modal content at the incident and output region as intensity plots overlaid on phase velocity dispersion curves with a red dash line indicating at which frequency the analysis is performed. To get the wavenumber spectrum in the incident region, the power flux along the x-direction is calculated by integrating the x-component of the Poynting vector through
the thickness and then applying the Fourier transform to the power flux along the x-direction. The Poynting vector is defined as

$$\mathbf{P} = -\mathbf{v}^* \cdot \mathbf{T}$$

(36)

where $\mathbf{v}^*$ is the complex conjugate of the velocity vector and $\mathbf{T}$ is the stress tensor.

It should be noted that the field values calculated from a frequency domain model, e.g. displacements, velocities and stresses, are complex numbers. This results in complex-value power flux as well. By applying the Fourier transform to the complex-value power flux, the wave propagating in the positive and negative x-direction can be differentiated and thus the incident wave and reflected waves can be resolved. The phase velocity spectrum can thus be easily obtained from wavenumber spectrum with a given frequency. It is observed that in Figure 6-5(d) the intersecting point of red dash line and the highest value in the intensity plot, brown color, lies right on the point corresponding to mode 3 at 200 kHz. This verifies the clean excitation of mode 3 at 200 kHz. From Figure 6-5 (a) and (b), no evident change is observed from the displacement fields in the incident and output regions indicating that this incidence is not sensitive to the disbond. This observation is verified again in the power spectrum plots that no reflection or mode conversion happens. Actually, the fact that mode 3 is insensitive to the disbond is the case for a range of frequency near 200kHz; all the mode 3 incidences from 150 kHz to 250 kHz are also insensitive to the disbond. In the following, all the results of frequency domain finite element results will have the same format as Figure 6-5.

The other two examples are shown in Figure 6-6 and Figure 6-7 for modes 5 and 6 at 400 kHz respectively. Similarly, these two incidences show no sensitivity to the disbond.
Figure 6-5: The frequency domain results of the wave-defect interaction for the incidence of mode 3 at 200kHz. Plots (a) and (b) show the contours of the in-plane and out-of-plane displacement fields. Plots (c) and (e) are modal content at the incident and output region as spectra in the phase velocity domain. Plots (d) and (f) show the modal content at the incident and output region as intensity plots overlaid on phase velocity dispersion curves with a red dash line indicating at which frequency the analysis is performed.
Figure 6-6: The frequency domain results of the wave-defect interaction for the incidence of mode 5 at 310kHz.

Figure 6-7: The frequency domain results of the wave-defect interaction for the incidence of mode 6 at 310kHz.
6.2.2.2 Incidences with good sensitivity

Different from the insensitive incidences, some incidences show excellent sensitivity to the disbond. A good example is mode 10 at 600 kHz as shown in Figure 6-8. The amplitude of the incident wave reduces significantly due to the interaction with the disbond. However, there is not much reflected power (Figure 6-8c). So the mode conversion is the main reason of the amplitude reduction. This behavior is observed at frequencies that range from 550 kHz to 650 kHz.

Another sensitive incidence is mode 5 at 540 kHz as shown in Figure 6-9. A large portion of its power is converted to another mode and thus causes a great reduction in its amplitude. Such a good sensitivity is only available in a narrow frequency bandwidth from 510 kHz to 550 kHz.

Figure 6-8: The frequency domain results of the wave-defect interaction for the incidence of mode 10 at 600 kHz.
6.2.2.3 Incidences with intermediate sensitivity

Besides the two extreme conditions discussed above, there are also some incidences showing intermediate sensitivity. Some examples are shown here while their actual performance will be examined experimentally in section 6.3.

The first example is mode 2 at 300 kHz as shown in Figure 6-10. It clearly shows that the displacement fields have changed before and after the region containing the disbond; both reflection and mode conversion are observed in the incident region and the output region respectively. The amplitude of the incident wave reduces due to reflection and mode conversion. Such a behavior is observed from 290 kHz to 340 kHz.

Another example is the incidence of mode 1 at 200 kHz which results in mode conversion from mode 1 to mode 5 as shown in Figure 6-11. However, the amplitude reduction of the incident wave, mode 1 at 200 kHz, is minor. Such a small change could be easily
overwhelmed by noise associated with changing of EOCs, making this incidence less useful in practice. The wave converted from the incident wave, mode 5, is located in the highly dispersive region of its dispersion curve which indicates that this mode will attenuate significantly due to the spreading of the waveform and can be difficult to detect in experiments. On the other hand, the incidence of mode 1 at 310 kHz, which is the same mode at higher frequency, could be a good candidate as shown in Figure 6-12. While the amplitude reduction of the incident wave is small, the converted mode, mode 5, is in a nearly non-dispersive region and could be detected by sensors in experiments. At 310 kHz, the increased mode 5 and decreased mode 1 could combine to enhance the contrast between good and disbonded conditions.

Figure 6-10: The frequency domain results of the wave-defect interaction for the incidence of mode 2 at 300kHz.
Figure 6-11: The frequency domain results of the wave-defect interaction for the incidence of mode 1 at 200kHz.

Figure 6-12: The frequency domain results of the wave-defect interaction for the incidence of mode 1 at 310kHz.
6.2.3 Wave modal amplitude and wave modal composition

With the knowledge of sensitive and insensitive incidence waves predicted by finite element analysis, two modal content based damage indicators are available.

6.2.3.1 Wave modal amplitude

Wave modal amplitude is the intensity of only one mode in wavenumber-frequency specta even though it may be immersed in a wave package which is comprised of multiple modes. Wave modal amplitude is enabled by using 2DFFT and is proposed for use for increasing sensitivity to disbond. Multi-modal wave propagation is usually the case for Lamb wave propagation. However, not all of these modes are useful for damage detection. By isolating the sensitive mode, its effectiveness of detecting defects could be increased.

6.2.3.2 Wave modal composition

Another proposed damage indicator is wave modal composition. This damage indicator is used for the incidence which shows significant mode conversions. If an incidence preferentially excites one mode at a certain bandwidth of frequency and the structure is pristine, the wave package propagating in the structure will maintain its modal content. EOCs like temperature and loading change may influence the amplitude or the velocity of the wave package but will not induce mode conversion. So the modal content will remain constant no matter what the EOCs are. On the other hand, when a defect which is substantially a discontinuity appears in the structure, it will interact with the incident wave and thus cause the change to modal content of the wave package. In other words, the mode conversion is a discontinuity-sensitive phenomenon and will
have better sensitivity and reliability in detecting defects under changing EOCs. It should be noted that for this damage indicator, only one incidence is sufficient.

### 6.3 Experimental results for damage detection and characterization

Experiments are carried out to demonstrate the detecting and characterizing capability of the two proposed modal-content-based damage indicators, the wave modal amplitude and the wave modal content. It should be noted that with the PATs introduced in chapter 3, it is not guaranteed that a single mode can be excited without excitation of other modes at that frequency. Sometimes, multiple modes are excited at one excitation and the modes could be separated with the knowledge of their group velocity. Also, since the PATs function best only in the frequency range of 0.2 to 0.7 MHz, for some damage indicators that requires higher frequency excitation, an angle beam transducer will be used.

The adhesive bond is fabricated by bonding two CFRP laminates with Hysol EA9696 sheet adhesive. The surfaces of the CFRP laminates are cleaned using Acetone before the bonding. An artificial disbond is simulated by inserting a PVDF film between the sheet adhesive and the bottom CFRP laminate. The size of the disbond shown in Figure 6-14 is 1” x 1” and the width of the adhesive bond is 3”.

#### 6.3.1 The detection of disbands in adhesive bonding CFRP plates

The detection of a defect is usually the first step in the hierarchy in SHM [81]. As stated in section 5.2.1, the detection of defects could be affected by the changing EOCs. In this work, the detection of the disbond will be demonstrated first at the room temperature (20°C). Then, the sample will be heated up locally along the wave propagation path with a hot plate set at 60°C.
The hot plate is in contact with the bottom surface of the plate samples. Since the hot plate heats up the plate locally, it is expected that the temperature varies at different locations on the plates. The temperature is measured at the top surface of the plate along the wave propagation path and the temperature field at different locations is plotted in Figure 6-13. The maximum temperature is not 60°C because the temperature is measured at the top surface and a temperature gradient exists along the thickness direction. Also, it is observed that the temperature is not uniform along the propagation path due to the limited size of hot plate. The total width of the hot plate is 100 mm, but the temperature distribution on the surface is not uniform either. This will produce a temperature gradient from the center of the hot plate and cause influence to the wave propagation.

The PAT introduced in Chapter 3 is used as an actuator and a PVDF array sensor introduced in Chapter 4 is used as a receiver.
Figure 6-13: The temperature distribution at the top surface of the plate along the propagation path. The center of the hot plate is located at 90 mm.

The experiment setup is shown in Figure 6-14. The disbond is located between the actuator and the receiver; through-transmission mode is used. The PAT has 8 piezoelectric fiber composite elements with a center-to-center spacing of 4 mm. Time delays are calculated for every point on dispersion curves shown in Figure 6-4 with specified frequencies and phase velocities. 5-cycle tonebursts are sent to elements in the PAT with precalculated time delays. All the possible incidences between 0.2 and 0.7 MHz are excited by the PAT. Since the PAT has different excitability for different incidences, it is not guaranteed that the PAT will excite any point on dispersion curves preferentially. Regions that can be excited preferentially by the PAT are listed in Table 6-2 and Figure 6-15.
Figure 6.14: The photo of the experiment setup showing the detection of a disbond using a PAT as an actuator and a PVDF array sensor as a receiver.

Table 6.2. Incidences can be experimentally excited by PATs

<table>
<thead>
<tr>
<th>Region Label</th>
<th>Incidence</th>
<th>Frequency range (kHz)</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Mode1</td>
<td>200-220</td>
<td>intermediate</td>
</tr>
<tr>
<td>B</td>
<td>Mode1</td>
<td>290-350</td>
<td>intermediate</td>
</tr>
<tr>
<td>C</td>
<td>Mode3</td>
<td>200-220</td>
<td>no</td>
</tr>
<tr>
<td>D</td>
<td>Mode5&amp;6*</td>
<td>300-450</td>
<td>no</td>
</tr>
<tr>
<td>E</td>
<td>Mode5</td>
<td>500-550</td>
<td>Good</td>
</tr>
<tr>
<td>F</td>
<td>Mode10</td>
<td>550-650</td>
<td>Good</td>
</tr>
</tbody>
</table>

* mode 5&6 are both excited and difficult to separate at this frequency range
For each incidence, the A-scan signals from 16 receiving channels in a PVDF array sensor are recorded and are stored in a matrix of received time signals. The 2D Fourier Transform is applied to this matrix to produce the spectra in the wavenumber-frequency domain. Then the spectra are converted to the phase-velocity-frequency domain. Details of the data post processing are introduced in Chapter 3.

The first example is the incidence of mode 10 at 600 kHz which is predicted to have good sensitivity to the disbonds. Figure 6-18 shows time signals and modal content for four conditions, namely:

a) good,
b) good at 60°C,

c) disbond and

d) disbond at 60°C.

The modal content is calculated using the time signals in the windows defined by the red dash lines. It is observed clearly in the time signals, Figure 6-18 (a) to (d), that the amplitudes for two conditions with disbond are much lower than those for good bond. The intensity in Figure 6-18 (e) to (h) is arbitrary amplitude calculated by applying the 2D Fourier Transform to time signals. It shows that the intensities for good cases are about 2500; for disbonded cases, the intensities are about 800 which is roughly 1/3 of those for good cases. Such a great difference gives high tolerance to the change of temperature. At regions with high intensity shown on Figure 6-18 (e) to (h), there are actually three modes existing, which are mode 8 (blue), mode 9 (green) and mode 10 (red). It is difficult to tell which mode is actually excited with given spectra. Thus, a group velocity calculation is carried out to check which mode is excited using the same method introduced in Sec. 5.3.1.

Figure 6-16 shows the envelopes of the received signals for the incidence of mode 10 at 0.6 MHz from all 16 channels of the PVDF sensor. Again, it is observed that the waveform retains its shape across different channels and the peak envelop values are greater than 0.75. The calculated group velocities are shown in Figure 6-19 for the frequencies from 0.55 MHz to 0.65 MHz. It is observed that below 0.58 MHz, the calculated group velocities are close to the group velocity dispersion curve of mode 8. But for the frequency range from 0.58 MHz to 0.65 MHz, the calculated group velocities have the same trend as theoretical group velocities of mode 10. It concludes that the excited wave could be a mix of mode 8 and mode 10 and mode 10 is the dominant one from 0.58 MHz to 0.65 MHz. Since the mode 10 is still the dominant one in the excited wave, the whole wave package could still show good sensitivity to the disbond.
Figure 6-16: Envelopes of the received signals (Mode 10 at 0.6 MHz) from each channel from the PVDF sensor.
Figure 6-17: Measured group velocities compared with theoretical group velocities for mode 8, 9 and 10.

Figure 6-18: The results of the disbond detection using the incidence of mode 10 at 600 kHz. (a) to (d) are received time signals for conditions of good, good at 60°C, disbond and disbond at 60°C respectively. (e) to (h) are the modal content of the wave signals in the windows defined by red dash lines plotted as intensity plots overlaid on phase velocity dispersion curves. The intensity has arbitrary unit and its value is a result of the summation of the spectra of 2D Fourier transforms.

Figure 6-19 shows the plot of intensity versus phase velocity. Since the excited time signal is a 5-cycle tone burst whose frequency content covers a range of frequencies, maximum values are picked at every phase velocity point in this frequency range. It is observed that the
elevated temperature does have an effect on the amplitude of the waves. The amplitude decreases to some extent with elevated temperature. However, such an effect is minor compared with the amplitude reduction due to the presence of a disbond. This incidence could still detect the disbond with a good contrast.

According to the prediction in Section 6.2, mode 10 shows good sensitivity to a disbond in the frequency range of 550 kHz to 650 kHz. This prediction is verified and demonstrated in Figure 6-20. The modal amplitudes of mode 10 are plotted vs. frequency for the four bond conditions. The frequency range is 550 to 700 kHz. It demonstrates that mode 10 has good sensitivity to the disbond across the frequency range from 550 to 650 kHz as predicted. The amplitudes for good bonds are always more than two times of that for disbonds. In the range of 650 to 700 kHz, the sensitivity to the disbond is still good, even though the absolute amplitude of

Figure 6-19: Phase velocity spectra for different bond conditions using the incidence of mode 10 at 600 kHz.
the mode decreases significantly because 700 kHz is the upper limit of the working frequency bandwidth of the PAT actuator.

Figure 6-20: Modal amplitudes for different bond conditions using the incidence of mode 10 at the frequency range of 550 to 700 kHz.

Another incidence with good sensitivity is mode 5 at 530 kHz whose result is shown in Figure 6-21 and Figure 6-22. Figure 6-21 and Figure 6-22 have similar styles as Figure 6-18 and Figure 6-19. It is observed from time signals that there are multiple modes excited. As stated beforehand, the PAT may not be able to excite any mode preferentially and a window is needed in such a situation to isolate the effect of one mode. Mode 5 can be isolated by selecting a window as shown in Figure 6-21. As shown in Figure 6-22, mode 5 at 530 kHz also has a significant amplitude reduction due to disbonds. The amplitudes for disbonds are about half of those for good bonds.
Figure 6-21: The results of the disbond detection using the incidence of mode 5 at 530 kHz. (a) to (d) are received time signals for conditions of good, good at 60°C, disbond and disbond at 60°C respectively. (e) to (h) are the modal content of the wave signals in the windows defined by red dash lines plotted as intensity plots overlaid on phase velocity dispersion curves.
Figure 6-22: Phase velocity spectra for different bond conditions using the incidence of mode 5 at 530 kHz.

The amplitudes of mode 5 at 500 to 550 kHz are plotted in Figure 6-23. For the range of 500 to 550 kHz, the amplitudes for good bonds are roughly twice the amplitudes for disbonds. This frequency range corresponds to low group velocity in a high dispersive region of the dispersion curves. In practice, this mode may be interfered with by reflected signals and may not propagate far enough due to its dispersivity.
Figure 6-23: Modal amplitudes for different bond conditions using the incidence of mode 5 at the frequency range of 500 to 550 kHz.

So far, two examples, mode 10 and mode 5 at 550 to 650 kHz and 500 to 550 kHz respectively, have been demonstrated experimentally that they have very good sensitivity to disbonds at both room and elevated temperature. For both cases, the amplitude itself is a good damage indicator and is robust to temperature change because the disbond-induced amplitude reduction is always the dominant one among the factors influencing the amplitude.

Next, incidences with intermediate sensitivity are used to detect the disbond. In Table 6-2, it indicates that mode 1 has sensitivity at ranges of 200-220 kHz and 290-350 kHz. These two ranges are close to each other, however, the frequency bandwidth of a 5-cycle toneburst is relatively wide and it may not be easy to constrain the frequency bandwidth of excited signals completely within the frequency ranges mentioned above. Thus, in the experiment, the results of
the frequency range of 200-350 kHz will be shown. The result of a representative incidence, mode 1 at 310 kHz is shown in Figure 6-24 to demonstrate the behavior of the wave-defect interaction. It is observed that the converted mode 5 shows up when there is a disbond. This agrees well with the FEA prediction.

Figure 6-24: The results of the disbond detection using the incidence of mode 1 at 310 kHz. (a) to (d) are received time signals for conditions of good, good at 60°C, disbond and disbond at 60°C respectively. (e) to (h) are the modal content of the wave signals in the windows defined by red dash lines plotted as intensity plots overlaid on phase velocity dispersion curves.
Figure 6-25 shows the phase velocity spectra for the four bond conditions. It is observed the amplitude of mode 1 decreases and mode 5 increases for disbonded conditions. This is because the power of mode 1 is transferred to power of mode 5 through mode conversions.

Different from incidences with good sensitivity, the amplitude of mode 1 only is not a good damage indicator, as shown in Figure 6-26. The curves for good conditions are entangled with curves for disbond conditions. It is because the sensitivity of mode 1 is greatly compromised by the temperature effect. For example, at the frequency range of 290-350 kHz, good condition at room temperature can be separated from the others. However, both elevated temperature and existence of disbond could cause the reduction in amplitude and their contributions to the amplitude reduction are at the same level. As a result, amplitudes for good bond at 60°C and
disbond at room temperature cannot be differentiated. This observation agrees with the results reported [82] that the SHM method could lose sensitivity to defects when temperature changes.

![Modal amplitudes of mode 1, for different bond conditions using the incidence of mode 1 at the frequency range of 200 to 350 kHz.](image)

**Figure 6-26:** Modal amplitudes of mode 1, for different bond conditions using the incidence of mode 1 at the frequency range of 200 to 350 kHz.

Similarly, if only looking at the amplitude of the converted mode, mode 5, its amplitude is still not a good damage indicator. For example, at the range of 320-350 kHz, all the four conditions have similar amplitudes as shown in Figure 6-27.
Figure 6-27: Modal amplitudes of mode 5, for different bond conditions using the incidence of mode 1 at the frequency range of 200 to 350 kHz.

With the knowledge that the behavior of wave-defect interaction can be depicted as mode 1 transferring its energy to mode 5, the ratio of the amplitudes of these two modes could give a better contrast between good conditions and disbanded conditions. Because the ratio change represents a change in modal content of a wave package, this damage indicator is regarded as wave modal composition. In Figure 6-28, it is demonstrated that by using wave modal composition, the sensitivity across the frequency range of 200-350 kHz is significantly improved. The curves for good bonds are tied together and the curves for disbonds separate from curves for good bonds. It is observed that for low frequency, 200-220 kHz, the sensitivity is still not very good. This is because the mode 5 at this range is highly dispersive and its receivability is very poor.
This is a good example showing that some damage indicator like raw amplitude could fail when temperature changes. But when a modal content based damage indicator is selected with the knowledge of wave-defect interaction, the damage indicator could be much more robust under different temperatures.

Figure 6-28: Modal amplitude ratio of mode 5/mode1, for different bond conditions using the incidence of mode 1 at the frequency range of 200 to 350 kHz.

The last example shows the incidence with no sensitivity to a disbond. The result of the incidence of mode 3 at 210 kHz is shown in Figure 6-29. The time signals, Figure 6-29(a)-(d), do not shown evident change and the modal contents, Figure 6-29(e)-(h), do not show any mode conversion.
Figure 6-29: The results of the disbond detection using the incidence of mode 3 at 210 kHz. (a) to (d) are received time signals for conditions of good, good at 60°C, disbond and disbond at 60°C respectively. (e) to (h) are the modal content of the wave signals in the windows defined by red dash lines plotted as intensity plots overlaid on phase velocity dispersion curves.

Figure 6-30 shows the modal amplitudes for the four bond conditions. They are all at the same level and do not show any sensitivity to disbands. Similar observation is shown in Figure 6-31 for the frequency range of 200-220 kHz.
Figure 6-30: Phase velocity spectra for different bond conditions using the incidence of mode 3 at 210 kHz.
Figure 6-31: Modal amplitude mode 3, for different bond conditions using the incidence of mode 3 at the frequency range of 200 to 220 kHz.

So far, the detection of disbond at different temperatures has been studied by using different incidences. It concludes that for incidences with good sensitivity, the modal amplitude itself is a robust damage indicator. But when it comes to incidences with intermediate sensitivity, the modal amplitude will fail because it is equally sensitive to temperature and disbond and the damage indicator should be constructed considering the behavior of wave-defect interaction. For this work, mode conversion happens in transmitted waves. The damage indicator is selected as the ratio between primary and converted modes and regarded as wave modal composition. The wave modal composition can be used for any defect that could induce mode conversion at transmitted or reflected waves.
6.3.2 The characterization of the size of disbonds in an composite adhesive bonding

Besides the detection of defects, the knowledge of defect characteristics, such as size and shape, are useful as well. The prediction of current health condition and remaining life of structures relies on the characterization of defects.

To simulate a growing disbond, the best way is to apply fatigue loading to an adhesive bond. However, the size of the disbond is hard to determine during the fatigue test and thus hard to control. To simulate different sizes of disbond, two movable PATs are used to inspect different paths such that these paths cover different sizes of a disbond. The diagram of four different inspection paths is shown in Figure 6-32. Path 1 does not cover the disbond at all. Path 2 is cutting on the edge of the disbond. Path 3 covers 20% of the disbond, namely, 5mm x 25mm. Path 4 covers 40% of the disbond, namely, 10mm x 25mm.

![Figure 6-32: A diagram shows the four inspection paths that cover different sizes of a disbond.](image)

Two examples, mode 10 at 550-650 kHz and mode 1 at 290-350 kHz, are shown to demonstrate the characterization of the size of disbond. The first example is shown in Figure 6-33. It is observed that the amplitude of mode 10 decreases monotonically with the increasing
size of the disbond. The other example is using the wave modal composition as the damage indicator for mode 1 incidence at 290-350 kHz. The result of wave modal composition change is shown in Figure 6-34. The averaged ratio is calculated to be 0.48 and 0.52 for path 1 and 2 and increases to 0.96 and 1.71 for path 3 and 4 respectively. Good capability of size characterization is demonstrated by using mode 1 as incidence.

Figure 6-33: The result of defect size characterization using mode 10 at 550-650 kHz as incidence. Raw amplitude is used as the damage indicator.
Figure 6-34: the result of defect size characterization using mode 1 at 290-350 kHz as incidence. Wave modal composition is used as the damage indicator.

6.3.3 The detection of notch in an aluminum plate

To further study the effectiveness of using wave modal composition as damage indicators. Other types of defects are considered to demonstrate that the wave modal composition has good versatility in other applications.

It has been reported by Alleyne and Cawley [59] that mode conversion from wave interaction with damage is a good damage indicator. This experiment on a 1 mm thick aluminum plate with a 0.4 mm deep notch will demonstrate that wave modal composition can be used to detect the mode conversion between the A0 and S0 modes after the incident wave interacts with the notch. The experimental setup is shown in Figure 6-35. Two PVDF sensors (R1 and R2) were bonded to the plate and a notch was saw cut in front of one sensor (R2) but not the other (R1). An
angle-beam actuator with a 25-degree incident angle (0.5 MHz) can be positioned to send a Lamb waves to sensor R1 (as shown in Figure 6-35) or to sensor R2.

Received signals from all 16 channels of sensors R1 and R2 are shown in Figure 6-36. The 2D-FFT described earlier has been used to obtain the phase velocity-frequency spectrum. In the frequency range investigated, only the fundamental A0 and S0 modes exist and both modes are evident in Figure 6-36 from the presence of two distinct wave packets. For sensor R1 the first one is from 25-55 μs and the second is from 55-90 μs (Figure 6-36a). The intensity plots for a toneburst having a central frequency of 0.5 MHz are overlaid on the dispersion curves in Figure 6-37. Figure 6-37(a) and (c) correspond to the two wave packages, where the first wave package is the S0 mode and the second package is the A0 mode. By applying the same time window to the notched case, Figure 6-37 (b), mode content change due to the notch can be observed in Figure 6-37 (b) and (d). Comparing Figure 6-37 (a) and (b), where the S0 mode dominates, the notch will cause mode conversion and the A0 mode is produced by the wave-damage interaction. For
Figure 6-37 (c) and (d) where the A0 mode dominates, a portion of power of A0 mode is converted to the S0 mode due to the notch. This observation agrees well with the results in literature [59].

The detection of the notch shows that the wave modal composition can be used as a universal damage indicator because it is targeting mode conversion which is usually a result of wave-defect interaction.

Figure 6-36: A-scans received by sensor R1 (a) and sensor R2 (b). The incident angle is 30 degree and the toneburst has a central frequency of 0.5 MHz.
Figure 6-37: Spectra from 2D Fourier transforms of received signals overlaid on dispersion curves: (a) unnotched case with a 25-55 μs time window, (b) notched case with a 25-55 μs time window, (c) unnotched case with a 55-90 μs time window, (d) notched case with a 55-90 μs time window.
6.3.4 The detection of disbands in an aluminum adhesive bonding

To further demonstrate the value of using wave modal composition as a damage indicator for detection of different defects, an experiment has been carried for an adhesive bond of aluminum plates as well. The experiment is performed using three samples with different bond conditions as shown in Figure 6-38. Samples are fabricated in a skin-stiffener configuration. Waves are sent along the adhesive bond following paths shown in Figure 6-38 such that path (a), (b) and (c) are corresponding to: good, partially disbonded (50%) and fully disbonded (100%) conditions respectively.

Following the same method used for composite adhesive bonds, finite element analysis is carried out first to identify incidences with good sensitivity. Then experiments will be carried out to verify the sensitivity in detection. Phase velocity and group velocity dispersion curves are given in Figure 6-39. With the PAT as the actuator, available frequency range is from 200 kHz to 700 kHz. Compared with composite adhesive bonds, limited number modes exist in this range. It should be noted that modes 2 and 4 are shear horizontal modes which could not be excited by PAT. Thus, the remaining possibilities are modes 1, 3, 5 and 6.
Figure 6-39: The dispersion curves of the aluminum adhesive bond. (a) is phase velocity dispersion curve plot and (b) is group velocity dispersion curve plot.

The behavior of wave-defect interaction has been studied using the frequency domain finite element model created for aluminum adhesive bond. It is found that only mode 3 shows intermediate sensitivity at certain frequency range, namely, 440 kHz to 600 kHz. A representative result is shown in Figure 6-40 with the same format as those shown in Sec. 6.2.2. It is observed that mode 3 at 520 kHz will mode convert to mode 6.
Figure 6-40: The frequency domain results of the wave-defect interaction for the incidence of mode 3 at 520 kHz in an aluminum adhesive bond.

Experimental results for the incidence of mode at 520 kHz is shown in Figure 6-41. It is clearly observed that for the disbonded conditions, (b) and (c), mode 6 become more evident. This is due to mode conversion.
Figure 6-41: The results of the disbond detection using the incidence of mode 3 at 520 kHz. (a) to (c) are received time signals for conditions of good, disbond 1, and disbond 2 respectively. (d) to (f) are the modal content of the wave signals in the windows defined by red dash lines plotted as intensity plots overlaid on phase velocity dispersion curves.

Summarized results are shown in Figure 6-42 and Figure 6-43 for using modal amplitude and wave modal composition as damage indicators respectively. By using modal amplitude only, the good bond condition can be differentiated from disbonded conditions easily. However, the discrimination of different sizes of disbond is poor. By using wave modal composition, all the three curves are separated and good sensitivity to sizes of disbond is observed.
Figure 6-42: The result of defect size characterization using mode 3 at 480-600 kHz as incidence. Raw amplitude is used as the damage indicator.

Figure 6-43: The result of defect size characterization using mode 3 at 480-600 kHz as incidence. Wave modal composition is used as the damage indicator.
6.4 Summary

Damage indicators based on modal content were introduced in this chapter. The procedure of predicting sensitive and insensitive incidences was introduced and its applicability in damage detection and characterization was demonstrated.

Modal content information is crucial for successful SHM using Lamb waves because the sensitivity of Lamb wave varies with both mode and frequency. This fact has been verified by both finite element analysis and experiments. In the finite element analysis, a frequency domain model is created such that the sensitivity of each point on dispersion curves could be examined. Compared with a time domain model, the frequency domain model enables the study of just one point on dispersion curves which is impossible for the time domain model because it always excites a range of frequency. Also, the frequency model is essentially a steady state model which needs much less computational power than a time domain model. It has been found that the points on dispersion curves, or incidences, can be divided into three groups, namely, sensitive, intermediate and insensitive incidences.

Then, experiments are carried out and demonstrate that different incidences indeed have different sensitivity to the disbond. Damage detection under elevated temperature is performed to study the extent to which the temperature could affect the sensitivity of wave to a disbond. Generally, elevated temperature could cause a decrease in the amplitude of waves. For sensitive incidences, such a decrease is usually minor compared with the amplitude reduction induced by the presence of disbond. However, for the incidences with intermediate sensitivity, the effect of temperature change is at the same level as that of the presence of a disbond. For this case, a good bond at elevated temperature and a disbond at room temperature will result in the same modal amplitude. To differentiate them, wave modal composition is proposed such that not only the amplitude of primary mode but the amplitude of the converted mode is also included in the design.
of a ratio representing the change in wave modal composition. It should be noted that the two modes for constructing the ratio are not randomly selected but based on the knowledge of the behavior of mode conversion at the disbond. Such a behavior can be predicted using the finite element model beforehand. The wave modal composition, as a novel damage indicator, proves to have better sensitivity to the disbond and is robust under elevated temperature. A counter example of insensitive incidence is also shown to have hardly any sensitivity to the disbond.

The characterization of the size of a disbond is also demonstrated by moving two PAT actuators to cover different areas of a disbond. Modal amplitude of sensitive incidence and wave modal composition of intermediate incidence both show good characterization capability.

Besides the disbond in a composite adhesive bond, notch in an aluminum plate and disbands in an aluminum adhesive bond are also studied using wave modal composition as the damage indicator and good sensitivity are demonstrated.
Chapter 7

Conclusions

7.1 Summary of Research

Composite materials, especially fiber reinforced polymers, have been gaining wide application in the aircraft and automobile industries. So far, co-cure and adhesive bonding are the two most common methods of joining composite materials. Composite structures assembled by these methods are subject to different types of defects and need reliable structural health monitoring (SHM) techniques. This work is focused on SHM of adhesive bonding, which is usually the hot-spot in structures. The guided wave technique is selected for this purpose because of its large coverage of structures and good sensitivity to defects. On the other hand, co-cure and adhesive bonding produce similar structures from the point of view of wave propagation. The scheme developed for adhesive bonding monitoring can be easily applied to monitoring co-cured bonds.

Extensive research has been carried out in the NDE domain for inspection of defects and material properties in adhesive bonds. However, most of these techniques are not directly applicable to SHM technique for different reasons. A common reason is the lack of appropriate instrumentation, namely, actuators and sensors. In this research, phased array transducers and PVDF array sensors are designed for SHM purposes and fabricated to small size and light weight. The actuator shows good capability in excite different modes preferentially at different frequencies. The sensor has excellent performance in extracting wave modal content and suppressing cross talk. In the NDE domain, such tasks could only be done by using movable sensors like laser vibrometers and air-coupled transducers. The actuator and the sensor together
make a good companion in on-line guided wave excitation and reception and prove to be powerful tool in experiments.

A finite element model is created to study the wave-defect interaction. A disbond at the interface between the adhesive layer and the lower adherend is simulated. The analysis shows that incidences have different sensitivities to the disbond. According to their sensitivities, they are divided into three groups with good, intermediate and no sensitivity to the disbond. The FEA model provides guidelines in mode selection and predicts the behavior expected to be observed in the experiments. Since mode conversion is observed for incidences with good and intermediate sensitivity, it is proposed to use wave modal composition as a damage indicator.

Finally, experiments demonstrate that the amplitude reduction of sensitive incidences is solely a good damage indicator. Its sensitivity is good at both room and elevated temperatures. For intermediate incidences, the amplitude reduction itself is no longer a robust damage indicator for different temperatures. Thus, wave modal composition is used and an evident improvement in sensitivity is observed. Furthermore, characterization of the size of a disbond is performed using two phased array transducers to cover different areas of a disbond. Damage indicators that are good for detection also show good capability for size characterization. The idea of using wave modal composition is extended to the detection of a notch in an aluminum plate and disbond between two adhesively bonded aluminum plates.

7.2 Research Contributions

The primary contributions of this research are:

1. A SHM-ready phased array transducer, which is of small size and low weight is designed and fabricated as actuators for Lamb wave excitation. Its good performance in preferentially exciting different modes at different frequencies is demonstrated
experimentally. Compared with commonly used PZT disks, the phased array transducer is broadband and capable of mode control. However, it requires a multi-channel pulsor/receiver card to control it, which is usually significantly more costly than a single channel pulsor/receiver card.

2. A PVDF array sensor with superior low profile is designed and fabricated for Lamb wave reception. Compared with conventional SHM sensors, like PZT disks, its multi-channel configuration enables the capability of extraction of wave modal content and velocity calculation. Also, the PVDF array sensor is as light as PZT disks but is flexible and can conform to surfaces with curvature. Not like the phased array transducer mentioned above, a multi-channel card is not a necessity for wave receiving using PVDF array sensor because the time signals of the 16 channels do not need to be recorded simultaneously. Thus, a single channel card combined with a multi-channel switching card could function as well.

3. A frequency domain finite element model is built to study the behavior of wave-defect interaction. The model could be extended to any type of defect as long as the defect can be properly represented in a finite element model.

4. Behavior of wave-defect interaction has been studied for disbonds in composite adhesive bonds. The sensitivity of an incidence is defined by its amplitude reduction due to the interaction with a disbond. All the incidences are classified into three groups by their sensitivities. Additionally, mode conversion of both transmitted and reflected waves contribute to the amplitude reduction.

5. Experiments that integrate the use of PATs, PVDF sensors and FEA predictions are carried out. A novel damage indicator, wave modal composition is proposed and its effectiveness is verified. Damage detection under different temperatures, size
characterization of disbond and detection of different defects are demonstrated experimentally.

6. A 16-channel phased array DAQ system is constructed and programmed based on an 8-channel phased array DAQ system. Main upgrades include

1) Compile numerous independent variables into data structures in LabVIEW for the readiness of future upgrades.

2) Functions like short-time Fourier transform and 2D Fourier transform are added to the program such that frequency and wavenumber spectra of received signals can be shown in real time. These functions provide helpful feedback to the user to interpret the complicated guided wave signals in real time during experiments.

3) Fix bugs. A common bug existing in a multichannel DAQ system is losing synchronism of switch status (on/off) of channels while assigning control parameters, e.g. frequency and time delay, to different channels. This bug is fixed in the current version of control program.

7.3 Recommendations for Further Research

The instrumentations, numerical models and experiment methods developed in this work provide a useful platform for future research. Some possible directions for future research are provided here:

1. Create a library of behaviors of wave-defect interactions

Creating a library of behaviors of wave-defect interactions for other representative defects and structures could be a helpful reference for selecting modes for inspection and classification of defect types. The behaviors of a wave-defect interaction include mode conversion, reflection and amplitude reduction of the incident mode.
2. Development of 2D array actuators and sensors

Compared with 1D array actuators and sensors used in this work, 2D array actuators and sensors will provide more powerful functions like direction control and defect localization in addition to mode control.

3. Multi-physics models of transducer-structure interaction

Currently, a multichannel phased array system is still expensive and needs lots of cables. By building a model which includes both piezoelectric device and wave propagation, the configuration of a single piezoelectric element, i.e. material and geometry, can be designed such that a propagating mode can be excited at a particular frequency. If such a design exists, phased array pulsor is no longer necessary because the configuration of the piezoelectric element can preferentially excite one mode at one frequency by itself. In this case only one channel is sufficient to drive the actuator.

4. Finite element model with shear horizontal wave simulation

The current finite element model could only model Lamb waves because it is a 2D plane strain model. However, shear horizontal waves, as another important family of guided waves, could potentially provide better sensitivity.

5. Probabilistic life prediction modeling based on quantitative SHM results.

With the knowledge of the size of disbonds and the operational loadings on the adhesive bonds, its fatigue life could be predicted with either theoretical or finite element model enabling condition-based maintenance.
References


Appendix

Nontechnical Abstract

The aircraft industry has been seeking light and strong materials for load bearing structures from the very beginning. Composite materials, especially carbon fiber reinforced polymers, are gaining more and more attention and considered as the most promising alternatives to aluminum alloys. However, the two-phase microstructure, anisotropy and laminated structure collectively result in new types of defects and failures like fiber breaking, matrix cracking, delamination and disbonds. This presents great challenge to operate newly composite aircrafts safely and economically.

To strike a balance between the safety and cost, it is desirable to perform the maintenance based on the current health condition of the structure. To provide sufficient knowledge of the structure, a structural health monitoring (SHM) system is needed. The SHM originates from the nondestructive evaluation technique (NDE) but provides real-time health and operational conditions of the structure with the help of surface-mounted on and embedded sensors. A number of SHM methods integrate existing NDE methods into structures by developing light weight and small size sensors such that the NDE technique can be performed online. This work will focus on the monitoring of the disbonds in a composite adhesive bond which usually represent the hotspots of the assembled structure.

Ultrasonic guided waves have been used for NDE for many decades. Their large volumetric coverage and good sensitivity to defects make them a promising tool for aircraft SHM system. However, most current SHM system using ultrasonic guided waves only focus on a limited number of modes which sometimes cannot perform reliable inspection. The work of this thesis is focused on the development of instruments and techniques for guided wave SHM. The design of phased array transducers and array sensors enables mode selection and extraction.
capabilities such that the excitation and interpretation of higher order guided wave modes are possible. Also, a frequency domain finite element model is created to predict the defect sensitivities of different modes at different frequencies. Wave-defect interactions for fundamental and higher order Lamb wave modes are studied; the wave modal amplitude and wave modal composition are proposed as new damage indicators. Then, the experiments demonstrate that the novel damage indicators have better sensitivity to disbond and reliable performance under elevated temperature. Additionally, the damage indicators can be used to characterize the size of disbond and detect other types of defects like disbands in an adhesive bonding aluminum plates and notches on aluminum plates.

In conclusion, both methodology and instrumentation are developed and demonstrated experimentally to be effective in monitoring disbonds in a composite structure. The methodology and instrumentation are designed for guided wave inspection and can be extended to other applications with minor modifications.
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