Structural Health Monitoring of Composite Laminates Through Ultrasonic Guided Wave Beam Forming

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ABSTRACT

The availability of military platforms is affected by design methods, damage detection, maintenance, and logistics. Structural health monitoring provides a means of detecting damage, which can be used to predict future structural performance of the platform and effectively schedule maintenance. Ultrasonic guided waves can be employed as an active structural health monitoring technique in a variety of ways. Recent progress in detecting damage in composite laminates is summarized. The paper culminates with a description of new phased array technology for beam forming to improve material coverage.

1.0 INTRODUCTION

The availability of a military platform is dependent upon the operability of all its systems. More specifically, the readiness of structures is influenced by many factors; especially design, damage detection, maintenance, and logistics. The focus of this paper is on damage detection in airframe structures, with emphasis on composite laminates. This is a part of the dynamic multidisciplinary field of structural health monitoring (SHM), which applies to military and civilian platforms ranging from aircraft, rotorcraft, and spacecraft to ships, trucks, and trains to power plants, chemical plants, and manufacturing plants as well as to bridges, buildings, pipelines, and dams. SHM provides information about the current state and projected performance of a structural system that enables decisions to be made regarding logistics and maintenance as well as safety. SHM has the potential to improve fleet readiness, safety, and design, and at the same time reduce whole life cycle costs. It includes diagnostics (detecting a change of state in the structure – damage), prognostics (how the damage affects the ability of the structure to perform its intended function in the future), and decision making about maintenance and operations. Effective structural health monitoring relies on the synthesis of nondestructive evaluation, damage mechanics, sensor technology, data acquisition, signal processing, life prediction modeling, as well as other technologies. SHM systems can be designed to mitigate problems associated with a known damage mode in the legacy fleet, or included in the design of new structures.

This paper focuses on the diagnostics element of SHM, that is, damage detection. There are numerous techniques currently under investigation for diagnostics including for example: embedded fiber optic sensors for strain measurement, microelectromechanical system (MEMS) accelerometers for vibration measurement, active ultrasonics, passive acoustic emission monitoring, and electromechanical impedance measurements. The paper briefly describes each of these techniques and then zooms in for a closer look at recent successes with guided wave ultrasonics for laminated composites. The use of ultrasonic guided waves for nondestructive evaluation of structures is rapidly expanding due to increased understanding of the underlying wave mechanics and improvements in sensors and signal processing. The ability of guided waves to travel long distances, and therefore to monitor a large volume of material from one location, makes them very attractive for use in an SHM system. One feature of a structure necessary for monitoring with ultrasonic guided waves is that it be a wave guide, i.e., it has boundaries or interfaces that channel the ultrasonic energy such as plates, shells, pipe, and rail for example. This is not a very restrictive requirement.

Carbon fiber reinforced polymer (CFRP) laminates are being used more and more in aircraft structures due to their high strength to weight and stiffness to weight ratios. The increased performance that they enable outweighs their relatively high cost. However, the damage modes in composite laminates are completely different and more complex than the well-known ones in conventional metal alloys. Furthermore, damage typically initiates much earlier in the life of the structure and often occurs inside the material where it is invisible. Thus, development of SHM diagnostics is critical. Detection and quantification of inter-ply delaminations, matrix cracking and degradation, and fiber fracture is necessary for prognostics.

Finally, the paper presents progress in development and application of ultrasonic guided waves for damage detection in composite laminates. This discussion is organized around the sensing technology employed and includes: surface mounted piezoelectric sensors, air coupled transducers, annular array sensors, embedded piezoelectric fibers, and phased arrays for ultrasonic beam forming.

2.0 DAMAGE DETECTION TECHNOLOGY OVERVIEW

Some of the more common and generally applicable technologies for damage detection within SHM are briefly summarized. This is not intended to be a comprehensive list.

2.1 Fiber Optic Sensors

Fiber optic sensors can be embedded in, or surface mounted to, structural materials. Fiber Bragg gratings (FBG) enable these passive sensors to measure strain at a point much like a conventional resistance strain gage. FBG are processed by focusing ultraviolet light on a small section of a doped optical fiber at a prescribed interference angle. Exposure of the fiber core to ultraviolet light modulates the local index of refraction, which creates a narrow band optical wavelength filter. As broad band light travelling down the fiber encounters a grating, light having the wavelength of the grating is reflected. Deformation of the FBG due to loads changes the grating spacing and hence the wavelength of the reflected light, which can be detected. Because FBG can be designed to reflect light at various wavelengths they can be multiplexed on a single optical fiber. Optical fibers with many FBG are capable of measuring the strain field at hot spots in structural materials, where large local strains indicate the presence of damage. More details and application to vibration monitoring are described by Todd et al. [2001].

2.2 MEMS Accelerometers

Accelerometers are widely used to measure vibrations for condition based maintenance and SHM of machines and equipment [Adams, 2007]. The use of microelectromechanical systems (MEMS) as accelerometers enables them to be extremely small in size, embedded, wireless, and integrated with signal conditioning. MEMS accelerometers are very simple devices, consisting of a cantilever beam with a proof mass.

2.3 Ultrasonics

Ultrasonics and radiography are broad classifications of methods widely used for nondestructive evaluation and testing. These methods are less applicable to SHM due to equipment requirements, that is, many of the methods are best suited for a dedicated laboratory and it is impractical to permanently affix the necessary instrumentation to the structure. One major exception is ultrasonic guided waves that can be generated by lightweight piezoelectric transducers permanently affixed to the structure. Guided waves have strong potential for SHM because they enable monitoring of a large volume of material from a single location. The structure must have boundaries or interfaces that make it a wave guide and channel ultrasonic energy in certain directions. Section 3 describes ultrasonic guided wave methods for SHM in more detail.

2.4 Acoustic Emissions

The initiation and propagation of damage results in a release of energy. In extreme cases, the strain energy converted to sound energy is in the audible range. Usually this is not the case, but the sound energy propagates through the structure nonetheless. Acoustic emission (AE) sensors passively listen to the structure by measuring the pressure due to the acceleration from the passage of sound waves. The sensor has a piezoelectric element that converts the mechanical signal to an electrical signal. The frequencies of AE are often in the 100 kHz to 1 MHz range. Features of an AE event such as counts, peak levels, and energies are correlated with the damage event. It is important to distinguish damage events from background noise and non-damage related events. AE monitoring can be applied to airframe, bridge, storage tank, and building structures.

2.5 Electromechanical Impedance

The electromechanical (E/M) impedance method is a variant of the mechanical impedance method of Lange [1978] and others. The E/M impedance method couples the mechanical impedance of the subject structural material to the electrical impedance measured by a piezoelectric wafer active sensor (PWAS) as described by Giurgiutiu [2008]. The PWAS is used as a high frequency modal sensor. The peaks and valleys of the real part of the electrical impedance measured between the sensor electrodes reflects the mechanical response spectrum of the structure. Damage can be detected through spectral changes characterized by simple statistical equations or probabilistic neural networks. Giurgiutiu's [2008] chapter on E/M impedance methods provides example applications for spot welds, bonded joints, composite overlays for the infrastructure, and aging aircraft panels.

3.0 ULTRASONIC GUIDED WAVE METHODS

Some of the ultrasonic guided wave methods under development for SHM applications are summarized in this section. Again, this is not a comprehensive list, but rather it focuses on some of the more exciting possibilities and culminates with phased array beam forming.

3.1 Surface Mounted Piezoelectric Sensors

Lead zirconate titanate (PZT) is the most commonly used material for surface mountable transducers because of it has relatively high piezoelectric coupling coefficients and it is reasonably affordable. These transducers are referred to as piezoelectric wafer active sensors (PWAS) by Giurgiutiu [2008] and are the subject of his monograph on structural health monitoring. Figure 1 shows a thin PWAS disk sensor. Typically these sensors have electrodes on the top and bottom surfaces and are polarized through the thickness. As an actuator, the through thickness electric potential is converted to a radial displacement that propagates into the base material as a stress wave. The sequence is reversed when the PWAS functions as a receiver. Below, PWAS applications for detection of fatigue damage and for tomography are discussed.

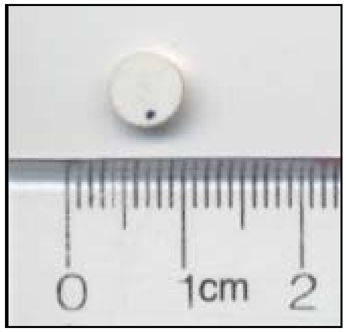

Figure 1: Surface mountable PZT sensor.

3.1.1 Fatigue Damage

Unlike metallic alloys, fatigue damage can initiate in CFRP materials relatively early in their life. Thus, detection of fatigue damage as early as possible is quite important. In a recent study [Lissenden et al., 2007], CFRP laminates were subjected to constant amplitude cyclic bending to induce fatigue damage. Cycling was interrupted periodically for ultrasonic monitoring by an array of six PWAS bonded to the top of the laminate. Nine different pitch-catch (through transmission) paths and a frequency range of 100-600 kHz were used. The signal difference coefficient (SDC), between the pristine laminate and the current state was calculated for each pitch-catch path. Figure 2 shows the evolution of the SDC as a function of the cyclic loading applied to the CFRP. In this case all of the pitch-catch paths between sensors in the array were able to detect damage for frequencies ranging from 200-400 kHz. This provides an earlier indication of damage than compliance changes.

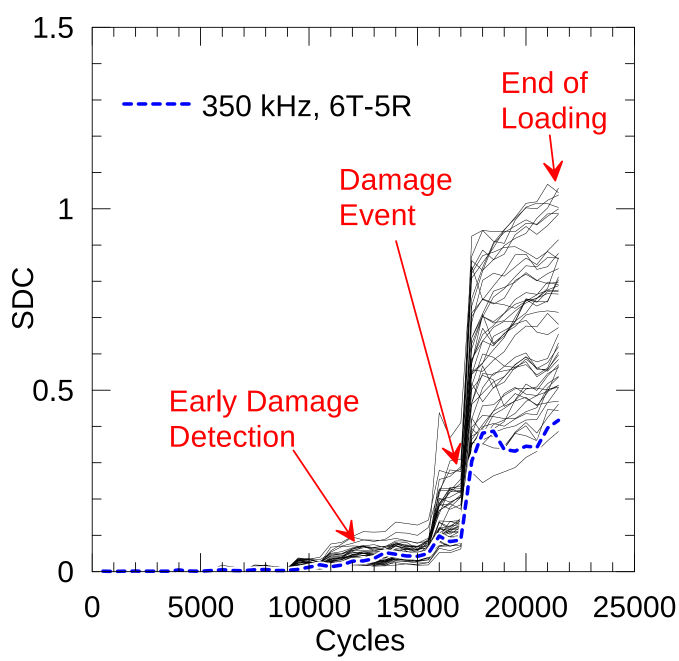

Figure 2: Signal difference coefficient evolution due to fatigue loading demonstrating the potential for early damage detection. Shown are results from 9 different pitch-catch paths and a frequency range of 200-400 kHz.

3.1.2 Tomography

In guided wave tomography, an array of PWAS is mounted around the area to be monitored as shown in Figure 3. Guided waves are sent and received from each PWAS using the pitch-catch approach. Signal features are selected and analyzed to create a computed tomographic image. Due to the multimode nature of guided waves there are a broad range of candidate features for damage detection. The reconstruction algorithm accounts for wave scattering and reflections from damage using a probabilistic method that results in the final tomogram being a superposition of ray ellipses (see Fig. 3). Additional details are provided by Gao et al. [2005], Royer et al. [2007], Van Velsor and Rose [2007], and Breon et al. [2007]. Applications in subsequent sections make use of ultrasonic guided wave tomography to detect and image damage.

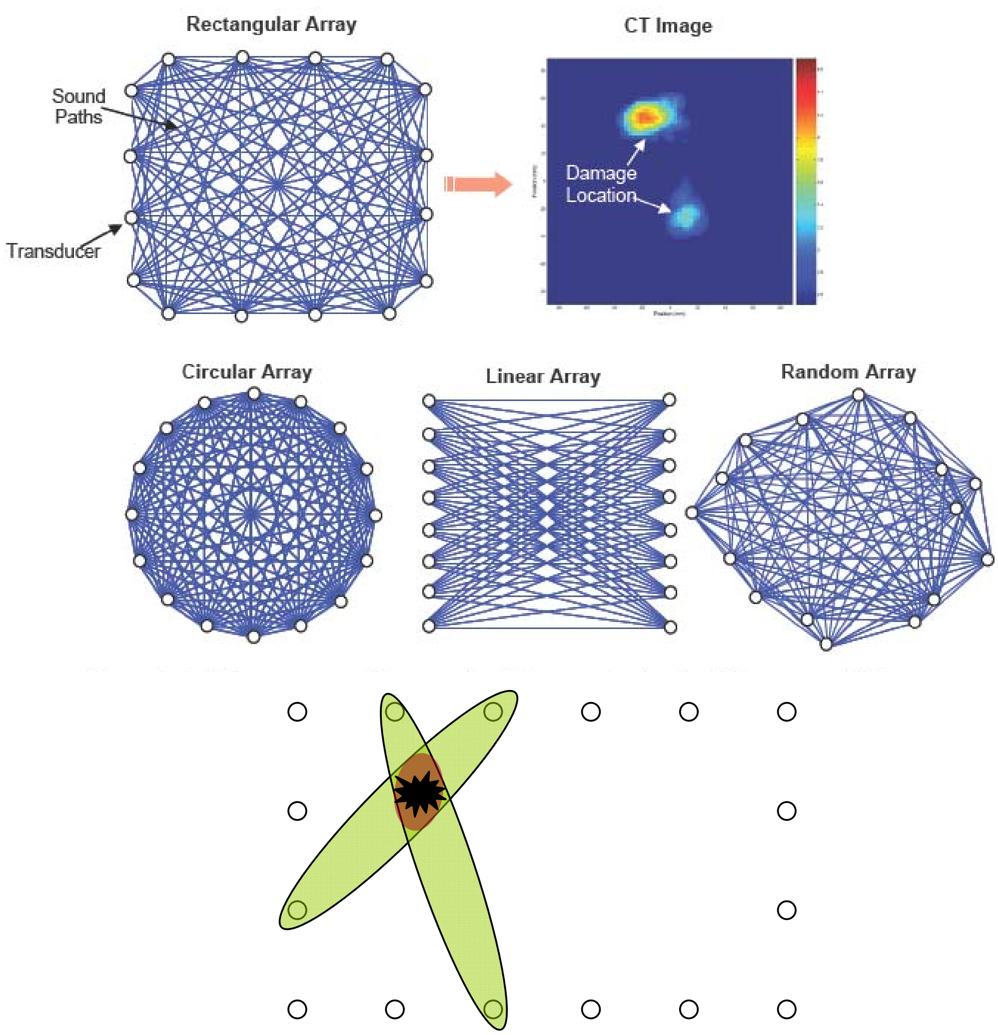

Figure 3: Schematic of sensor arrays showing chords between sensors and a computed tomographic image of damage.

3.2 Air Coupled Transducers

The use of air coupled ultrasonic transducers has become viable for nondestructive evaluation and SHM of composite materials, which is extremely attractive because it is both non-contact and non-contaminating. The proportion of the ultrasonic energy transmitted through an interface depends on how closely the acoustic impedance of the two materials match. The closer the match, the more energy is transmitted. The acoustic impedance of air is low, resulting in large losses (100 dB higher than water couplant in a path from sensor to couplant to test piece to couplant and back to sensor). Thus, it is important to minimize these losses to obtain an acceptable signal to noise ratio. Acoustic impedance mismatch between air and a polymer is much less than that between air and metal. Grandia and Fortunko [1995] discuss advances in technology that make air coupled ultrasound viable for SHM. Castaings and Hosten [2001] generated and detected Lamb and quasi shear horizontal (SH) waves with frequencies in the 100-600 kHz range in a glass/epoxy plate using air coupled ultrasonic transducers. Hsu and Barnard [2006] used air coupled transducers to inspect thick composites and honeycomb structures.

In recent work, our Penn State group has employed air coupled transducers having a 100-400 kHz frequency range to detect delaminations in a CFRP laminate. The set up and results are shown in Figure 4. Three delaminations of varying size were created by dropping different size balls on the plate. Multiple pitch-catch scans were made in 4 different directions using air coupled transducers at a frequency of 200 kHz. Group wave velocities were calculated for each sensor set up and then superimposed to create the contour map that indicates the size and location of the delaminations (Fig. 4d). These compare well with the C-scan results in Fig. 4c (no results are shown here from the ring of 16 PWAS shown in the figure) except there is a false delamination indicated on the right hand side. Future work should eliminate this false indicator.

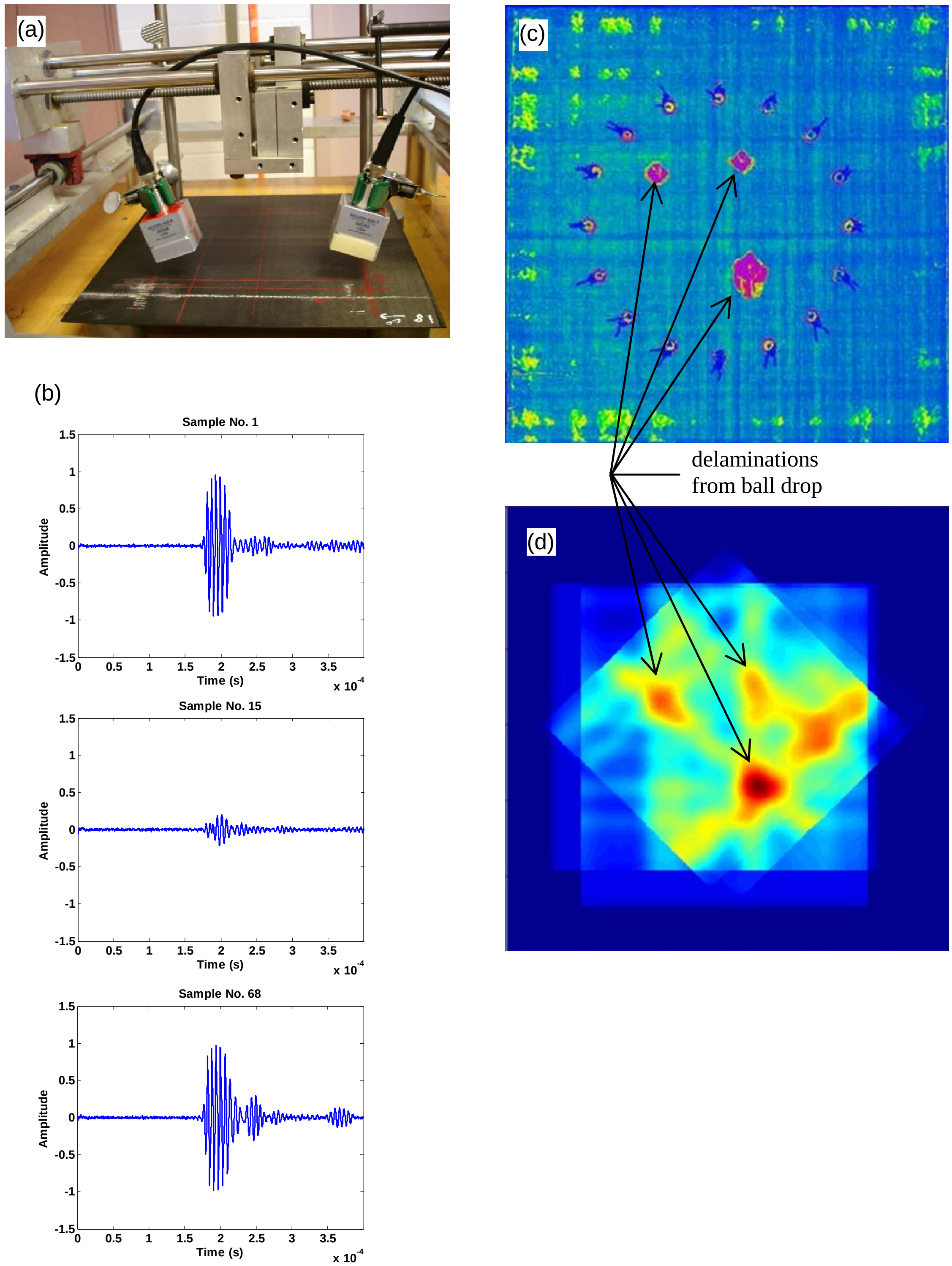

Figure 4: Delamination detection with air coupled transducers and imaging; (a) air coupled transducers set off from composite plate, (b) sample signals received by air coupled transducer, (c) C-scan image, (d) air coupled transducer image.

3.3 Annular Array Sensors

New sensors for improved ultrasonic guided wave tomography are being developed with funding from the Center of Excellence in Structural Health Monitoring (www.esm.psu.edu/shm). The work addresses a strong need for embedded sensor technology in SHM for structural self diagnostics. The overall work area involves sensor development, wireless technology, and energy harvesting techniques with all three areas eventually to be integrated together into a robust SHM system for rotorcraft, aircraft, and other structures. The work here is related to a small but critical element of the overall SHM program; that of developing new, more robust and efficient sensor designs for improved SHM analysis. Great strides have been made in SHM the last decade or so, especially in utilizing small ultrasonic disk-like sensors (PWAS). With the recent development of ultrasonic guided wave tomography, even stronger advances have been made in imaging potential for defect detection, location analysis, and growth characteristics in a variety of different applications including aircraft, pipeline, and welded structures. In a recent application of ultrasonic guided wave tomography a similarity coefficient was used as the key feature. Recent work looks at geometrically new sensor designs for improved physically based imaging. An example is locating and visualizing corrosion of an aluminum plate. Figure 5a shows a corrosion defect encircled by 8 PZT disk sensors and 8 PVDF annular sensors. The annular sensors enable mode control, which can be crucial for distinguishing damage detection from false positive indicators. By applying knowledge of the dispersion curves (Fig. 5b) and wave structure, the optimal mode and frequency can be selected for damage detection. The tomograms in Figures 5c and 5d are for an aluminum plate with a corrosion defect and surface water. PZT disk sensors have no mode control and give a false positive indication associated with surface water (Fig. 5c), while the annular sensors can be controlled and clearly indicate the corrosion damage (Fig. 5d) but not the surface water.

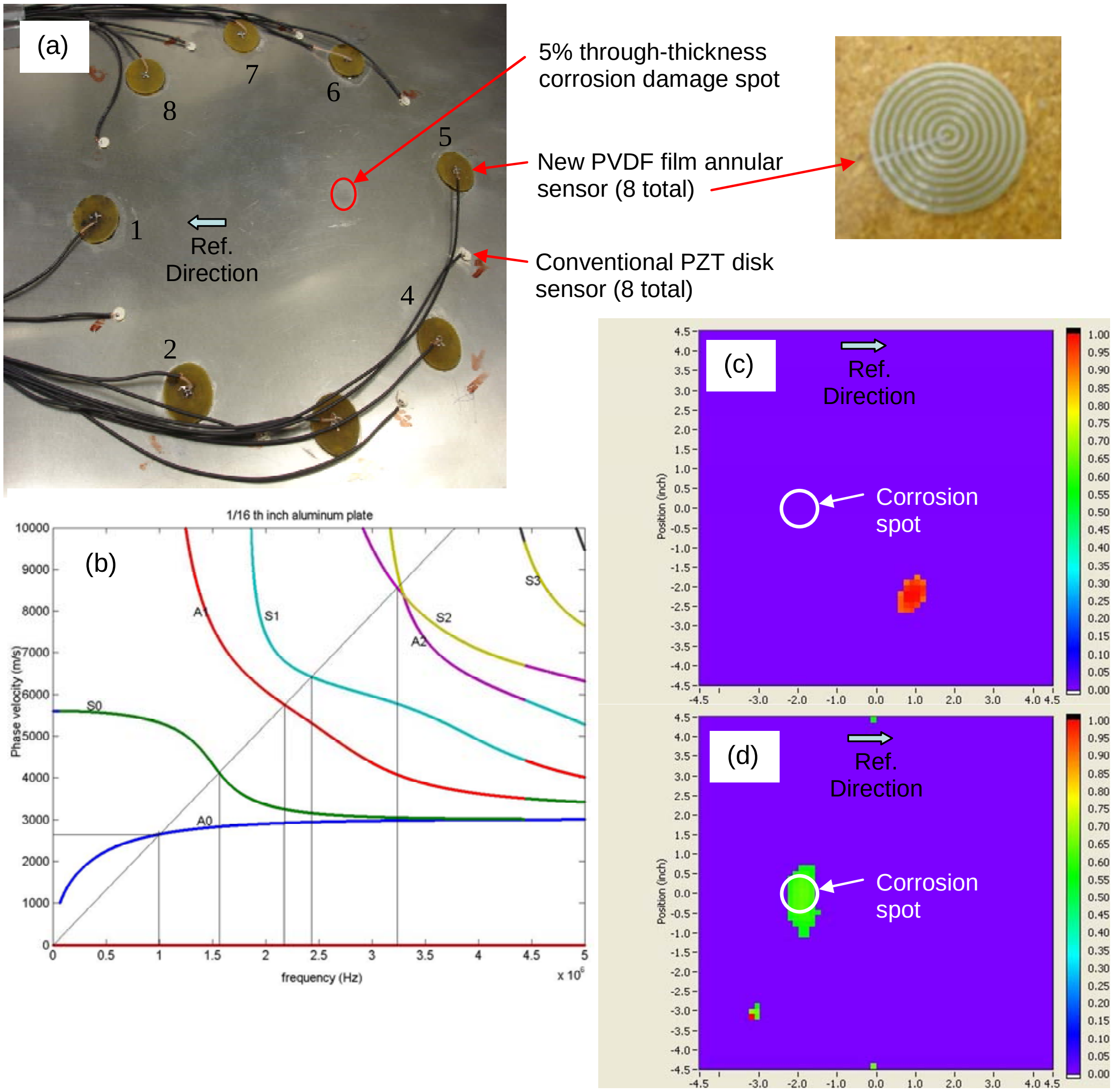

Figure 5: Corrosion damage detection, (a) sensor arrays enclosing the damage, (b) dispersion curves for aluminum plate with annular array activation line shown, (c) tomogram from PZT sensors did not identify defect and show a false positive, (d) tomogram from PVDF sensors identified corrosion in the presence of surface water.

3.4 Embedded Piezoelectric Fibers

Piezoelectric fibers have been used for harvesting vibrational energy and to actively damp undesirable vibrations. They can also be used for SHM. Piezoelectric fibers having a metal core can activate guided waves in a CFRP laminate transverse to the fibers with radial displacement components originating from the d33 coupling coefficient. They can also generate guided waves in the direction of the piezoelectric fibers using the d31 coupling coefficient. A linear array of fibers embedded at the midplane of a CFRP laminate can generate guided waves as shown in Figure 6 from numerical modeling. Additional details of the finite element analysis are provided by Lissenden et al. [2008, 2009]. The contour plots are from a 2D model containing the cross sections of the parallel fibers and the contours are of elastic strain energy density. Analysis of these and other finite element simulations show that a significant source influence is associated with the small diameter piezoelectric fibers. The source influence needs further study to realize the potential of piezoelectric fiber networks for SHM.

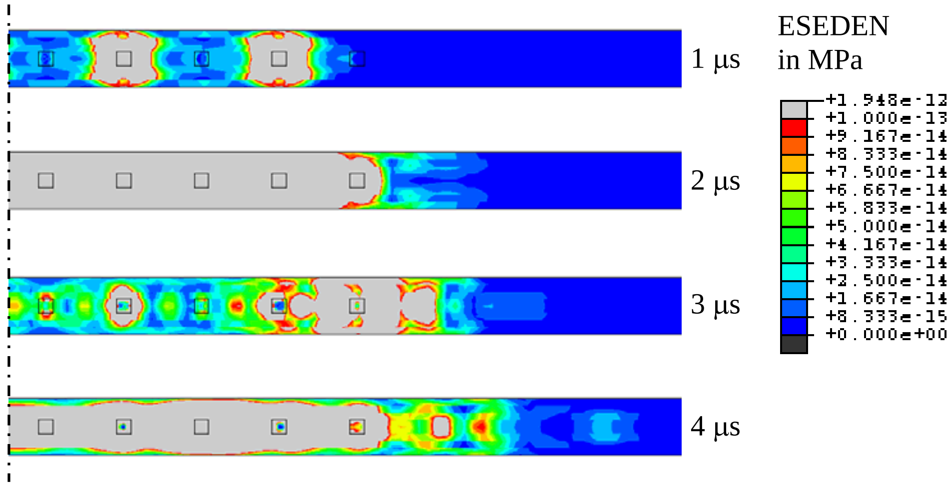

Figure 6: Finite element simulation of generation of waves from embedded piezoelectric fibers in a CFRP laminate.

3.5 Phased array

Through beam forming, the penetration power and sensitivity to damage of guided waves emitted from a single location can be increased. Beam forming technology is of particular interest in monitoring hot spots, or where uniform coverage is needed in order to increase sensor spacing. In order to successfully form a focused beam of ultrasonic energy in a prescribed direction it is necessary to select the proper mode and frequency. A comparison of theoretical and experimental dispersion curves from Gao [2007] is shown in Fig. 7. These dispersion curves, in conjunction with the wave structure, and other information about excitability, skew angle, attenuation, and beam spreading enable coherent beam forming as shown in Fig. 8b. Ultrasonic guided waves show strong potential for beam forming, even in complex laminated composites.

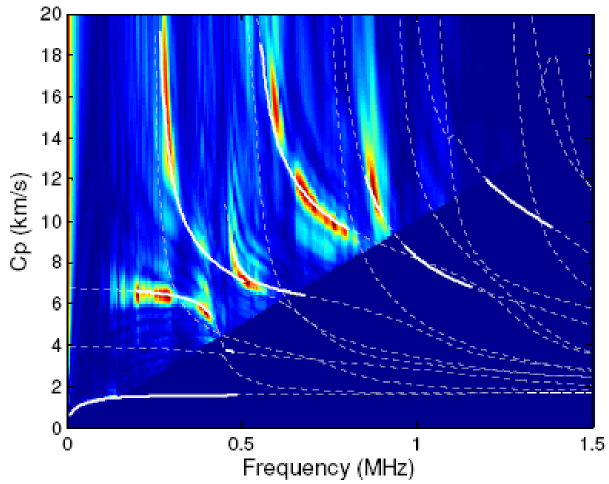

Figure 7: Experimentally determined dispersion regions overlaid upon dispersion curves with optimal regions based upon excitability, skew angle, and attenuation [Gao, 2007].

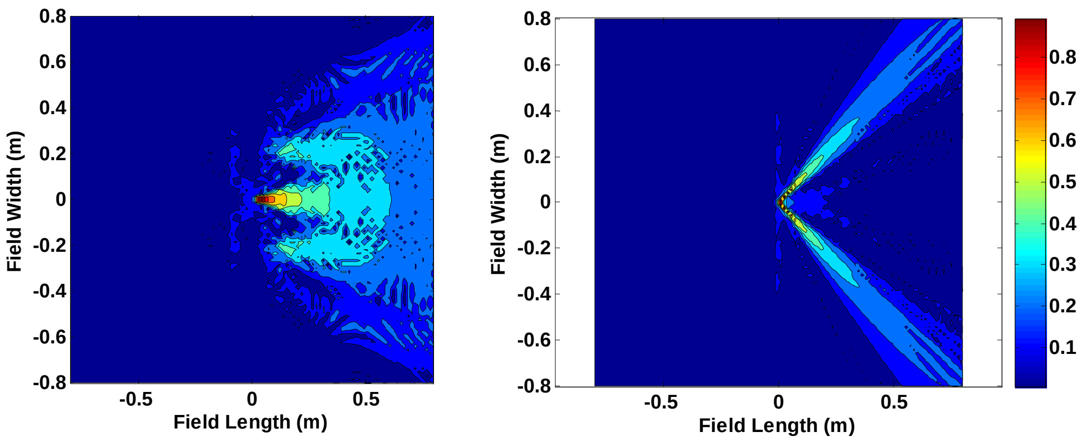

Figure 8: Beam forming at 45 degrees in a unidirectional composite plate with a nine element linear array of sensors using a delay-and-sum algorithm, (a) failed due to improper selection of mode and frequency, (b) successful due to understanding the underlying wave mechanics [Yan and Rose, 2007].

Yan and Rose [2007] and Yan et al. [2008] apply the beam steering methodology of Giurgiutiu and Bao [2004] and Yu and Giurgiutiu [2005] for aluminum plates to composite plates. Beam steering in isotropic plates is achieved by an array of transmitters using a delay-and-sum algorithm. But wave group velocities in anisotropic composites are direction dependent, that is to say the slowness curve is not circular. Furthermore, for dispersive guided waves there is a different slowness curve for each frequency of every mode. Yan and Rose [2007] found that at certain frequency points along a mode that the slowness curve can be nearly circular, and at these points the delay-and-sum algorithm for isotropic materials can be applied. Figure 8 shows two examples of beam forming at 45 degrees in a laminated composite plate. In Fig. 8a, where beam forming failed, a frequency and group velocity pair having an elliptical slowness curve was used, while in Fig. 8b a frequency and group velocity pair having a nearly circular slowness curve was used, resulting in a strong beam oriented at 45 degrees. We look forward to developing algorithms that are less restrictive.

4.0 CLOSURE

Recent research has elevated ultrasonic guided wave technology for structural health monitoring of composite laminates to a high readiness level. A phased array of sensors can form a steerable beam to actively monitor for damage in a large area of an airframe structure. Detection of inter-ply delaminations or fatigue damage can be used to effectively schedule maintenance.

5.0 ACKNOWLEDGEMENT

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