Disbond detection in adhesively-bonded structures using piezoelectric wafer active sensors

Adrian Cuc*, Victor Giurgiutiu**, University of South Carolina, Department of Mechanical Engineering, Columbia, SC 29208

ABSTRACT

Adhesively bonded joints between metallic and composite plates are gaining increasing acceptance in safety critical applications such as automotive and aerospace structures. Lamb wave methods have considerable potential for the inspection of adhesive joints and assemblies for two reasons: they do not require direct access to the bond region, and they are much more amenable to rapid scanning than are compression wave techniques. Lamb waves can be excited in one plate of a bonded assembly, propagated across the joint region, and received in the second plate of the assembly. The paper will present a study of the use of guided Lamb waves for disbond detection in adhesively bonded layered media using piezoelectric wafer active sensors (PWAS). The focus is on developing and compare methods for damage and disbond detection in adhesively bonded structures. For far-field detection, propagating Lamb waves will be used in pitch-catch and pulse-echo modes. The pitch-catch method will send Lamb waves across the adhesive joint, while the pulse-echo method will send Lamb waves along the joint line. For near-field detection, high-frequency standing Lamb waves will be used to evaluate the presence of disbond from the changes in the mechanical impedance of the bonded joint. The standing wave approach is achieved with the self-sensing electromechanical impedance method. Both, the propagating and the standing Lamb waves are generated with the same PWAS installation. The combination of far-field and near-field damage detection in the same sensor installation is a unique feature of our work.

Keywords: Disbond, Ultrasonic, PWAS, Lamb waves, Adhesive Joints, Structural Health Monitoring, Damage Detection, NDE

1 INTRODUCTION

With an increasing use of adhesively bonded joints in the industry, there is a correspondingly growing need for the inspection of adhered joints in two aspects. First, it is necessary to detect defects in the adhesive materials such as voids inclusions or the possibility of chemical misformulation or miscure of the adhesive. Second, in situations of automated assembly typical of mass manufacture, it is important that the dimensions of the adhesive bondline are both measurable and within tolerance. Ultrasonic compression wave scanning of adhesive bondlines requires physical access to the joint region, and it is time consuming and expensive.

In the aerospace applications it is important that the size and the location of the damage that exist in the structure can be detected as accurately as possible. There has been extensive work done by many researchers in this direction and nondestructive evaluation (NDE) methods are successfully used for damage detection and damage localization in aerospace applications. Conventional ultrasonic methods for damage detection in metallic plates and composite materials using traditional ultrasonic transducers have been used by various researchers. However, guided waves used for NDE have shown encouraging results and are becoming more popular in the NDE field versus conventional through-the-thickness bulk wave ultrasonic methods.

A large number of nondestructive inspection (NDI) techniques have been developed to identify local damage and detect incipient failure in aerospace structures. In the past years some of these techniques have been tested in the automotive industry as well. Among them, ultrasonic inspection based on elastic wave propagation is well established and has been used in the engineering community for several decades[1]. Also used is the mechanical impedance method[2]. The piezoelectric wafer active sensors (PWAS) methodology bears substantially on the experience accrued with conventional ultrasonic techniques. However, major differences exist between conventional ultrasonics and active-

*aicuc000@engr.sc.edu; phone (803) 777-0619, fax: (803) 777-0106
**victorg@sc.edu; phone: (803) 777-8018, fax: (803) 777-0106

sensor methods. Drawbacks of the ultrasonic techniques are the bulkiness of transducers and the need for a normal (perpendicular) interface between the transducer and the test structure. The former limits the access of ultrasonic transducers to restricted spaces. The latter influences the type of waves that can be easily generated in the structure. In contrast with conventional ultrasonics, the embedded active-sensors methods use wafer-like transducers (PWAS) that are permanently bonded to the structural surface. These active sensors are small, thin, unobtrusive, and non-invasive. They can be placed in very restrictive spaces, like in built-up aerospace structures. The surface-bonded active sensors can easily produce guided waves traveling parallel to the surface and could detect damage that would escape an ultrasonic method. Additionally, the ultrasonic probes must be moved across the structural surface through manual or semi-automated scanning, whereas embedded active sensors are permanently wired at predetermined locations. They can be remotely scanned through electronic switching.

2 STATE OF THE ART

Viktorov[3] was one of the pioneers in the NDE field, and he has published extensively on the use of guided waves (Rayleigh and Lamb waves) for nondestructive testing. Rayleigh waves are waves that occur on the surface of semi-infinite elastic media and so they are suitable to detect surface defects, while Lamb waves are guided waves traveling through the thickness of the thin plates therefore they are used for crack, inclusions, and disbond detection in metallic and composite structures. Worlton[4,5] recognized the advantages that Lamb and Rayleigh waves offer versus the compression waves. The potential of guided waves to be used for monitoring metallic aircraft structure was investigated by Alleyne and Cawley[6] and Dalton et al.[7] using dispersion analysis and numerical modeling of the Lamb waves in metallic plates. The work addresses the selection of the Lamb wave modes, the tapering skin, the effect of the sealant on the skin of the aircraft as well as the painted skin, the propagation across double skin systems, and propagation across aircraft joints. The results showed that guided waves offer good potential for localized structural monitoring. Long range propagation through tapered skin presents little problem as long as dispersion is avoided. However, sealant layers can create severe damping problems. The fasteners present in the structure were neglected in the study. New Lamb-wave based NDE techniques have recently emerged. Schwartz et al.[8] proposed a Lamb wave ultrasonic tomographic imaging system for aircraft structural health assessment. The acquisition and processing of Lamb wave data uses the image reconstruction method and is based on algorithms developed for cross-borehole tomography. The transducers geometry consists of parallel arrays of transmitter-receiver locations. The damage was a simulated circular defect with a 2.5 mm diameter in an aluminum plate. The results showed that the method could accurately determine the dimension, shape, and location of defect by reconstructing an area of 30.5x30.5 cm^2.

An automated structural health monitoring system embedded into the aircraft structure is not possible using conventional bulk wave transducers. For such a system, the sensors must be as much as possible part of the structure on which they are attached. New technology using piezoelectric wafer active sensors (PWAS)[9] is being developed based on the piezoelectric ceramic wafers (lead-zirconate-titanium – PZT). The direct piezoelectric effect is when the applied stress on the sensor is converted into electric charge. The inverse effect, conversely, will produce strain when a voltage is applied on the sensor. In this way the PWAS can be used as both, transmitter and receiver. The advantage of such sensors is that they are small, unobtrusive, and can be embedded in the structure. Giurgiutiu and Zagrai[10] characterized the PWAS for structural health monitoring and developed quality assurance techniques. Liu et al.[11] investigated the input-output characteristic of piezoelectric structural health monitoring systems for composite plates. Lee and Staszewski[12,13] studied Lamb waves for damage detection in metallic structures.

2.1 Wave propagation methods

Ultrasonic methods rely on elastic wave propagation and reflection within the material, and identify the field inhomogeneities due to local damage and flaws. Ultrasonic testing involves one or more of the following measurements: time of wave transit (or delay), path length, frequency, phase angle, amplitude, impedance, and angle of wave deflection (reflection and refraction). Conventional ultrasonic methods include the pulse-echo, the pitch-catch (or pulse-transmission), and the pulse-resonance techniques[14]. A piezoelectric ultrasonic probe placed on the structural surface induces ultrasonic waves in the material. Good contact between the probe and the structure is obtained by using special coupling gels. Depending on the incidence of the probe with respect to the structural surface, the waves created in the structures may be normal, shear, or a combination of the two. Normal waves are best suited for through-the-thickness detection. In the pulse-echo method, defects are detected in the form of additional echoes. In the pitch-catch method, wave dispersion and attenuation due to diffused material-damage is used as a flaw indicator. Since ultrasonic waves cannot be practically induced at right angles to the structural surface, localized surface flaws, and cracks with their plane perpendicular to the structural surface cannot be readily detected with conventional ultrasonic techniques.

Advanced ultrasonic techniques rely on the generation, propagation, and detection of Rayleigh, Lamb, and Love waves[1] that act at the surface and can cover both normal and flexure modes. These waves can be generated, with some difficulty, using conventional ultrasonic transducers and wedge couplers, provided the angle of the coupler is sufficiently large to trigger mode conversion. Further advancements in this direction were achieved through acousto-ultrasonics[16]. These techniques are now being transitioned to embedded active sensor applications using PWAS technology (Figure 1). Chang and his students[17,18,19] used this technology to identify impacts and detect delaminations in composite structures. Damage detection results with PWAS transducers were also reported by other investigators[20,21]. Other investigators[22] studied the detection and characterization of damages by PWAS-generated longitudinal waves in aluminum beams. PWAS pairs placed at the end of the beam acted as transmitters and a PWAS pair in the middle of the beam acted as receiver. A small aluminum clamp was used to simulate damage. The Daubechies 'db8' wavelet transform was used to process the signal. It showed some improvement over time-domain methods. Interesting results using wavelet transforms during active sensors structural health monitoring experiments were also presented by Deng et al.[23] and Lemistre et al.[24].

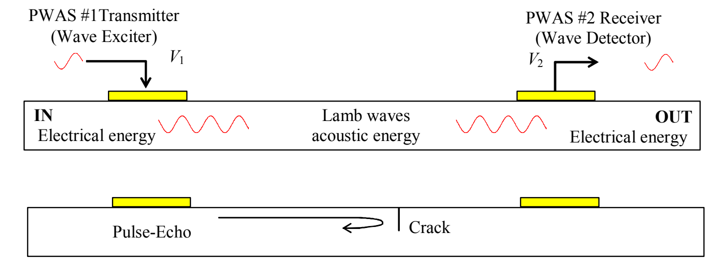


Figure 1 Ultrasonics damage detection techniques with the pulse-echo method

2.2 Electromechanical impedance (E/M)

The impedance method is a damage detection technique complementary to the wave propagation techniques. Ultrasonic equipment manufacturers offer, as options, mechanical impedance analysis (MIA) probes and equipment[25]. The mechanical impedance method consists of exciting vibrations of bonded plates using a specialized transducer that simultaneously measures the applied normal force and the induced velocity. Cawley[2] extended Lange's work on the mechanical impedance method and studied the identification of local disbonds in bonded plates using a small shaker. Though phase information was not used in Cawley's analysis, present day MIA methodology uses both magnitude and phase information to detect damage.

The electro-mechanical (E/M) impedance method[26,27,28] is an emerging technology that offers distinctive advantage over the mechanical impedance method. While the mechanical impedance method uses normal force excitation, the E/M impedance method uses in-plane strain. The mechanical impedance transducer measures mechanical quantities (force and velocity/acceleration) to indirectly calculate the mechanical impedance, while the E/M impedance active sensor measures the E/M impedance directly as an electrical quantity. The principles of the E/M impedance technique are illustrated in Figure 2.

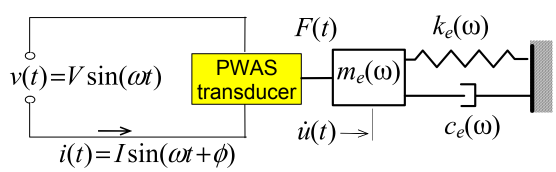


Figure 2 Electro-mechanical coupling between the PWAS and the structure.

The effect of a piezoelectric wafer active sensor affixed to the structure is to apply a local strain parallel to the surface that creates stationary elastic waves in the structure. The structure presents to the active sensor the drive-point impedance, $Z_{str}(\omega) = i\omega m_e(\omega) + c_e(\omega) - ik_e(\omega)/\omega$. Through the mechanical coupling between the PWAS and the host structure, on one hand, and through the electro-mechanical transduction inside the PWAS, on the other hand, the drive-point structural impedance is directly reflected into the effective electrical impedance as seen at the active sensor terminals. The apparent electro-mechanical impedance of the piezoelectric active sensor as coupled to the host structure is:

$$Z(\omega)=\left[i\omega C\left(1-\kappa_{31}^2\frac{Z_{str}(\omega)}{Z_{PWAS}(\omega)+Z_{str}(\omega)}\right)\right]^{-1}, \quad (1)$$

where $Z(\omega)$ is the equivalent electromechanical admittance as seen at the PWAS terminals, C is the zero-load capacitance of the PWAS, κ_{31} is the electromechanical cross coupling coefficient of the PWAS ($\kappa_{31}=d_{13}/\sqrt{\bar{s}_{11}\bar{\varepsilon}_{33}}$), Z_{str} is the impedance of the structure, and Z_{PWAS} is the impedance of the PWAS. The electromechanical impedance method is applied by scanning a predetermined frequency range in the hundreds of kHz band and recording the complex impedance spectrum. By comparing the impedance spectra taken at various times during the service life of a structure, meaningful information can be extracted pertinent to structural degradation and the appearance of incipient damage. It must be noted that the frequency range must be high enough for the signal wavelength to be significantly smaller than the defect size.

A comprehensive overview of the impedance-based structural health monitoring method and its applications was presented by Park et al[28]. Lopes et al.[29] used neural network techniques to process high-frequency E/M impedance spectra. In analytical simulation studies, a three level normalization scheme was applied to the E/M impedance spectrum based on the resonance frequencies. When applied to actual E/M experiments, the neural network approach was modified to another set of normalized values: (i) the area between damaged and undamaged impedance curves; (ii) the root mean square (RMS) of each curve; and (iii) the correlation coefficient between damaged and undamaged curves. These values were calculated for both real and imaginary parts of the impedance spectrum. Good identification of damage location and damage amplitude was reported. Bhalla and Soh[15] proposed a new method of analyzing the electromechanical-admittance signatures obtained from bonded PWAS. They developed a new complex damage metric to quantify the damage based on the drive point mechanical impedance of the structure. The results showed that the PWAS were successful in identifying flexural and shear cracks and that the method has a high sensitivity to the presence of damage. The delamination of a laminated beam using electromechanical impedance measurements was studied by Bois and Hochard[26]. A good description of the electromechanical model of a damaged composite beam was presented. The delamination was introduced between the 11th and 12th ply of a carbon/epoxy laminated beam (45°, -45°, 90°, 0°). The influence of the relative position between sensor and damage as well as the delamination depth and the sensor size was investigated.

2.3 Bond/adhesion detection

Ultrasonic testing of adhesively bonded joints using guided waves for both aerospace and automotive applications is gaining more and more attention. In the nondestructive evaluation of adhesively bonded joints of particular interest are the Lamb waves. Lamb wave methods have considerable potential for the inspection of adherent assemblies for two reasons: they do not require direct access to the bond region, and they are much more amenable to rapid scanning than are pressure wave techniques. Lamb waves can be excited in one plate of a bonded assembly, propagated across the joint region, and received in the second plate of the assembly. Inspection of the joint then would be based on the differences between the signals received on one side of the assembly compared to those transmitted on the other side.

Lowe and Cawley[30] studied the applicability of plate wave techniques for inspection of adhesive and diffusion bonded joints. They found that the Lamb wave techniques are sensitive to the material properties and the thickness of the adhesive layer. Rose et al.[31] used the ultrasonic guided waves for NDE of adhesively bonded structures. They developed a double spring hopping probe (DHSP) to introduce and receive Lamb waves. This method was used to inspect a lap splice joint of a Boeing 737-222. Preliminary results showed the capability of through transmission for disbond detection. Severe corrosion area was also pointed out using the DHSP hand held. Lee et al.[32] studied the problem of wave propagation in a diffusion bonded model using spectral elements (SE) and a new local interaction simulation approach (LISA) for numerical modeling. The novelty of their work was the sensor/actuator configuration consisting of five different layers of materials with one piezoceramic element generating a thickness mode vibration. The five layers were: two electrodes used for actuating and sensing (Sonox P5), two copper layers, and in the middle a couplant layer. The experiments validated the numerical simulation, showing that the actuator/sensor configuration could operate either in S_0 or A_0 mode using an excitation frequency of 260.5 and 100 kHz, respectively. However the coupling layer distorts the wave propagation, due to its low impedance at the interface point and low speed within the couplant medium. The reliability of piezoelectric monitoring of adhesive joints was studied by Kwon et al.[33]. A single lap adhesively bonded tubular joint was tested during a torsional fatigue test. The results showed that the piezoelectric properties of the joint are related to the crack propagation. The measured electric flux density is a good estimator of the failure strain, and is sensitive to the maximum stress or strain in the layer rather than the average stress.

Repair patches are widely used in the aircraft industry for small repairs of the aircraft fuselage in order to extend the operational life of aging aircrafts. Chiu et al.[34] reported on the development of a 'perceptive repair' or 'smart' system which will provide information on the in-service performance of the repair and the associated structure. Their results showed the possibility to use piezoelectric elements to develop a 'smart' patch, and use the impedance measurements to determine the presence of damage. For impedance measurements the sensor/actuator must be located close to the damaged area. Galea et al.[35] described two in-situ health monitoring systems, one consisting of a piezoelectric polyvinylidene fluoride (PVDF) film-based, and the second one consisting of an electrical –resistance strain gauge-based sensing system. The methods were tested on a composite bonded patch applied to an F/A-18 aircraft. The 'smart patch' approach described was to detect disbond growth in a safe life zone of the patch where disbonds are unacceptable, and to monitor the damage growth in a damage tolerant region. The method used to asses the "health" of the patch was to measure the load transfer in the safe-life zone. This was achieved by monitoring the ratio of (patch strains)/(strain in the component) during service life. Any decrease in this ratio was an indication of the disbonding of the patch. The results showed that the concept of "smart patch" approach for an autonomous health monitoring system is viable. However, more work needs to be done to minimize the power requirements of the system, and to develop other confidence building indicators. More recent Koh and Chiu[36] did a numerical study of the disbond growth under a composite repair patch. They used impedance method and the transfer function method to identify typical disbond growth shapes and sizes underneath the repair patch. The results showed that using signal processing techniques and by a strategic placement of the PWAS, information about the location, type, and severity of disbond could be provided.

3 THE PROBLEM TO BE ADDRESSED

In-service disbonding and delamination, has become a real concern in many applications. So far, the "detection technology" has been limited to visual inspection techniques ("follow the dew line during an early morning visual inspection"). Although the maintenance crews have become very innovative in their inspection procedures, the process remains, as a whole, a manual labor-intensive job. In lack of good detection technology, the repair limits are frequently exceeded and the blades are returned to depot where they may sit for months in quarantine status, and may be sometimes even destroyed. The overall cost associated with this problem equates to millions of dollars, significant loss of aircraft availability and serious safety concerns. An automated, early-damage detection system for rotating mechanical systems would be invaluable to the maintainers of a helicopter fleet. This system could be used for both military and civilian helicopters.

One type of helicopter rotor blade is constructed by adhesively bonding titanium sheet metal C-sections together (Figure 3). This bond is susceptible to extreme temperature conditions, particularly in cold weather in a climate where the relative humidity is high. The rotor blade has a built-up construction consisting of sheet-metal members adhesively bonded with high-performance structural adhesive. Composite substructures are also incorporated at the blade tip. The blade trailing consists of a non-metallic honeycomb construction. In-service blades have shown disbonds appearing between the structural elements due to in-flight vibrations. In our laboratory, we have a full size helicopter blade instrumented with piezoelectric wafer active sensors. This blade is used in health monitoring and damage detection proof-of-concept demonstrations. Several detection approaches are being attempted.

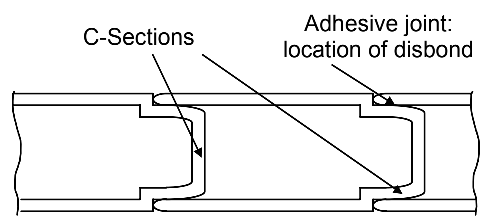


Figure 3 Typical helicopter rotor blade; detail of the blade cross-section indicating the adhesive joining of C-sections

The problem that occurs is that the blade sections, held together with the adhesive, can be separated when moisture is trapped between sections and freezes. This separates the C-sections of the blade and forms a crack in the outer skin of the blade. Currently the only way to detect these flaws is to visually inspect the blade for the appearance of cracks, and if one is detected, insert a putty scraper to determine if the epoxy has separated. This rudimentary and time-consuming task is both inefficient and unable to detect a separation until the skin of the blade cracks. If the detected separation is less than 6-12", new epoxy can be injected using a hypodermic needle, and the sections are then clamped down until the adhesive takes hold. However, if the separation is larger than 6-12", it is considered un-reparable, and must be sent for a depot repair It is possible to prevent such costly repairs with early detection. Piezoelectric wafer active sensors (PWAS) may present a solution to this early detection need. PWAS can both transmit and collect data on ultrasonic vibrations within the structure to which they are attached. Studying the variations in the transmitted signal and the received signal, one can determine if there is a discontinuity in the material.

4 DETECTION STRATEGIES

Piezoelectric wafer active sensors (PWAS) are small, non-intrusive, and inexpensive piezoelectric wafers that are intimately affixed to the structure and can actively interrogating the structure[37,38]. Piezoelectric active wafer sensors are non-resonant devices with wide band capabilities. They can be wired into sensor arrays that are connected to data concentrators and wireless communicators. Piezoelectric wafer active sensors have captured the interest of academia and industry due to their low cost and non-intrusive nature[39].

4.1 Wave propagation method for disbond detection

4.1.1 Pitch-catch method

Adhesively bonded lap joints are often used in high performance structures such as airframes. Periodic inspection of these joints can be time consuming. Figure 4 shows the inspection of a lap splice joint specimen (other configurations of adhesively bonded joints are also possible). Using PWAS, wave energy is generated on one side of the joint, transmitted through the adhesive bond line, and received on the other side of the joint.

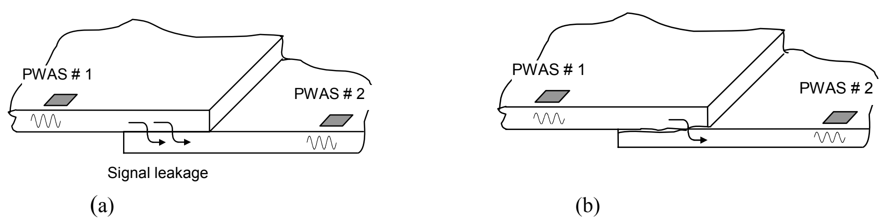


Figure 4 Pitch-catch method for joint inspection: (a) pristine joint carries the signal well from PWAS # 1 to PWAS # 2 through "leakage"; (b) Disbonded joint cannot carry well the signal resulting in degradation of signal received at PWAS # 2

The amplitude of the transmitted signal is a measure of the bond quality. In order to find the best transmission mode across the joint, tuning is necessary. Tuning the frequency allows inspection of bonded joints having various thickness, structural configurations, and even joints having more than two layers. For a healthy bond the amplitude of the received signal is large. If disbonding has occurred, there will be a decrease in amplitude of the received signal proportional with the severity of the disbonding.

4.1.2 Pulse-echo method

Disbonding detection can be also performed using the pulse-echo technique which will be able to detect surface crack and subsurface cracks within the detection depth. (The subsurface detection depth will be determined through numerical simulation and laboratory experiments). When an incident wave encounters a crack transverse to the wave propagation path, wave reflection may occur as shown in Figure 5.

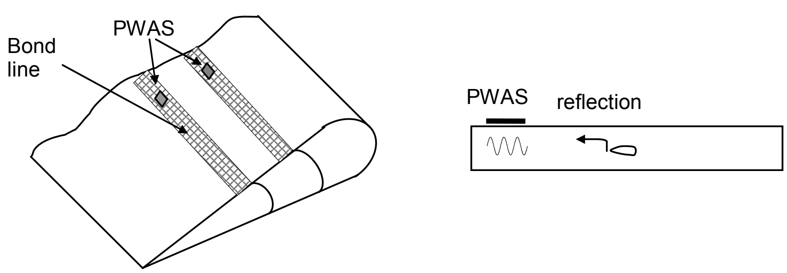


Figure 5 Pulse-echo method for damage detection

This wave reflection may be sensed as an echo at the transmitter sensor (PWAS). The echo time of flight (TOF) is proportional with twice the distance between the transmitter sensor and the crack. In order to distinguish the echo from the background noise, a differential signal method, using historically recorded baseline signatures will be utilized.

4.2 E/M impedance method

Electromechanical impedance can be used for structural health monitoring and showed promising results. This method is based on the piezoelectric effect. Piezoelectric materials generate surface charge when a mechanical stress is applied (direct effect) and conversely when a voltage is applied they will undergo mechanical deformation (inverse effect). These two effects enable piezoelectric materials to be used both as sensors and actuators, being able to sense and to excite the structure. In our work the PWAS is bonded to the surface using M-Bond 200 adhesive. In this way, the sensor is part of the structure and will act as an actuator generating both axial and flexural vibrations in the structure. The PWAS will dynamically expand and contract when an alternating electric field is applied. In this way stationary elastic waves are introduce in the structure and the host structure can be scanned over a frequency range, typically in the kHz band. The complex impedance spectrum is recorded.

The frequency spectrum is then analyzed for new features like: frequency shift of existing peaks; increase in peak amplitudes; appearance of new peaks. For a bonded structure, we expect the frequency spectrum to be the same for measurements taken where a good bond exists. In the presence of disbonds the electromechanical impedance of the structure will change and those changes should be reflected in the frequency spectrum. The spectrum should present the types of features described above. This method will be used for the near-field detection of disbonds.

5 PRELIMINARY RESULTS

5.1 Wave propagation results

A helicopter main rotor blade was instrumented with an array of PWAS sensors as shown in Figure 6. The array consists of 15 sensors disposed in five columns and three rows. The sensors on the first and the third row are mounted along the bond line (see Figure 6) while the sensors on the second row are mounted on the skin of the blade. The capability of successfully sending Lamb waves from one sensor and receiving the signal one the other sensors was investigated. A schematic of the instrumentation setup is presented in Figure 6 along with the location of the PWAS sensors on the main rotor blade.

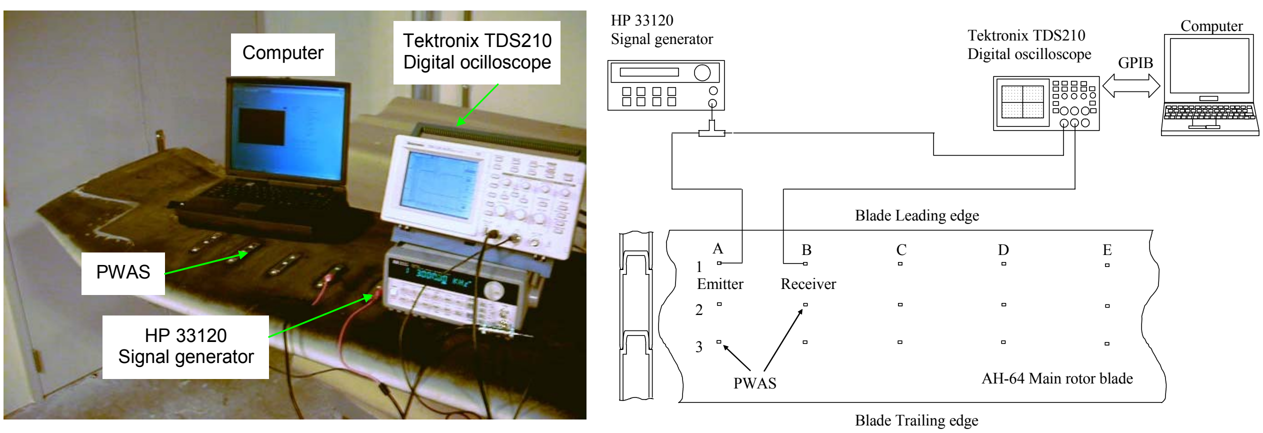


Figure 6 Schematic of the instrumentation setup

The instrumentation setup consists of an HP 33120 signal generator to generate the excitation signal, a Tektronix TDS210 digital oscilloscope to collect the signal from the PWAS, and a computer to store and analyze the signal. In our preliminary investigation we sent and received signals using an array of 15 PWAS, some used as transmitters, other used as receivers. Using the signal generator, a 3-count sinusoidal burst signal at a frequency of 330 kHz was sent from sensor A1 and received at sensors B1 and C1 along the bond line, as shown in Figure 7a. Also the same signal was sent from sensor A1 to sensor B1, B2 and B3 across the bond line as shown in Figure 7b. This shows clearly the possibility of sending and receiving surface Lamb waves along and across the bond line of a helicopter blade. It should be noticed the attenuation of the amplitude of the signal received at sensor B3 due to the fact that is traveling across two bond lines (Figure 7b). The same attenuation is observed also for Lamb waves traveling along the bond line, the further the sensor from the transmitter the smaller is the amplitude of the received signal (Figure 7a).

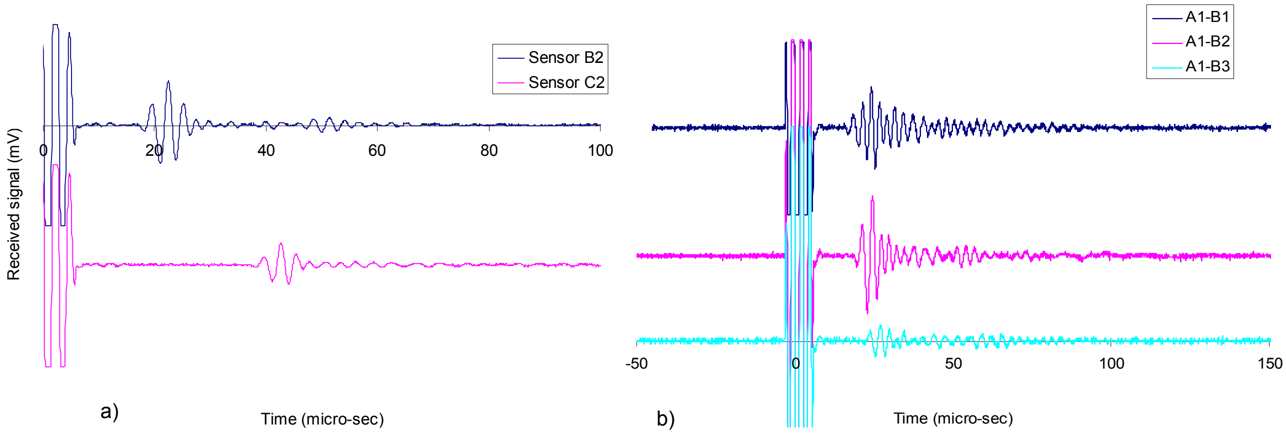


Figure 7 (a) Surface-guided Lamb waves received at (a) sensors B2 & C2 (100 mm apart) when excited from sensor A2 along the bond line (b) received at sensors B1, B2 & B3 when excited from sensor A1 across the bond line

Figure 8a represents the signal received at locations B1, C1, D1, and E1 when the PWAS at A1 was excited in the frequency band 1-500 kHz. These signals traveled over the bond area, consisting of the two titanium layers plus the adhesive in between. However it is remarkable that signals of good quality and strength are observed in spite the small size of our PWAS devices. Also noticed in Figure 8 is how frequency affects the amplitude of the signal transmission. This aspect is important for designing PWAS installation that is tuned to certain Lamb modes. Figure 8 shows that, at relatively low frequency, good signals are received. However, as indicated by the Lamb theory, these signals are of the flexural type (A_0) and thus highly dispersive. Of considerable interest are the signals of axial type (S_0), which have a lower dispersion rate, and hence are better suited to ultrasonic NDE. In the bonded region, we observe that the S_0 Lamb waves are preferentially excited in the 300-450 kHz range. This fact is very encouraging because the S_0 modes have very little dispersion at 300-450 kHz and hence could be use in the pulse-echo mode.

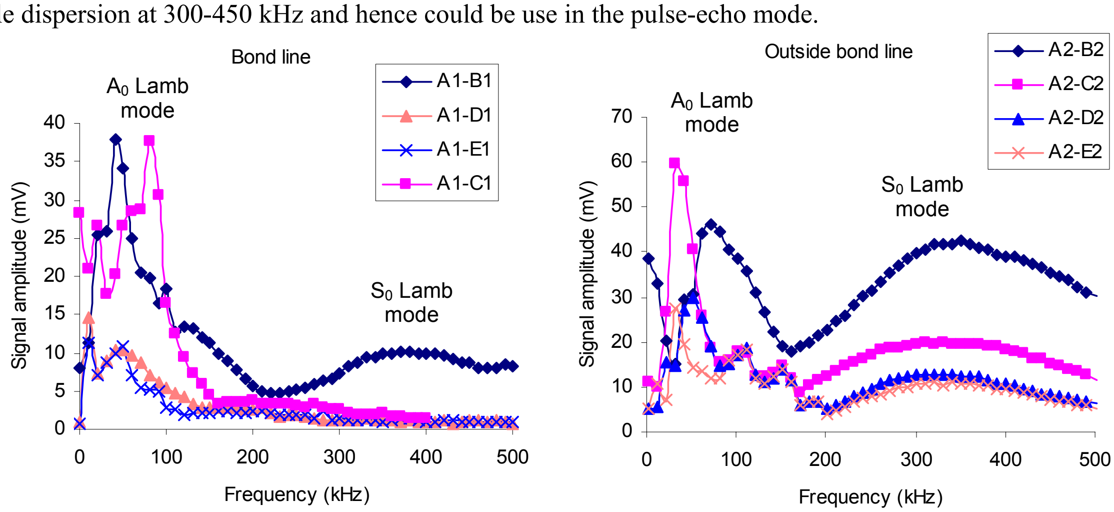


Figure 8 Lamb waves traveling (a) along the bond line; (b) outside the bond line

The attenuation of the signals when traveling along the bond line is presented in Figure 9. From the two graphs presented it can be seen that the attenuation of the A_0 mode is much less than the attenuation of the S_0 mode. Also, we observed that the adhesive layer has a higher influence on the S_0 mode. Looking at the Figure 8a vs. Figure 8b, bond line vs. outside the bond line, the amplitude of the S_0 mode is much smaller for the Lamb waves traveling in the bond line. This is expected since the adhesive layer will absorb part of the energy and the signal that arrives at the sensing PWAS is much weaker than the original excitation signal.

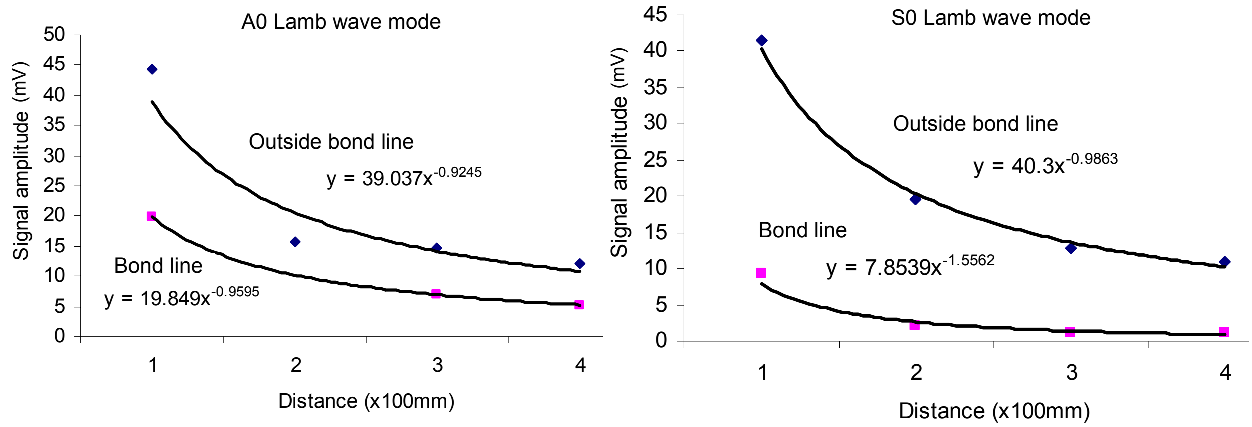


Figure 9 Attenuation of the (a) A_0 mode Lamb waves traveling along the bond line; (b) S_0 mode Lamb waves traveling along the bond line

Considering now the wave signals transmitted from the PWAS at A2 and received at PWAS B2,…, E2 (outside the bond line), we observed that the optimal excitation frequency to excite the S_0 Lamb mode appeared in the 250-400 kHz frequency band (Figure 10). This is explainable through the Lamb wave theory because in the area between two bonding lines the material thickness is much less than in the bonded area. To illustrate this Figure 10 presents the raw signals collected on sensor B2 and C2 when sensor A2 was excited with a 300 kHz sinusoidal tone burst, as discussed earlier. The amplitude of the signal collected by the sensor B2 is the highest one, since sensor B2 is closest to the transmitter, and the amplitude of the signal is smaller and smaller as we get further away from the sensor A2 (the transmitter).

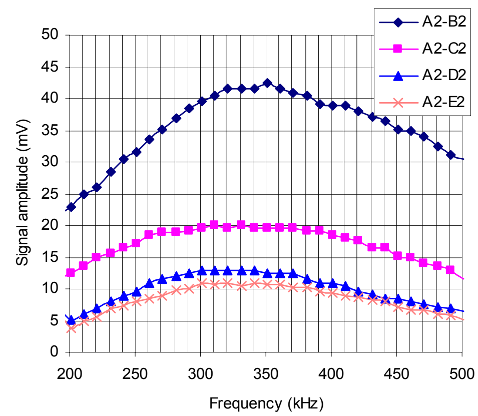


Figure 10 Optimal frequency band for transmitting and receiving surface Lamb waves

5.2 E/M impedance results

In order to simulate the bonding of the C-sections of a helicopter main rotor blade, an aluminum specimen was designed. Two aluminum strips, 178 x 37 x 1.55 mm, where bonded using an epoxy paste adhesive, Hysol® EA 9309.3NA. The disbonding of the two aluminum strips was simulated as a discontinuity of the epoxy paste in the middle of the specimen, having the length of 25 mm. This was done using a strip of teflon tape. The specimen was instrumented with PWAS sensors and the location of the sensors is shown in Figure 11a.

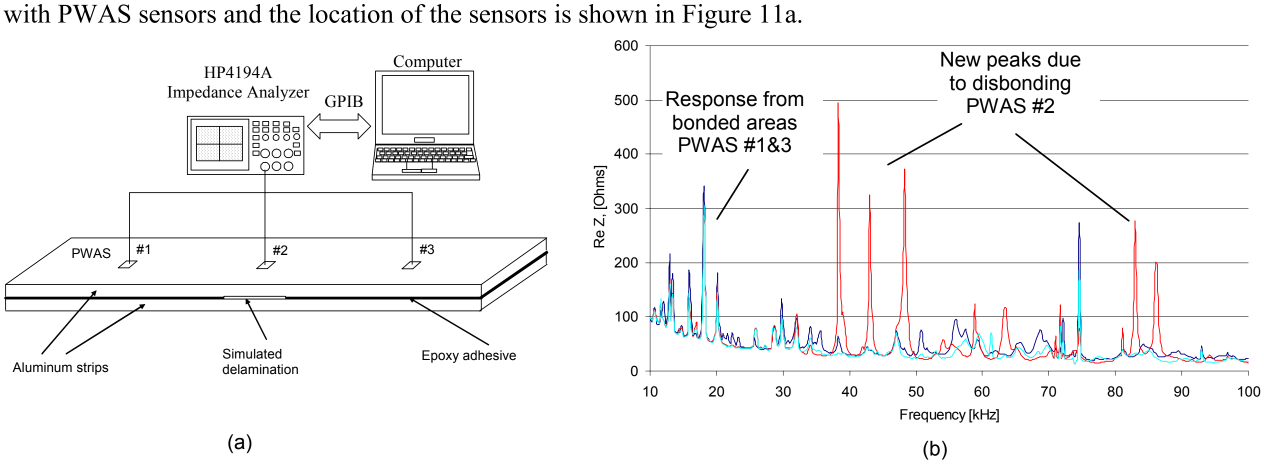


Figure 11 The aluminum bonded specimen: (a) experimental setup; (b) the E/M frequency response measured in three locations

Using an HP4194A impedance analyzer the E/M impedance was measured in three locations as shown in Figure 11a. The E/M frequency response for the three PWAS is presented in Figure 11b. It can be observed that the frequency response is very similar for PWAS # 1&3 which are located on a bonded area, but is different for PWAS #2 located on the disbond. We can clearly see new sharp peaks in the frequency spectrum due to disbond.

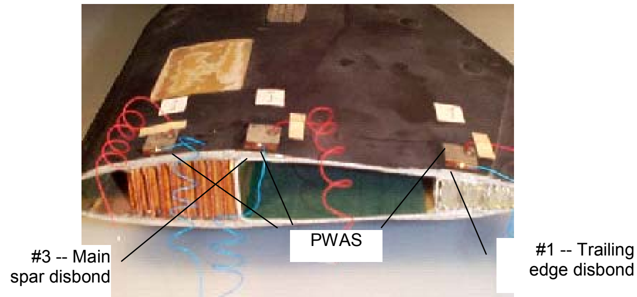
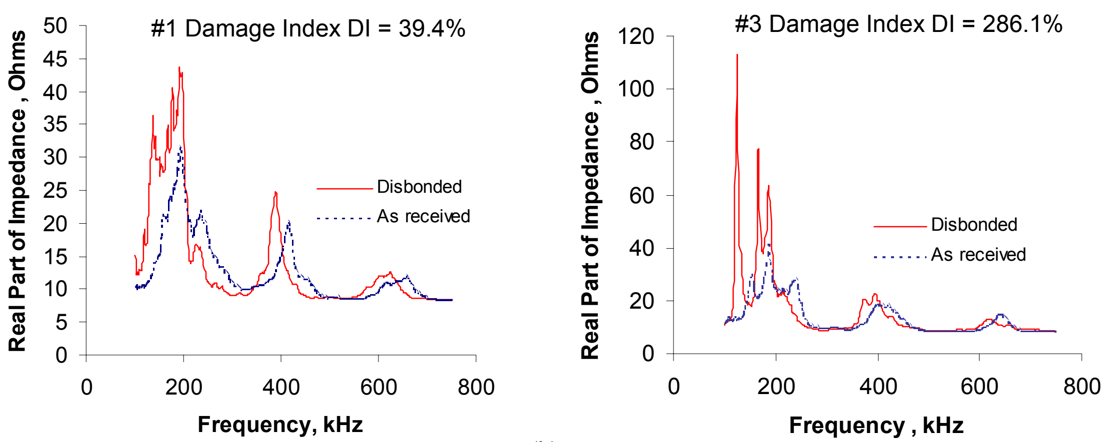


Figure 12 Piezoelectric active wafer sensors were used on a rear-rotor blade section to detect delamination between the adhesively bonded structural elements

A rear blade helicopter section was considered next (Figure 12). The section was instrumented with several PWAS (0.5-in × 0.5-in). The PWAS were adhesively bonded to the surface using standard strain-gauge installation procedures. An HP4194A impedance analyzer was used to measure the E/M impedance signature of the PWAS attached to the structure. Based on initial exploratory tests, the frequency range 100 to 750 kHz was selected. A base-line measurement of the E/M frequency response of the structure in the "as received" condition was first recorded (Figure 13, dashed line). Repeated sampling of the data indicated a stable and reproducible pattern of the impedance spectrum. Strong activity (clearly defined response peaks) was observed in the 200 kHz band. Activity of lesser amplitude also appeared in the 400 kHz and 650 kHz bands, but. The data was stored as base-line signature of the structure in the "as received" condition.

Damage was mechanically induced in the structure in the form of local disbonds. A sharp knife blade was used to induce local disbonds starting at the edge of the test section. The extent of the disbonds was about 0.5-in spanwise, i.e., ~10% of the total bond length. The E/M impedance spectrum of the damaged structure is also shown in Figure 13 (continuous line). Examination of the damage-structure E/M impedance spectra in comparison with the base-line spectra (dashed-line) reveals three important phenomena: frequency shift of existing peaks; increase in peak amplitudes; appearance of new peaks.



(a) (b)

Figure 13 Comparison of the E/M impedance response curves measured for the "as received" and "disbonded" structure shows clear identification of the disbond: (a) spectrum of the disbond gauge at location #1; (b) spectrum of the disbond gauge at location #3.

The frequency shifts were consistently towards lower frequencies. This left shift in frequency could be explained by the increase in local compliance due to disbonds. In a disbond region, the effective sheet thickness is much less than in the well bonded regions. The increased impedance amplitude can be also correlated with the decrease in local damping that appears when the two faying surfaces were separated. The appearance of new peaks is justified by the new local modes that are created when disbonds appear. The damage index (DI) was calculated using the Euclidean norm.

$$DI = \sqrt{\frac{N^{\left[\mathrm{Re}(Z_i)-\mathrm{Re}(Z_i^0)\right]^2}}{N^{\left[\mathrm{Re}(Z_i^0)\right]^2}}} \qquad (2)$$

where N is the number of sample points in the spectrum, and the superscript 0 signifies the initial (base-line) state of the structure. The damage index values are shown as text in Figure 13. It can be seen that the damage index has a moderate value at the #1 location (DI = 39.4%) and a higher value at the #3 location (DI = 286.1%). This difference is consistent with the visual appearance of the E/M impedance curves. The changes observed in the #1 location spectrum are less intense than the changes observed in the #3 location spectrum.

6 CONCLUSION

In this paper we discuss two methods for disbond detection in adhesively-bonded structures using embedded piezoelectric wafer active sensors (PWAS). One method is based on the propagation of guided Lamb waves. The other method is based on the electromechanical impedance approach. For far-field detection, propagating Lamb waves could be used in pitch-catch and pulse echo modes. We demonstrated that embedded PWAS can be used for successfully sending and receiving Lamb waves across the bond line. We have also demonstrated that PWAS can be used to send Lamb waves along the bond line. We noticed that the attenuation along the bond line is stronger than outside the bond line. This strong attenuation was especially observed for the S_0 Lamb wave mode. For the A_0 Lamb wave mode, the attenuation along the bond line was less pronounced. These observations are useful for developing a disbond detection method using wave leakage and acusto-ultrasonic techniques. However, further work needs to be done in order to understand and determine how the Lamb waves interact with the bond layer, how dispersion and attenuation of the excitation signal will affect the measurements.

For near-field detection, the electromechanical impedance method was used. We examined two specimen types, a bonded specimen as well as a rear helicopter blade section. Disbonds were artificially introduced at certain locations. The real part of the complex electromechanical impedance was analyzed. The results showed that, in both cases, the presence of disbonds was detected as a clear change in the impedance spectrum consisting of frequency shifts, peak increases, and appearance of new peaks. This proves that the electromechanical impedance method using surface bonded PWAS can be used for near-field disbond detection.

ACKNOWLEDGMENTS

Support from the Air Force Research Lab through UTC Contract #03-S470-033-C1 of F33615-01-D-5801 is thankfully acknowledged.

REFERENCES

1. Krautkramer, J.; Krautkramer, H (1990) *Ultrasonic Testing of Materials*, Springer-Verlag, 1990
2. Cawley, P., (1984) "The Impedance Method for Non-Destructive Inspection", *NDT International,* Vol. 17, pp. 59-65, 1984
3. Viktorov, I. A. (1970) *Rayleigh and Lamb waves*, Plenum, New York, 1967
4. Worlton, D. C. (1957) “Ultrasonic testing with Lamb waves”, *Non-Destructive Testing*, Vol. 15, pp. 218-222, 1957
5. Worlton, D. C. (1961) “Experimental confirmation of Lamb waves at megacycles frequencies”, *Journal of Applied Physics*, Vol. 32, pp. 967-971, 1961
6. Alleyne, D. N.; Cawley, P.(1992) “The interaction of Lamb Waves with Defects”, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency control*, Vol. 39, pp. 381-397, 1992
7. Dalton, R. P.; Cawley, P.; Lowe, M. J. (2001) “The Potential of Guided Waves for Monitoring Large Areas of Metallic Aircraft Fuselage Structure”, *Journal of Nondestructive Evaluation*, Vol. 20, pp. 29-45, 2001
8. Schwartz, W. G.; Read, M. E.; Kremer, M. J.; Hinders, M. K.; Smith, B. T. (1999) “Lamb wave tomographic imaging system for aircraft structural health assessment”, *Proceedings of the SPIE Conference on Nondestructive Evaluation of Aging Aircraft, Airports, and Aerospace Hardware III*, Vol. 3586, pp. 292-296, Newport Beach, 1999
9. Giurgiutiu, V.; Redmond, J.; Roach, D.; Rackow, K. (2000)“Active sensors for health monitoring of aging aerospace structures”, *Proceedings of the SPIE Conference on Smart Structures and Integrated Systems*, Vol. 3985, pp. 294-305, Newport Beach, 2000
10. Giurgiutiu, V.; Zagrai, A. (2000) “Characterization of piezoelectric wafer active sensors”, *Journal of Intelligent Material Systems and Structures*, Vol. 11, pp. 959-976, 2000
11. Liu, T.; Veidt, M.; Kitipornchai, S. (2003) “Modeling the input-output behavior of piezoelectric structural health monitoring systems for composites plates”, *Smart Materials and Structures*, Vol. 12, pp. 836-844, 2003

12. Lee, B.C.; Staszewski, W. J. (2003) "Modeling of Lamb waves for damage detection in metallic structures: Part I Wave propagation", *Smart Materials and Structures*, Vol. 12, pp. 804-814, 2003
13. Lee, B. C.; Staszewski, W. J. (2003) "Modeling of Lamb waves for damage detection in metallic structures: Part II Wave interactions with damage", Smart Materials and Structures, Vol. 12, pp. 804-814, 2003
14. Blitz, J.; Simpson, G. (1996) *Ultrasonic Methods of Non-Destructive Testing,* Chapman & Hall, 1996
15. Bhalla, S.; Soh, C. K. (2003) "Structural impedance based damage diagnosis by piezo-transducers", *Earthquake Engineering And Structural Dynamic*, Vol. 32, pp. 1897-1916, 2003
16. Duke, J. C. Jr. (1988) *Acousto-Ultrasonics – Theory and Applications*, Plenum Press, 1988
17. Keilers, C. H., Chang, F.-K. (1995) "Identifying Delaminations in Composite Beams Using Built-in Piezoelectrics: Part I - Experiments and Analysis; Part II An Identification Method", *Journal of Intelligent Material Systems and Structures*, Vol. 6, pp. 649-672, 1995
18. Ihn, J.-B.; Chang, F.-K. (2002) "Built-in diagnostics for monitoring crack growth in aircraft structures", Proceedings of the SPIE's 9th International Symposium on Smart Structures and Materials, 17-21 March 2002, San Diego, CA, paper #4702-04
19. Wang, C. S.; Chang, F.-K. (2000) "Built-In Diagnostics for Impact Damage Identification of Composite Structures", in *Structural Health Monitoring 2000*, Fu-Kuo Chang (Ed.), Technomic, 2000, pp. 612-621
20. Lin, X.; Yuan, F. G. (2001a) "Diagnostic Lamb Waves in an Integrated Piezoelectric Sensor/Actuator Plate: Analytical and Experimental Studies", Smart Materials and Structures, Vol. 10, 2001, pp. 907-913
21. Diamanti, K.; Hodgkinson, J.M.; Soutis, C. (2002) "Damage Detection of Composite Laminates Using PZT Generated Lamb Waves", 1st European Workshop on Structural Health Monitoring, July 10-12, 2002, Paris, France, pp. 398-405
22. Jiang, Z.; Kabeya, K.; Chonan, S. (1999) "Longitudinal wave propagation measuring technique for structural health monitoring", *Proceedings of the 1999 Smart Structures and Materials - Smart Structures and Integrated Systems*, Vol. 3668, pp. 343-350, Newport Beach, 1999
23. Deng, X.; Wang, Q.; Giurgiutiu, V. (1999) "Structural Health Monitoring Using Active Sensors and Wavelet Transforms", *SPIE's 6th Annual International Symposium on Smart Structures and Materials*, Newport Beach, 1999
24. Lemistre, M.; Gouyon, R.; Kaczmarek, H.; Balageas, D. (1999) "Damage Localization in Composite Plates Using Wavelet Transform Processing on Lamb Wave Signals", *2nd International Workshop of Structural Health Monitoring*, Stanford University, September 8-10, 1999, pp. 861-870
25. Staveley NDT Technologies, http://www.staveleyndt.com/
26. Giurgiutiu, V.; Zagrai, A. (2000) "Damage Detection in Simulated Aging-Aircraft Panels Using the Electro-Mechanical Impedance Technique", *Adaptive Structures and Materials Systems Symposium, ASME Winter Annual Meeting*, November 5-10, 2000, Orlando, FL.
27. Bois, C.; Hochard, C. (2004) "Monitoring of Laminated Composites Delamination Based on Electro-mechanical Impedance Measurement", *Journal of Intelligent Material Systems and Structures*, Vol. 15, pp. 59-67, 2004
28. Park, G.; Sohn, H.; Farrar, C. R.; Inman, D.J. (2003) "Overview of Piezoelectric Impedance-Based Health Monitoring and Path Forward", *The Shock and Vibration Digest*, Vol. 35, pp. 451-463, 2003
29. Lopes Jr., V.; Park, G.; Cudney, H.; Inman, D., (1999) "Smart Structures Health Monitoring Using Artificial Neural Network", *2nd International Workshop of Structural Health Monitoring*, Stanford University, September 8-10, 1999, , pp. 976-985
30. Lowe, M. J. S.; Cawley, P. (1994) "The Applicability of Plate Wave Techniques for the Inspection of Adhesive and Diffusion Bonded Joints", *Journal of Nondestructive Evaluation*, Vol. 13, pp. 185-199, 1994
31. Rose, J. L.; Rajana, K. M.; Hansch, K.T. (1995) "Ultrasonic Guided Waves for NDE of Adhesively Bonded Structures", *Journal of Adhesion*, Vol. 50, pp. 71-82, 1995
32. Lee, B. C.; Palacz, M.; Krawczuk, M.; Ostachowicz, W.; Staszewski, W. J. (2003) "Wave propagation in a sensor/actuator diffusion bond model", *Journal of Sound and Vibration*, Article in press
33. Kwon, J. W.; Chin, W. S.; Lee, D. G. (2003) "Piezoelectric monitoring of the reliability of adhesive joints", *Journal of Adhesion Science and Technology*, Vol. 17, pp. 777-796, 2003
34. Chiu, W.K.; Koh, Y.L.; Galea, S.C.; Rajic, N. (2000) "Smart structure application in bonded repairs", *Composite Structure*, Vol. 50, pp. 433-444, 2000
35. Galea, S. C.; Powlesland, I. G.; Moss, S. D.; Konak, M.; Steve van der Velden, Stade, B.; Baker, A. A. (2001) "Development of Structural Health Monitoring System for Composite Bonded Repairs of Aircraft Structures", *Proceedings of the SPIE Smart Structures and Materials 2001: Smart Structures and Integrated Systems*, Vol. 4327, pp. 246-257, Newport Beach, 2001
36. Koh, Y. L.; Chiu, W. K. (2003) "Numerical study of detection of disbond growth under a composite repair patch", *Smart Materials and Structures*, Vol. 12, pp. 633-641, 2003
37. Giurgiutiu, V.; Zagrai, A.N. (2001) "Electro-Mechanical Impedance Method for Crack Detection in Metallic Plates", *SPIE's 8th Annual International Symposium on Smart Structures and Materials and 6th Annual International Symposium on NDE for Health Monitoring and Diagnostics*, Newport Beach, 2001
38. Giurgiutiu, V. , Bao, J., Zhao, W. (2001) "Active Sensor Wave Propagation Health Monitoring of Beam and Plate Structures", *Proceedings of the SPIE's 8th International Symposium on Smart Structures and Materials*, Newport Beach, 2001
39. Boller, C.; Biemans, C.; Staszewski, W.; Worden, K.; Tomlinson, G. (1999) "Structural Damage Monitoring Based on an Actuator-Sensor System"*, Proceedings of SPIE Smart Structures and Integrated Systems Conference*, Newport, 1999