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Enhanced Composites Integrity Through Structural Health Monitoring

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Abstract This paper discusses the topic of how the integrity of safety-critical structural composites can be enhanced by the use of structural health monitoring (SHM) techniques. The paper starts with a presentation of how the certification of flight-critical composite structures can be achieved within the framework of civil aviation safety authority requirements. Typical composites damage mechanisms, which make this process substantially different from that for metallic materials are discussed. The opportunities presented by the use of SHM techniques in future civil aircraft developments are explained. The paper then focuses on active SHM with piezoelectric wafer active sensors (PWAS). After reviewing the PWAS-based SHM options, the paper follows with a discussion of the specifics of guided wave propagation in composites and PWAS-tuning effects. The paper presents a number of experimental results for damage detection in simple flat unidirectional and quasi-isotropic composite specimens. Calibrated through holes of increasing diameter and impact damage of various energies and velocities are considered. The paper ends with conclusions and suggestions for further work.

Keywords Composites · Composite structures · Structural integrity · Structural health monitoring · Piezoelectric wafer active sensors · SHM · NDE · PWAS

1 Introduction

In order for composite materials to be used more extensively in load carrying aircraft structures, they have to be maintained in a safe and economical manner. Critical defects/cracks may be induced in the structure requiring repair before the next scheduled inspection. Continuous monitoring will significantly increase operational safety. The information

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acquired in real-time would also benefit the understanding on fracture mechanics of composites, improving the confidence in their use and broadening their applications. Currently the cost of primary components inspection can be as high as one third of acquiring and operating these composite structures [1–3]. In order to compete in the increasingly demanding area of aircraft structures cost effective techniques need to be developed. Large areas need to be scanned rapidly without removal of individual components, minimizing the disruption of the structure's operation.

Large structures such as the Boeing 787 Dreamliner and Airbus A350 XWB (extra wide body) are now at various stages in the design/manufacture/certification/delivery cycle. One of the most difficult problems to be overcome during the certification process of such aircraft by the civil aviation authorities for safe commercial use is to guarantee the structural integrity of large composite structures over the 30 years life of the aircraft. This is a technological new ground for large integral composite structures, with wing lengths of more than 25 m, fuselage barrel lengths of 50 m and diameter 5 m [4].

A critical safety issue for the design of primary aircraft structures is vulnerability and damage tolerance due to mechanical loading such as foreign object impacts from bird strike, hail, tire rubber and metal fragments [5, 6]. New composite aircraft structures are vulnerable to impact damage, due to the relatively thin composite skins and the generally brittle behavior of carbon fiber reinforced epoxy resins. This aspect of structural integrity is a major problem for the industry as it seeks a viable strategy for design and certification of large composite aircraft structures subjected to impact damage, particularly with respect to the known composite problems of Non-Visible Damage / Barely Visible Impact Damage (NVD/BVID).

The route to certification adopted by the aircraft manufacturers is based on the well known test pyramid for aircraft structures, which foresees 5 levels of tests from materials test specimens in level 1 up to full aircraft structures in level 5, see Fig. 1. This is a 'building block' approach as each level strongly relies on the results obtained at the level below. The complexity of the test specimens and the subsequent cost drastically increases on the next higher level, although the number of specimens is reduced. Such an approach has proven its robustness and efficiency in the last decades and has been applied for most European aircraft developments. However when new materials are introduced, the lead time and associated cost are very high; for the Airbus A380 it implied around 7 years of test programs and a budget of several hundred million Euros [1, 4].

Structural health monitoring (SHM) is an emerging technology with multiple applications in the evaluation of critical structures. The goal of SHM research is to develop a monitoring methodology that is capable of detecting and identifying, with minimal human intervention, various damage types during the service life of the structure. Numerous approaches have been utilized in recent years to perform structural health monitoring [7–9]; they can be broadly classified into two categories: passive methods and active methods. Passive SHM methods (such as acoustic emission, impact detection, strain measurement, etc.) have been studied longer and are relatively mature; however, they suffer from several drawbacks which limit their utility (need for continuous monitoring, indirect inference of damage existence, etc.). Active SHM methods are currently of greater interest due to their ability to perform on-demand interrogation of a structure while the structure is still in service. One of the promising active SHM methods utilizes arrays of piezoelectric wafer active sensors (PWAS) bonded to a structure for both transmitting and receiving ultrasonic waves in order to achieve damage detection [10]. When used to interrogate thin-wall structures, the PWAS are effective guided wave transducers which couple their in-plane motion with the guided wave particle motion on the material surface.

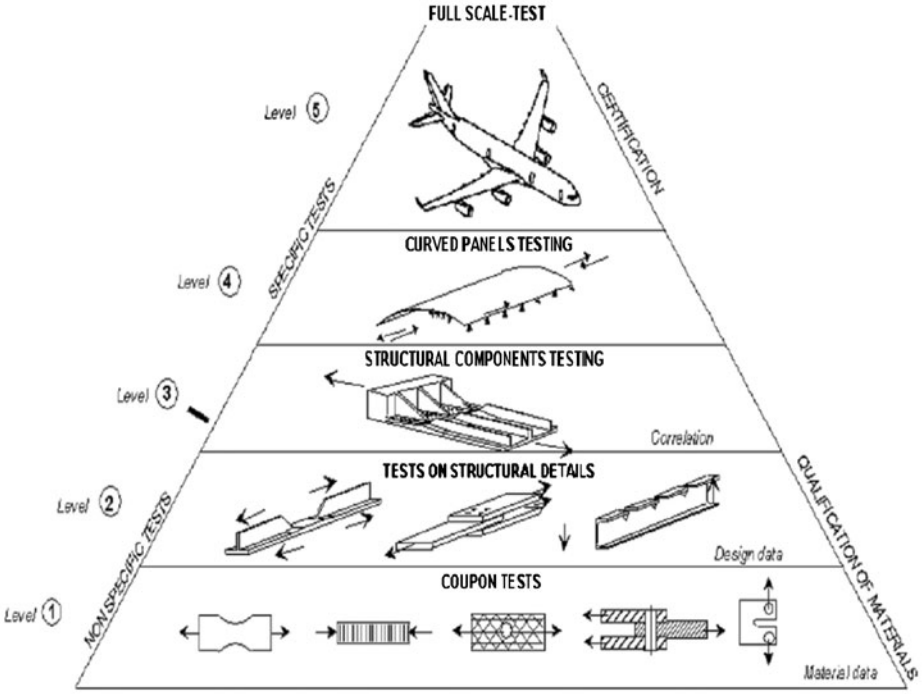

Fig. 1 The test pyramid for civil aircraft composite structures (a building block approach based on certification requirements)

The aircraft requirements do not prescribe a rigid test methodology. Compliance to the requirements may be demonstrated either by means of testing or analysis. It is here where the composites scientists and engineers are required to support the aircraft designers. With improved understanding of composites damage mechanisms, effect of fabrication processing parameters, improved test methodologies, new non-destructive evaluation (NDE) and structural health monitoring (SHM) technologies, and the ability to describe these effects in analytical and numerical (Finite Element) models, analytically based justifications can contribute to reduce large test programs. Thus a central theme for the research community is to develop and validate computational tools to support the design of an optimized composite aircraft under the full range of flight and service loads. The introduction of 'virtual testing' and hence 'certification by analysis' with a scientific basis at the composites micro-scale implies a cultural change in the way of working of the airframe community. It will have a clear positive impact on development cost and lead time, which is especially important for the introduction of composite materials into large aircraft structures. The simulation-based designs will significantly speed-up the decision path by allowing earlier decisions at each level of the test pyramid, and will reduce the development and testing at each level. A smaller number of physical tests will remain to validate the simulation based decisions.

Thus the societal need is clear in the case of the aircraft industry where scientific developments at the composites micro-scale level, which improve our understanding of structural integrity, will lead to optimized structures and validated computational tools for direct application by the industry in future aircraft developments. The same issues apply of

course to other industries, for example in the development of large composite hulls on naval ships and fast patrol boats, or 60 meters composite wind rotor blades for renewable energy generation. In all cases a coordinated effort is urgently needed between the academic community, which tends to concentrate on composites analysis at the micro and macro-scales and the applications engineers in the aircraft, marine, transport and energy industries.

The aim of this paper is to demonstrate how active SHM techniques, especially those based on Lamb waves generated by piezoelectric wafer active sensors (PWAS) can be used to continuously monitor mechanical induced damage in composite structures, typical to that experienced by aircraft components and to assess their structural integrity.

2 Damage Mechanisms and Damage Accumulation in Composite Structures

Fatigue life prediction for composite materials has generally not been a major issue in the design of composite structures, due to the low levels of ultimate design strain used currently [4]. However, if composite materials are to be used to their full potential, design strain levels will have to rise and damage growth in fatigue will then become a serious design consideration. To develop improved life predicting methodologies that would result in more weight- and cost-effective composite structures, the understanding of fatigue failure process in composites needs to be broadened and links between observable damage/failure mechanisms and fatigue life need to be established.

Fatigue behavior of composite laminates is characterized by sequential accumulation of damage in the form of matrix cracking, local and edge delamination, fiber/matrix debonding and fiber breakage [11, 12]. Figure 2 shows a schematic drawing of a composite with such damage; the upper drawing showing a plan view and the lower schematic showing an edge view. The upper drawing shows (i) a longitudinal split (a type of matrix cracking damage in which the cracks run parallel to the fibers in the loading direction), (ii) matrix cracks running parallel to fibers in plies oriented at 90^0 to the loading direction (transverse ply cracks), and (iii) two types of ply delamination—one associated with matrix cracking but initiated from a free edge, i.e., edge delamination with the second type being local delaminations associated with longitudinal splits or matrix cracks. The lower drawing shows the edge view of this damage and the inset in Fig. 2 shows a fourth type of damage: fiber breakage and associated fiber/matrix debonding (interface failure). All of these types of damage lead to a permanent degradation of the laminate stiffness and strength and shorten the fatigue life (number of cycles to failure) of the laminate.

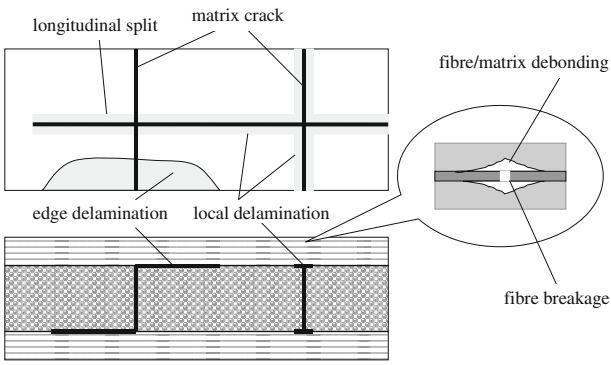

Fig. 2 A schematic of damage mechanisms observed in composite laminates under tension-tension fatigue [12]

Fatigue performance of composites may be quantified by the residual stiffness, residual strength and fatigue life (number of cycles to failure). As indicated above, fatigue life prediction for composite materials has generally not been a major issue in the design of composite structures, which has been dominated by impact and static notch performance. At present the ultimate design strain levels are kept low, in the region of 0.30% to 0.4%, where composite materials can withstand large numbers of fatigue cycles without failing [4, 11, 12]. At this strain level, damage growth is not viewed as a major problem (except in rotor blades, propellers, suspension parts etc). However, if some of the potential of composite materials in performance and cost are to be realized in structural applications, e.g. in primary aircraft structures, design strain levels will have to rise and damage growth in fatigue will start to become a major design consideration. It is therefore very important to develop a damage growth predictive methodology and accurate fatigue life prediction tools for composite materials if the advantages offered by composites are to be exploited through designs at higher strains and stresses. In such a model however the knowledge of damage mode, location and extent (size of damage) will be required and for this to be achieved a reliable damage detection method is needed that can continuously monitor damage evolution.

3 Structural Health Monitoring for Composite Materials

A significant amount of work has been conducted in order to determine the influence of defects on the strength and life of composite structures and determine the critical size of damage. This work is always done in parallel with the development of non-destructive inspection /evaluation/ testing (NDI/E/T) techniques. Much effort is being taken to find the most reliable NDE technique for the detection, location and characterization of damage in composite materials. The state-of-the-art NDT techniques for composite materials can be found in [8, 13] and the main ones are: Visual Inspection; Optical methods; Eddy-current (electro-magnetic testing); Ultrasonic Inspection; Laser Ultrasonics; Acoustic Emission; Vibration analysis; Radiography; Thermography; Lamb waves. In the following paragraphs three promising SHM methods are briefly presented followed by a more detailed analysis of guided waves and more specifically low frequency Lamb waves generated by piezoelectric transducers where some practical examples that demonstrate capability and limitations of the method are discussed.

Optical Fiber Sensor SHM systems have been developed for composites which rely on the capability of embedded Fiber Bragg-Grating (FBG) sensors to monitor strain and temperature at multiple internal locations within the host composite structure (Fig. 3). Hybrid active SHM systems using FBGs as dynamic strain transducers to monitor vibration and waves induced by piezoceramic actuators are also developed [14, 15]. Embedding FBG sensors in a laminate exposed to mechanical loads poses specific difficulties and challenges

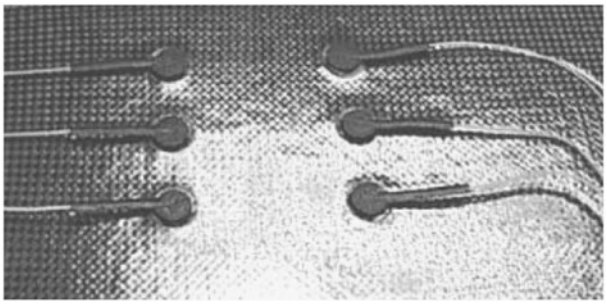

Fig. 3 A typical composite plate with embedded FGB sensors [8]

which require solution. The method used to ingress/egress the optical fiber into and out of the laminate is important for the sensor performance. The effect of non-unidirectional residual and thermal stress on the fiber spectral peak further complicates the response of Fiber Bragg Gratings embedded in a composite laminate which deviates from the ideal behavior of bonded FBGs in room temperature. The behavior of FBGs in composites especially under elevated temperature conditions needs to be further investigated and optimized before the technique can be applied in service. Also the effect of the embedded devices on the strength/stiffness of the laminated structure requires further attention, since under thermo-mechanical loading damage in the form of delamination can be triggered.

Nonlinear Acousto-ultrasonic methods are emerging NDE techniques which rely on the detection of nonlinear effects caused by damage on the vibro-acoustic response (changes in resonance frequencies, wave distortion, and appearance of accompanying harmonics) as a function of the driving amplitude. The sensitivity of nonlinear methods in detecting damage (cracks, flaws) is reported to be far greater than that of linear acousto-ultrasonic methods (measures of wave speed and wave dissipation) [15–17]. The nonlinear methodologies also can coexist with Lamb wave based methods. A widely used NDE technique for detecting cracks in metals and adhesive joints [18, 19], the nonlinear wave modulation, uses a high-power low-frequency excitation to induce non-linear waves or vibrations and monitors the nonlinear wave modulation of a high frequency carrier wave, which appears as wave distortion and generation of additional harmonics (sidebands) (Fig. 4). It should be noted though that these references [18, 19] are research papers and not engineering specifications of inspection of composites. Some recent work has addressed the development of nonlinear acoustic NDE technology for application to aircraft structures, including cracks in metals, adhesive joints, polymers and composites. However, the majority of the nonlinear acousto-ultrasonic methods essentially provide an NDE technology suitable for ground inspections, but not for in-flight SHM of aircraft structures, as they use external low frequency excitations (impact hammers, shakers, speakers [20, 21]) and expensive NDE transducers (Fig. 4). Preliminary research by Saravanos and his colleagues [24] has demonstrated the potential to develop nonlinear acousto-ultrasonic SHM techniques for composite aircraft components by developing active nonlinear acousto-ultrasonic piezoelectric sensors implementing solely low profile, low weight, and permanently attached piezoelectric wafer transducers (Fig. 5). The evolution of this technology for detection of thermo-mechanical damage in aircraft composite structures could be a major step forward.

Active SHM systems based on vibration and wave propagation in composite structures, using bonded piezoceramic wafer type actuators and sensors have demonstrated clear advantages in damage detection capabilities vs. passive ones, as they provide the authority to "interrogate" the composite structure with induced dynamic excitations of varying frequency

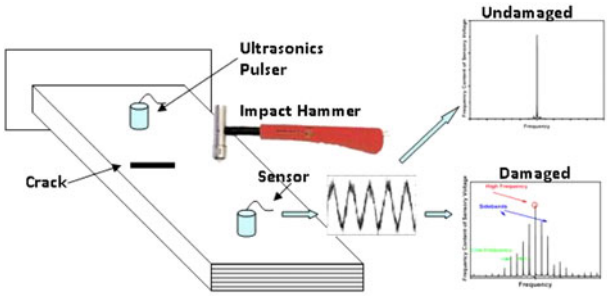

Fig. 4 The nonlinear acousto-ultrasonic wave modulation NDE technique [24]

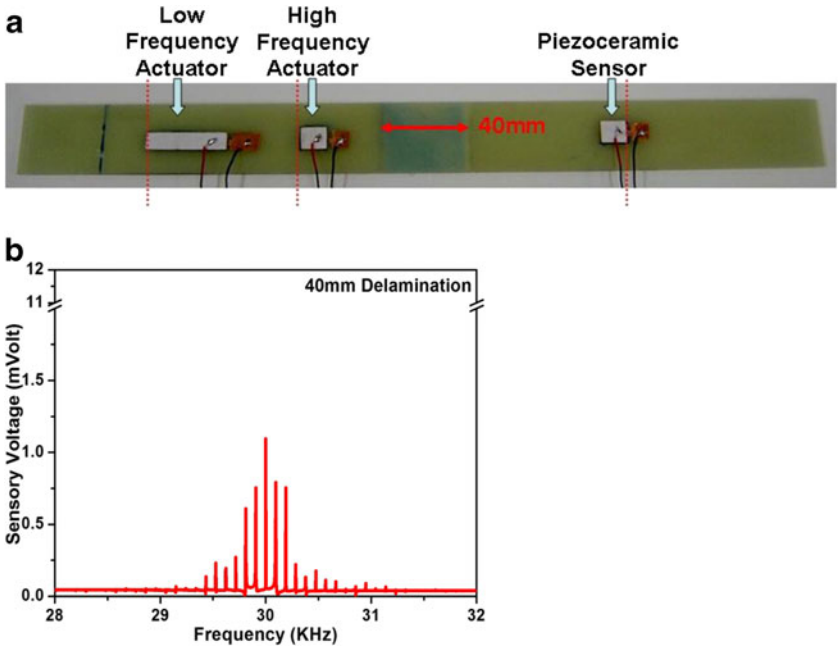

Fig. 5 The concept of Active Nonlinear Acousto-ultrasonic Piezoelectric Sensor developed by Saravanos [25]. **a** composite beam with delamination crack and piezoceramic wafer actuators and sensor **b** nonlinear carrier wave modulation indicates delamination presence from sideband spectral components

and wave lengths, thus enabling adaptation of excitation to the type and size of damage. A promising SHM technology has evolved from the adaption of NDE techniques which rely on the alteration of linear wave propagation characteristics of Lamb waves in damaged structures, using surface attached piezoelectric wafers as transmitters and receivers [10, 22–25]. Research developments have demonstrated the capability of revealing small damage sizes in the form of matrix cracks and delaminations. On-going research addresses the usage of integrated sensors for continuous health monitoring of aircraft composite components based on the response of propagating Lamb waves, but is not yet extended to heat damage. Reported NDE results indicate dramatic decrease in wave velocity in the presence of thermal damage [26–28]. Therefore, the development of Lamb wave based SHM technologies for detecting thermo-mechanical and heat damage in composites can be a step forward, as neither research work nor any technological developments are currently available in this area.

4 PWAS Principles

Piezoelectric wafer active sensors (PWAS) are the enabling technology for active SHM systems. PWAS couples the electrical and mechanical effects (mechanical strain, S_{ij}, mechanical stress, T_{kl}, electrical field, E_k, and electrical displacement D_j) through the tensorial piezoelectric constitutive equations [29, 30]

$$\begin{aligned} S_{ij} &= s^E_{ijkl} T_{kl} + d_{kij} E_k \\ D_j &= d_{jkl} T_{kl} + \varepsilon^T_{jk} E_k \end{aligned} \tag{1}$$

where, s^E_{ijkl} is the mechanical compliance of the material measured at zero electric field (E=0), ε^T_{jk} is the dielectric permittivity measured at zero mechanical stress (T=0), and d_{kij} represents the piezoelectric coupling effect. As a transmitter, PWAS utilize the d_{31} coupling between transverse electric field and in-plane strain to generate high-frequency ultrasonic waves in the structure. As a receiver, PWAS utilize the d_{31} coupling between in-plane strain and transverse electric field to convert the ultrasonic waves into high-frequency electric signals.

Just like conventional ultrasonic transducers, PWAS utilize the piezoelectric effect to generate and receive ultrasonic waves. However, PWAS ultrasonic transducers are fundamentally different from conventional ultrasonic transducers in several aspects:

1. PWAS are firmly coupled with the structure through an adhesive bonding, whereas conventional ultrasonic transducers are weakly coupled through gel, water, or air.
2. Conventional ultrasonic transducers act through surface tapping, i.e., by applying vibration pressure to the structural surface. PWAS transducers act through in-plane coupling with the structural surface.
3. PWAS transducers are strain coupled with the structural surface. This allows the PWAS transducers to have a greater efficiency then conventional ultrasonic transducers in transmitting and receiving ultrasonic and guided waves (surface acoustic waves and Lamb waves).
4. PWAS are non-resonant devices that can be tuned selectively into several guided Lamb-wave modes, whereas conventional ultrasonic transducers are resonant narrow-band devices. With PWAS transducers, optimum excitation and detection takes place when the PWAS length is in certain ratios with the wavelength of the guided wave modes.
5. PWAS transducers cannot be considered in the same class as acoustic emission (AE) sensors because AE sensors are passive devices which only detect the elastic waves created by other events (e.g., elastic waves created when a crack advances in a material creating energy release events). In contrast, PWAS transducers can both detect and generate elastic waves, i.e., they are active sensors.
6. PWAS are inexpensive and can be deployed in large quantities on the structure, whereas conventional ultrasonic transducers are expensive and used one at a time.

By using Lamb waves in a thin-wall structure, one can detect structural anomaly, i.e., cracks, corrosions, delaminations, and other damage. Because of the physical, mechanical, and piezoelectric properties of PWAS transducers, they act as both transmitters and receivers of Lamb waves traveling through the structure. Upon excitation with an electric signal, the PWAS generate Lamb waves in a thin-wall structure. The generated Lamb waves travel through the structure and are reflected or diffracted by the structural boundaries, discontinuities, and damage. The reflected or diffracted waves arrive at the PWAS where they are transformed into electric signals.

PWAS transducers can serve several purposes [10, 31–33]: (a) high-bandwidth strain sensors; (b) high-bandwidth wave exciters and receivers; (c) resonators; (d) embedded modal sensors with the electromechanical (E/M) impedance method. The PWAS transducers have various modes of operation (Fig. 6): (i) active sensing of far-field damage using pulse-echo, pitch-catch, and phased-array methods, (ii) active sensing of near-field damage using high-frequency E/M impedance method and thickness-gage mode, and (iii) passive sensing of damage-generating events through detection of low-velocity impacts and acoustic emission at the tip of advancing cracks. Damage detection using PWAS phased arrays can detect both broadside and offside cracks independently with scanning beams emitting from a central location.

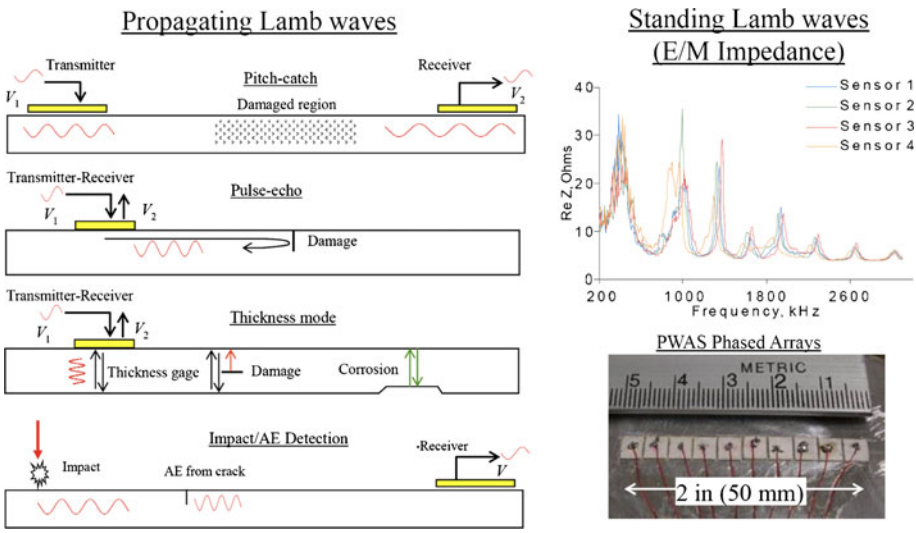

Fig. 6 Modes of operation of piezoelectric wafer active sensors (PWAS) transducers: **a** propagating guided Lamb waves; **b** standing guided Lamb waves; **c** PWAS phased arrays [10]

5 Guided Waves in Composites

Laminated composites are made up of high strength/stiffness unidirectional layers stacked at various angles have gained wide application. A basic lamina has orthotropic properties, with the higher stiffness, strength, and wave speed in the longitudinal (i.e., fiber) direction. The simplest layup sequence is the 0/90 (cross-ply) laminate. Some layup sequences such as 0/45/90 and 0/60/120 are dubbed 'quasi-isotropic' because they try to equalize the effective properties of the laminate in various directions although the through-the-thickness anisotropy remains.

The guided waves propagating in composite structures are more difficult to model than in isotropic metallic structures because of the composite material is inherent anisotropic and multilayered, with each layer having a different orientation and hence elastic properties. Since a composite plate is made of N unidirectional layers of various orientations, the study of wave propagation is achieved by linking together the wave propagation in each layer with that in adjacent layers. This is achieved by applying the equilibrium and compatibility conditions at the interfaces between layers and boundary conditions at the top and bottom surfaces of the laminated composite plate.

6 Dispersion Curves for Composite Structures

A computer code was developed to predict the wave propagation properties in a laminated composite using the analysis method presented in ref. [34] and run a number of simulation examples that were subsequently compared with experiments. Figure 7 shows these dispersion curves of a unidirectional carbon fiber-epoxy composite (65% carbon, 35% epoxy, v/v) for two orientation angles, θ=0° and θ=36°. It is apparent that, for θ=0° (i.e., wave propagating along the fiber direction, Fig. 7a) the dispersion curves of the symmetric,

antisymmetric, and shear horizontal modes are clearly decoupled. For illustration the first symmetric, antisymmetric, and shear horizontal modes have been marked as S0, A0, and SH0 in Fig. 7a. However, for the off-axis direction θ=36°, the three mode types are strongly coupled. The wave velocity is higher when the wave propagates along the fiber direction. As the angle of the wave propagation direction increases, the phase velocity decreases till reaching a minimum in the direction perpendicular to the fiber. This is due to the fact that along the fiber the material stiffness is greater than in all the other directions and it decreases while θ increases. When we analyzed the dispersion curves for a $[(0/45/90/-45)_{2s}]$ quasi-isotropic CFRP laminated composite plate (upon which we later conducted experimental tests) we found even more complicated dispersion curves. However, we observed that at low ξd values a simpler pattern emerges with only the quasi-A_0, quasi-S_0, and quasi-SH_0 modes being present. Low ξd values correspond to low values of the fd product since $\xi=\omega/c$, where $\omega=2\pi f$ and c is the wave speed. Therefore, the presence of only quasi-A_0, quasi-S_0, and quasi-SH_0 modes is to be expected in most thin-wall aerospace composite structures. However, for thicker composite structures, higher order wave guide modes would be also present.

7 Tuned Guided Waves in Composite Structures

The tuning between PWAS transducers and guided waves in isotropic metallic plates is relatively well understood and modeled [10]. The gist of the concept is that manipulation of PWAS size and frequency allow for selective preferential excitation of certain guided wave modes and the rejection of other guided wave modes, as needed by the particular SHM application. A similar tuning effect is also possible in anisotropic composite plates, only that the analysis is more complicated due to the anisotropic wave propagation characteristics inherent in composite materials [35].

To verify our analysis, experiments were performed on a 1240-mm by 1240-mm quasi-isotropic composite plate with a PWAS transmitter and several PWAS receivers installed along various directions with respect to the fiber orientation in the top layer of the composite plate. The plate had an overall thickness of 2.25 mm; the plate of a $[(0/45/90/-45)_2]_S$ layup was fabricated from the T300/5208 carbon fiber unidirectional prepreg. Figure 8 shows the

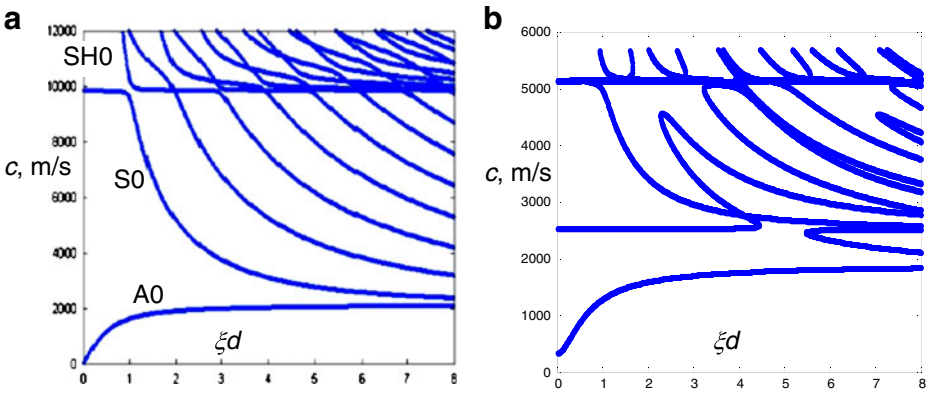

Fig. 7 Dispersion curves for unidirectional 65/35 carbon fiber-epoxy plate: **a** θ=0°; **b** θ=36°. Note: c is the wave speed in m/s; ξd is the dimensionless wavenumber-half thickness product

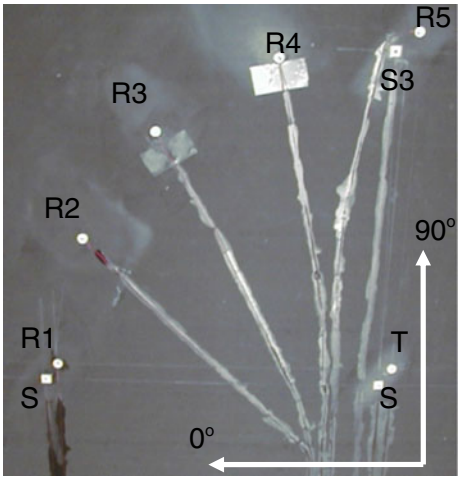

Fig. 8 Experiment setup measuring directional wave speeds in a $[(0/45/90/-45)_2]_S$ plate 1240-mm × 1240-mm, 2.25-mm thick. The plate was laminated from a T300/5208 unidirectional CFRP tape

central part of the composite plate where 7-mm round PWAS transducers (0.2-mm thick, American Piezo Ceramics APC-850) were installed. The PWAS denoted with the letter T was the transmitter while those denoted with R were the receivers (R1…R5). The distance between the receivers and the transmitter was 250 mm. The increment angle between sequential receivers was $\Delta\theta = 22.5°$. In addition, a pair of 7-mm square PWAS were placed along the fiber direction, with S1 being the transmitter and S2 the receiver. Standard laboratory equipment was used in the experiment. The signal was generated with a function generator (Hewlett Packard 33120A) and sent to the transmitter PWAS. A data acquisition instrument (Tektronix TDS210 digital oscilloscope) was used to measure the signal measured by the receiver PWAS. The TDS210 was set to high-impedance option and the voltage signal was picked up with a conventional oscilloscope probe. Smoothed 3-count tone-burst excitation signals were used with frequency varying from 15 kHz to 600 kHz in steps of 15 kHz. At each frequency, we collected the wave amplitude and the time of flight for all the waves present. Three guided wave modes were detected: quasi-S0, quasi-A_0, and quasi-SH_0. Figure 9a shows the experimentally measured signal amplitudes for the three guided waves. The quasi-A0 reaches a peak response at around 50 kHz and then decreases. In fact, the quasi-A0 mode disappears as soon as the quasi-SH wave appears. The quasi-S_0 mode reaches a peak at 450 kHz and then decreases. The quasi-SH_0 mode reaches a peak response at around 325 kHz. Figure 9b shows a comparison between theoretical prediction and experimental values for the A0 mode; the match between theory and experiment is quite good, which gives confidence in our modeling approach.

8 Damage Detection Experiments in Composite Materials

A series of experiments were performed to detect two types of damage in the composite plates. The first type of damage used in these experiments was a small hole of increasing diameter. Holes are generally not a representative type of damage for composite structures; however, we decided to use holes first in our damage detection tests because this type of damage can be easily manufactured and reproduced with accuracy. The second type of damage considered in these experiments was impact damage that can be alternatively

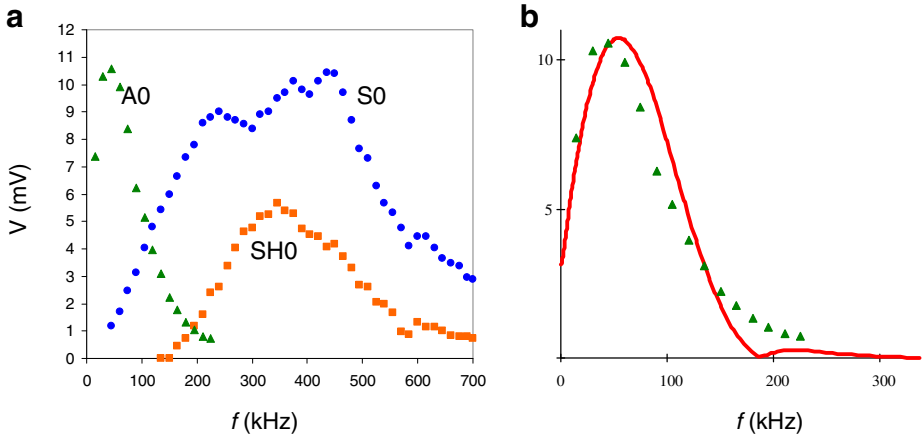

Fig. 9 Tuning of PWAS guided waves in composites: **a** quasi-A_0 mode, quasi-S_0 mode, quasi-SH0 mode. **b** comparison of theoretical prediction (full line) vs. experimental values for A_0 mode

observed by ultrasonic scanning or X-ray radiography. This type of damage was introduced using an inertial impactor of various weights dropped from various heights.

The specimen consisted of a 1240-mm by 1240-mm quasi-isotropic plate with a $[(0/45/90/\text{-}45)2]_S$ layup of T300/5208 unidirectional tape; the overall thickness was 2.25 mm. The experimental setup is shown in Fig. 10; the label 'hole' indicates the location of the hole damage and the labels '1' and '2' indicate the impact locations. A set of twelve PWAS transducers were installed in pairs. The PWAS pairs were (p0,p1), (p2,p3), (p4,p5), (p8,p9), (p10,p11), (p12,p13). The distance between the PWAS transducers in each pair was 300 mm. Standard laboratory equipment was used in the experiment. The signal was generated with a function generator (Hewlett Packard 33120A). A data acquisition instrument (Tektronix TDS210) was used to measure the signal measured by the receiver PWAS (Fig. 10). The excitation signal was a 3-count 11-V smoothed tone burst. The data were collected automatically from PWAS p0, p1, p5, p8, p12, p13 using an ASCU2 automatic signal collection

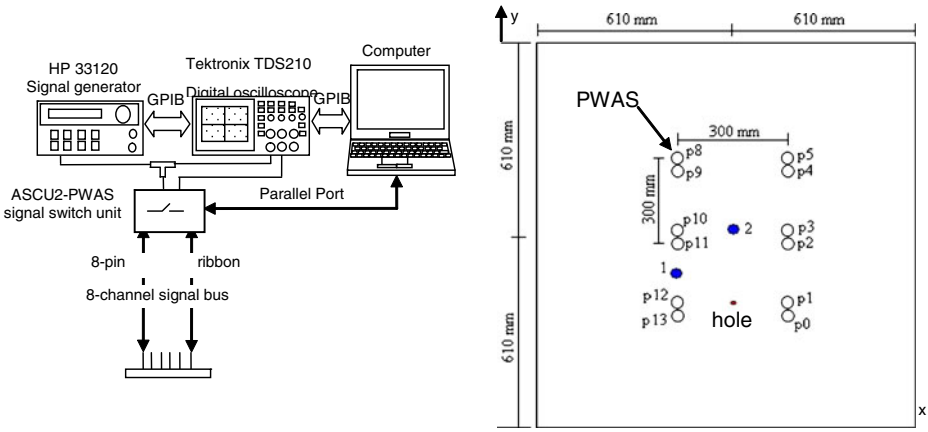

Fig. 10 Experimental set-up for damage detection in a quasi-isotropic composite panel: Featured on the plate are: 14 PWAS transducers (p0 through p13); one open hole (defect); two impact locations (1 and 2)

unit [36]. The ASCU2 unit was purpose-built to enable to collection of multiple signals in round-robin fashion under computer control. Full details of ASCU2 unit are provided in ref. [36]. Each PWAS was in turn transmitter and receiver. Three frequencies were chosen according to the wave tuning principle: (i) f=54 kHz, when only the A_0 mode is present; (ii) f=225 kHz, when only the S_0 mode is present; and (iii) f=255 kHz, when the S_0 mode has maximum amplitude. Four sequential baseline readings were taken with the plate undamaged. Subsequent readings were taken after each damage type was applied to the plate.

8.1 Hole Damage Detection in a Quasi-Isotropic Composite Plate

A hole of increasing size was drilled between PWAS p1 and p12. The location of the hole was halfway between these two PWAS transducers. The diameter of the hole was increased in 14 steps from zero through ~6 mm (Table 1). At each damage step, at least six readings were taken. Data processing consisted in comparing each reading with the baseline (reading 00) and calculating the damage index (DI). The DI value was computed with the root mean square deviation (RMSD) algorithm (see ref. [10], page 391). We analyzed the DI data with statistical software and stated our conclusions to a significance of 99%. Results for f= 54 kHz, when only the A_0 mode is present, are shown in Fig. 11. Similar results were obtained for the other tuning frequencies. From these experiments it was found that, with 99% confidence, the minimum detectable hole size was 2.77 mm.

8.2 Impact Damage Experiments

Two impact damage levels were produced on the plate by choosing different impactor configurations (i.e., weights and heights). Thus three steps were identified (Table 2), with step 1 being 'no damage' and step 3 being 'maximum damage'. The impactor used for damage location 1 had a total weight of 1391 g (3 lb 1.1 oz.). The first impact had an energy level of 6 ft-lb and hit the plate at about 3.42 m/sec (11.22 ft/sec); the second impact had an energy level of 12 ft-lb and hit the plate at about 4.84 m/sec (15.87 ft/sec). The impactor used for damage location 2 had a total weight of 891 g (1 lb 15.5 oz.). The first impact had an energy level of 6 ft-lb and hit the plate at about 4.28 m/sec (14.03 ft/sec); the second impact had an energy level of 12 ft-lb and hit the plate at about 6 m/sec (19.83 ft/sec). The detection consisted in sending pitch-catch waves packets at each of the three tuning frequencies: (i) f=54 kHz, when only the A_0 mode is present; (ii) f=225 kHz, when only

Table 1 Hole diameters for the damage detection experiments on quasi-isotropic composite panel

Step	Reading #	Hole size in mil [mm]	Step	Reading #	Hole size in mil [mm]
1	00–03	0	2	04–07	032 [0.81]
3	08–11	059 [1.50]	4	12–15	063 [1.60]
5	16–19	078 [1.98]	6	20–23	109 [2.77]
7	24–28	125 [3.18]	8	29–32	141 [3.58]
9	33–36	156 [3.96]	10	37–40	172 [4.37]
11	41–44	188 [4.78]	12	45–48	203 [5.16]
13	49–52	219 [5.56]	14	53–56	234 [5.94]

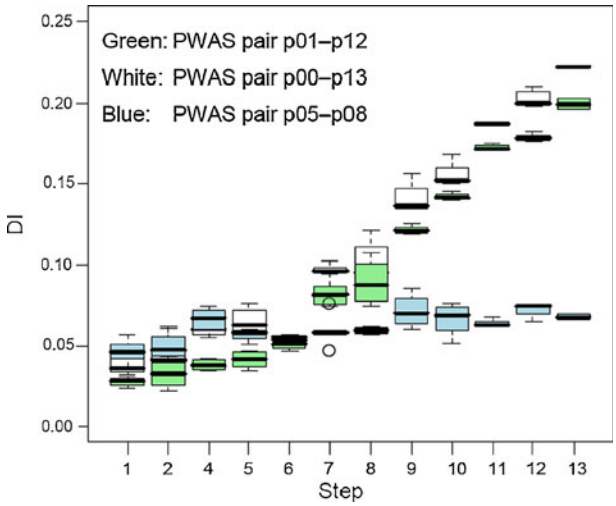

Fig. 11 Pitch-catch hole detection results showing DI values at different damage step values and different PWAS pairs for f=54 kHz, i.e., when only asymmetric A_0 mode is present

the S_0 mode is present; and (iii) f=255 kHz, when the S0 mode has maximum amplitude. Figure 12 shows the results for the impact at location 1 and two PWAS pairs, 10-09 and 12-11. It is apparent that the damage is detected. However, the PWAS pair 12-11 shows a higher sensitivity to the detection of the 12 ft-lb damage than the PWAS pair 10-09. Similar results were obtained for the damage location 2. In post-test examination, the damage produced by the impact on the specimen could be barely observed visually and tactilely (i.e., 'barely observable damage'). It is encouraging to note that the SHM method described here could successfully detect the damage presence. However, further work and more experiments are required to identify the damage type, location through the thickness and of course size and to confirm them with ultrasonic scanning and/or X-ray radiography. Different specimen geometries (e.g., curved panels) and structural configurations (e.g., panels with stiffeners) need also to be considered to give further confidence in the method and repeatability of results.

9 Summary and Conclusion

This paper has presented an investigation in the use of piezoelectric wafer active sensors (PWAS) to perform structural health monitoring (SHM) of composite structures using tuned guided waves. The paper started with an introduction of the PWAS transducers and a review

Table 2 Synopsis of the impacts applied to the composite plate at location 1

Damage location	Readings	Energy	Velocity	Step
1	00–10			1
	11–20	6 ft-lb	11.2 ft/sec	2
	21–30	12 ft-lb	16.0 ft/sec	3

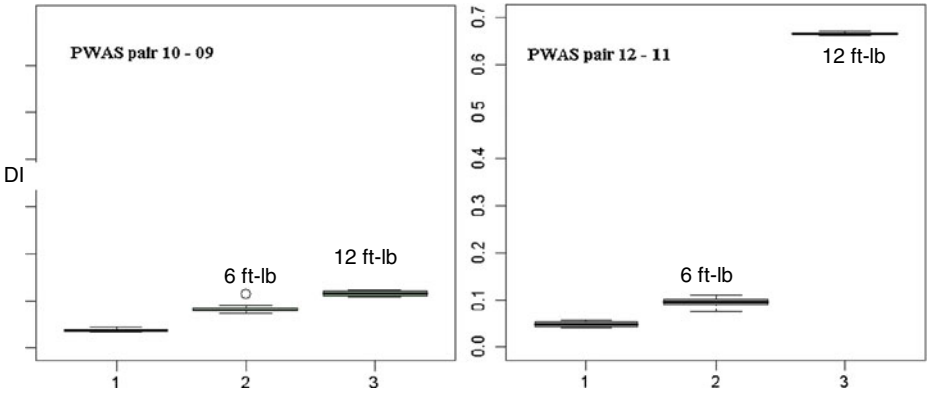

Fig. 12 Detection of impact damage at location 1: DI values as a function of the damage level for PWAS pairs p9-p10 and p11-p12 (f=54 kHz, i.e., when only A_0 mode is present)

of the various ways in which PWAS may detect damage using traveling guided waves, standing waves, and phased arrays. Next, the paper discussed the challenge of guided wave propagation in composite materials and presented some analytical predictions of the dispersion curves which are more complicated that for isotropic metallic materials. However, it was shown that the wave tuning effect initially identified for metallic materials can also be identified in composite materials; tuning measurements performed on a composite plate were presented in comparison with theoretical predictions.

After discussing briefly the damage modes commonly met in structural composites, the paper presented experimental results obtained on a large composite plate. Two types of defects/damage were considered: (i) open hole; and (ii) low velocity impact damage. The detection method used in these experiments was pitch-catch with three tuning frequencies: (i) f=54 kHz, when only the asymmetric A_0 mode is present; (ii) f=225 kHz, when only the symmetric S_0 mode is present; and (iii) f=255 kHz, when the S_0 mode has maximum amplitude. It was found that, with 99% confidence, the minimum detectable hole size was 2.77 mm. In the impact damage experiments, it was found that tuned A_0 guided wave mode were much more effective in detecting impact damage in quasi-isotropic carbon-epoxy plates than S_0 mode. It was also found that, because of the anisotropy of the composite material, the directional placement of the PWAS transducers plays an important role in their detection capabilities.

However, the results presented in this paper are exploratory in nature and preliminary. It should also be said that without a fail-safe capability the utility of the proposed method could be limited. Propagation of the various acoustic waves in a composite structure is a very complex process as most structural components do not have the simple shape one associates with the simple straight test specimens used in this paper. In addition, there are the numerous reflections and mode conversions at boundaries that can complicate the signals and signal analysis. Further research needs to be done to better understand the interaction of guided waves with damage in composite materials and how various guide-wave types interact with various types of damage such as delamination [37] and fiber breakage, especially fiber microbuckling that is observed when the laminate is loaded in uniaxial compression [38]. Two technical reports on aircraft damage tolerance requirements and aircraft structural integrity that may be useful to the reader/researcher can be found in references [39, 40].

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