Lamb waves-based technologies for structural health monitoring of composite structures for aircraft applications

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ABSTRACT
The most common researched area of damage in a composite material such as carbon fibre reinforced plastics (CFRP) used currently in aircraft construction is barely visible impact damage (BVID), significantly reducing mechanical properties. Early detection and qualification would improve safety and reduce the cost of repair. In this context, structural health monitoring (SHM) techniques have been developed that could monitor a structure at any time by using a network of sensors. Widely used discrete ceramic transducers can generate and sense Lamb waves travelling in the structure. Wave propagation must then be analysed for effective damage identification. An effective SHM system is desired to meet several demands, such as minimised weight penalty, non-intrusive system not interfering with the structure performance, cost-effectiveness for implementation with targeted sensitivity and area coverage, capability of monitoring non-accessible and critical hot spot regions, robustness, and reliability. This review starts with an introduction on Lamb waves fundamentals and their use in SHM, and then particularly focuses on methods using piezoelectric transducers and mode selection. Some relevant applications on different structural configurations are discussed. Finally, recent developments on piezoelectric coating and direct-write sensor technology for tailored transducers are highlighted with some thoughts for near future research work.
Introduction

Composite structures

Applications of composite materials for aerospace applications were first limited to secondary structures but extended to primary structures in the mid-1980s allowing weight savings from 20% to 40% (Giurgiutiu, 2016; Ren, Chen, & Chen, 2017; Soutis, 2005). The main driver for using composites in aircraft is the significant reduction of structural weight while maintaining the required loading capacity, considered for both economic and environmental goals. Around 2010, the Boeing 787 was introduced, followed by the Airbus A350; both with more than 50% of the aircraft structural weight made of composites, corresponding to about 80% by volume. Composites in new aircraft are used for airframe, wings, nacelle, and fuselage. The development and availability of carbon fibres and polymer matrices with improved mechanical properties, the decline in material and processing prices over the years, and the improvements of the fibre–matrix interface allow carbon fibre reinforced polymer (CFRP) composites to be increasingly used, not only in the aerospace industry, but also in the sporting goods industry, automotive, marine, or construction. In fact, the global aerospace composites market is estimated to grow at a compound annual growth rate of 11.7% between 2020 and 2025, reaching USD 41.4 billion by 2025, despite COVID-19 negative impact (MarketsandMarkets, 2020a). In CFRP, carbon fibres are the major load-bearing components providing good tensile strength, whereas the thermoset epoxy resin commonly used provides its good resistance to compression. Major advantages in using composites are the design diversity able to improve aerodynamic efficiency and optimisation to various loading conditions by placing fibres along preferential stress directions and by locally reinforcing the structure at design hot spot regions. In addition, CFRP structures have good thermal stability and exhibit corrosion and fatigue resistance.

Common damage

Composites are vulnerable to impact damage coming from mishandling and foreign objects, such as runway debris, bird or hail strikes, dropped maintenance tools, ground handling (Ren et al., 2017). Impact events lead to combinations of damage either apparent (scratches) or internal (delamination, debonding). Low-velocity impact damage would clearly show as a dent or scratch on metallic structures, whereas it may be less obvious in composites (Banerjee, Ricci, Monaco, Lecce, & Mal, 2007; Dziendzikowski, Dragan, & Katunin, 2017; Ooijevaar et al., 2016). While
damage may be insignificant on the surface, the possible high severity on the inside raises concerns about low-velocity impacts. Such barely visible impact damage (BVID) may remain undetected during line maintenance and even for the whole life of the aircraft. However, BVID can cause extensive shear-driven delamination and significantly reduce mechanical properties, reducing the residual compressive strength of up to 60%, while being exposed to in-service growth, further reducing the residual strength (Giurgiutiu, 2016; Irving & Soutis, 2020).

Not only impact, but defects during manufacturing may cause delamination and debonding, propagating due to fatigue and environmental effects (Ren et al., 2017). Examples of fabrication defects include improper curing, voids and porosity, resin rich and poor areas, foreign inclusions, improper impregnation, fibres, and plies misalignment (Giurgiutiu, 2016). Under cyclic loading, tension or compression may initiate damage, such as matrix cracking, fibre/matrix debonding, progressive delamination, stiffness loss, and eventual fracture and failure. Some other concerns are raised with moisture that may accumulate in cracks or delamination and expand damage when freezing at high altitude over flight cycles (Katafiasz, Greenhalgh, Allegri, Pinho, & Robinson, 2021).

The failure of CFRP results from multiple damage modes, which are difficult to predict, and tends to be progressive, meaning failure may occur for a certain lamina in a certain direction only (Giurgiutiu, 2016; Ren et al., 2017; Soutis, 2005). Matrix cracks may propagate and cause debonding, delamination or fibre breakage. When a fibre breaks, the load is redistributed to adjacent fibres through the matrix, making them more susceptible to fail. As the fibres carry most of the load, fibre breakage affects the composite overall strength and leads to final failure, which is associated with a sharp drop of stiffness.

Damage initiates much earlier in critical locations subjected to high stress, commonly called “hot spot regions” such as near fastener holes, riveted, or bolted joints. Instead of mechanical fasteners interrupting fibre flow, adhesively bonded joints with gradual transition to other parts, such as T-joints, allows manufacturing composite structures with fully integrated co-cured stiffeners. Stiffened composite panels are commonly used in aircraft wings, helicopter rotor blades, or wind turbine blades to increase bending strength, link elements and transfer load. However, such complex designs involve complex maintenance and are still sensitive to the delamination of joints. Because of the structural discontinuity in CFRP T-joint structures, damage in form of cracks and delamination have been reported under 3-point bend testing (Kapoor, Blackshire, & Soni, 2010), pull-off loading (Ma, Bian, Liu, Wang, & Xiong, 2020), or impact testing (Ooijevaar et al., 2016).
**Maintenance**

Damage tolerance is investigated for determining optimised inspection intervals and thus ensuring structure reliability (safety) and minimised maintenance cost (Ren et al., 2017). However, damage tolerance of composite structures is challenging to determine. Other challenges to consider in composite structure design are inspection and repair, which must be considered in structure design (Irving & Soutis, 2020; Soutis, 2005). With the increasing demand for composites in aircraft comes the need for adequate inspection methods able to inspect challenging hidden damage (BVID). Current ultrasonic techniques for inspection of composites require specialised equipment and training of qualified personnel, associated with high costs. Inspection of composite materials are performed using non-destructive techniques (NDT) to determine if the flaws detected can be handled by the structure considering damage progression between scheduled maintenance intervals or need appropriate measures to be taken (repair or replace) (Giurgiutiu, 2016; Irving & Soutis, 2020). The sensitivity and reliability of current NDT methods are influenced by on-site inspection conditions, very different from laboratory environment.

Once repair of composite structures is requested, it must restore the damaged part to its service condition performances, in terms of strength, stiffness, and service life duration, considering changes in weight and surface aerodynamic (Irving & Soutis, 2020; Ren et al., 2017). When the damage size is in acceptable limits (scratches, small holes, etc), minor repairs only consist of resin brushed and left to cure at ambient temperature for surface protection and damage seal. Otherwise, tooling and material replacement for major repair of composites are much more expensive than for metals. Material availability may also be an issue, as some parts need to be refrigerated. Major repair techniques (resin injection for limited delamination, bolted or bonded repairs or structure replacement) are laborious and require qualified personnel, being costly and time-consuming. Composites in aircraft are mainly used for cumbersome parts, such as wings and fuselage, hindering major repairs, whereas minor repairs are easy and cheap. Internal damage should be detected and repaired before they progressively grow under hydro-thermo-mechanical loading into critical defects. Thus, detection at an early stage by NDT is essential. Modern inspection techniques could improve maintenance effectiveness or even prevent time-consuming parts removal.

**Structural health monitoring**

Scheduled maintenance requires the aircraft to be out of service (downtime) to perform expensive, time-consuming, and laborious NDT
inspections and necessary repairs, requiring disassembling and reassembling structural components. About 25% of commercial aircraft operating costs are spent on maintenance and repairs (Dong & Kim, 2018; Giurgiutiu, 2014). Thus, a gradual shift from inspection at determined time intervals to inspection based on the structure condition is observed (Ren et al., 2017). Hence, an integrated system able to inspect an aircraft without parts removal and without downtime, on demand at scheduled maintenance, or even more conveniently, autonomously and continuously, would be of great interest. This system could also minimise human involvement, and hence, reduce human error. Developments of such a system able to inspect structures difficult to access and including life prognostics decision-making have been pursued in a growing multidisciplinary field known as structural health monitoring (SHM) (Irving & Soutis, 2020). While NDT methods are well advanced, the SHM field only emerged in the community in the late 1990s (Balageas, Fritzen, & Güemes, 2006; Giurgiutiu, 2016). Since then, the SHM market is estimated to grow at a compound annual growth rate of 14.1% between 2020 and 2025, reaching USD 2.9 billion by 2025, even after taking account of COVID-19 impact (MarketsandMarkets, 2020b). The approaches and motivations for SHM have been extensively reported (Balageas et al., 2006; Giurgiutiu, 2016; Lammering, Gabbert, Sinapius, Schuster, & Wierach, 2018; Ren et al., 2017). A SHM system relies on a network of advanced sensors permanently and strongly coupled to the structure. Different type of sensors might be used to acquire and gather different data, which must be automatically processed and analysed. The given diagnosis of the state of the structure may comprise different aspects of damage information: detection, location, quantification, identification (Lammering et al., 2018). Lastly, the concept of structural prognosis can be introduced. The remaining residual service lifetime can be evaluated by understanding the damage evolution (Balageas et al., 2006; Su & Ye, 2009). By considering a historical database giving damage diagnosis and acquired knowledge of damage progression, a prognosis is provided. Corrective actions and future maintenance scheduling can thus be advised, or even self-repair can be activated if such a system is integrated to the structure. Therefore, the main motivations in developing a SHM system are to save time, reduce costs, and improve reliability and safety (Balageas et al., 2006; Giurgiutiu, 2014; Lammering et al., 2018). It was estimated that a SHM system installed on a modern fighter aircraft featuring metallic and composite structures could save about 40% of inspection time (Balageas et al., 2006). Furthermore, by taking into account the SHM system from the design stage of the structures, new composite structures can be developed with reduced life-cycle
cost: design optimised with weight reduction thanks to eased safety margins (Balageas et al., 2006; Giurgiutiu, 2014; 2016). Therefore, the future of aircraft would be to improve aerodynamic contours with use of composites, to integrate a system similar to the animal nervous system for collecting and analysing data of aircraft state of health, and then to use self-healing structures (Cohades, Branfoot, Rae, Bond, & Michaud, 2018; Williams, Trask, & Bond, 2007).

The limitations in the application of SHM system in actual structures mainly concern the sensors: the interference with structural performance, the weight penalty, the degradation with time and maintenance, the cost implied, the reliability, the power consumption (Irving & Soutis, 2020; Su & Ye, 2009). Another requirement is the damage sensitivity: damage must be efficiently detected without confusion with boundaries and environmental conditions (Giurgiutiu, 2014). Indeed, environmental and operational variations (EOV) highly affect sensors measurements by introducing noise and impacting sensor lifetime. The maintenance cost-effectiveness of the Boeing 737NG metallic fuselage has been compared for conventional maintenance and scheduled-SHM of same inspection quality (Dong & Kim, 2018). The case study found that a network of 9988 piezoelectric sensors was required to monitor the fuselage, implying that about 167 hours were necessary to collect and process large amount of data. The time saved when using such SHM system was the time for parts removing (if no need for repairing). However, the cost due to extra weight was estimated 10 times higher than the saving over the aircraft lifetime. Nonetheless, a condition-based SHM would be significantly more cost-efficient. Indeed, structural weight could be reduced as structures would not need to tolerate growing damage until next maintenance. Additionally, higher potential for SHM on composite structures can be expected, as structures are lighter and with less fastener holes. Anyhow, the case study clearly showed that improving current sensor technologies is necessary for developing cost-effective SHM systems, mainly by using lighter sensors and/or sensors with larger range of detection.

**Lamb waves characteristics**

**Fundamentals**

Ultrasonic testing is currently one of the most popular NDT methods and is estimated to be the largest contributor in the NDT and inspection market during the forecast to 2025 (MarketsandMarkets, 2020c). Ultrasonic methods for NDT and SHM use elastic waves propagating in the tested
structure. Different modes may appear simultaneously, which are wave packets of similar frequency travelling at a certain group velocity (Giurgiutiu, 2014; Lammering et al., 2018; Su & Ye, 2009). The phase velocities associated with the two basic types of wave motion in unbounded solids, i.e., longitudinal and transverse waves are defined by material density and elastic properties.

Guided waves are confined by the boundaries of a structure, allowing them to travel large distances, typically excited at ultrasonic frequencies above 20 kHz (Giurgiutiu, 2014; Lammering et al., 2018; Su & Ye, 2009). Some common guided waves are Lamb waves and shear-horizontal (SH) waves travelling along thin plate-like structures, and Rayleigh waves, which are constrained to the free surface of relatively thick structures (relative to the wavelength) (Su & Ye, 2009; Worden, 2001). The particle motion of SH waves is in the direction perpendicular to wave propagation and parallel to the surface (in-plane). Lamb waves propagate with wavelengths of the order of the plate thickness and with elliptical particle motion (in the direction perpendicular to the surface and in the propagation direction) (Balageas et al., 2006; Su & Ye, 2009).

Lamb waves are divided into antisymmetric $A_n$ and symmetric $S_n$ modes with respect of the median plane of the plate. At lower ultrasonic frequencies, only the antisymmetric $A_0$ mode and the symmetric $S_0$ mode (called fundamental modes) exist. At this low frequency-thickness product region, the motion of the $A_0$ mode is mainly out-of-plane, tending to bend the plate, as represented in Figure 1(a). On the other hand, the motion of the $S_0$ mode is stretching and compressing the plate, dominated by in-plane displacement, as represented in Figure 1(b), and tends to travel farther, particularly in soil or water (Su & Ye, 2009). Further understanding of wave motion in solids can be found in literature (Graff, 1975).

Figure 1. Representation of fundamental Lamb waves in thin plate-like structures with boundaries defined by dashed lines: (a) antisymmetric $A_0$ mode and (b) symmetric $S_0$ mode (Marks, Clarke, Featherston, Paget, & Pullin, 2016).
Dispersion

The propagation of Lamb waves is influenced by the elastic constants, density and geometry of the solid structure, the excitation frequency, and the entry angle (Su & Ye, 2009). As most guided waves, Lamb waves are dispersive: their velocities are function of wave frequency and plate thickness. For a homogeneous isotropic plate, Lamb waves follow the Rayleigh-Lamb equation (Worden, 2001). Finite plates support two infinite sets of dispersive Lamb wave modes: the symmetric modes and the antisymmetric modes. The group velocity, $C_g$, of a wave group (of the envelope) is derived from the phase velocity.

Dispersion curves are established by plotting phase or group velocities versus the frequency-thickness product. Several methods are used to establish these curves in theory. For multi-layered composite plates, they can be obtained by analytical tools such as transfer matrix or global matrix approaches (Lowe, 1995). The higher the frequency-thickness product, the more different modes exist simultaneously. For a CFRP plate, Lamb and SH wave modes are often coupled (Lammering et al., 2018).

For higher frequency-thickness products, the wavelength is smaller relative to the plate thickness. The propagation of Lamb waves is then along a single surface and resembles that of Rayleigh waves. In fact, the velocity of Lamb waves where modes are merging and stabilising in the dispersion curve of a material corresponds to that of Rayleigh waves.

Attenuation

The amplitude attenuation is due to geometric spreading and structural damping (Gresil & Giurgiutiu, 2015; Lin, Gao, Luo, & Zeng, 2016). Geometric spreading is due to the growing length of a wave front spreading in all directions from the excitation source. It can be visualised as ripples in the water created by a drop and spreading into concentric circles. Structural damping is due to viscoelastic material behaviour that implies the dissipation of wave energy. CFRP composites have higher attenuation than metallic structures because of the viscoelastic nature of the resin and anisotropy (scattering across fibres). By plotting mode amplitudes according to the distance from the actuator, attenuation curves are obtained from fitting with equation (Gresil & Giurgiutiu, 2015; Lin et al., 2016):

$$D (r) = \frac{D e^{-ar}}{\sqrt{r}}$$  \hspace{1cm} (1)
with \( r \) the distance from the excitation source, \( D_i \) the initial displacement, and \( \alpha \) the attenuation coefficient, which is a function of frequency. The square root represents the geometry spreading, which involves high amplitude reduction near the actuator, where waves are not as affected by material damping (Ramadas, 2014). With increasing distance from the actuator, the effect of structural damping (represented by the exponential term) increases.

Furthermore, the amplitude reduction when Lamb wave modes propagate through damage is due to both the change in geometry and the change in material properties (Gresil & Giurgiutiu, 2015). The wave dispersion attenuation comes from the fact that waves are composed with different frequency components having different velocities, spreading in the time domain (Gresil & Giurgiutiu, 2015). The attenuation increases with excitation frequency in CFRP structures and is caused by viscoelastic losses in the epoxy matrix and scattering losses by the fibres (Kim & Park, 1987).

In CFRP plates, some values of the attenuation coefficient are reported in Table 1. The directivity of Lamb waves in CFRP depends on the subsurface ply fibre direction and on the initial wave entry (Ono & Gallego, 2012). The attenuation is generally higher when the propagation is not in the fibres’ direction, higher for quasi-isotropic laminates than for cross-ply laminates, and higher for woven laminates than for unidirectional laminates because of fibres undulations and higher resin content. The lower the attenuation, the larger the area monitored, and the less transducers needed (lighter network and cheaper inspection) (Diamanti & Soutis, 2010). The transducers position is important to overcome attenuation and wave reflections from structural boundaries (Lee & Staszewski, 2007). Actuators bounded close to an edge can reduce wave reflections in the received signal (Janarthan, Mitra, & Mujumdar, 2012; Lee & Staszewski, 2007). Moreover, surface-driven actuators would preferentially generate antisymmetric modes, which have higher attenuation than symmetric modes.

**Lamb waves actuators and sensors**

Although very complex, Lamb waves, introduced in 1917, became highly employed for NDT in composites because of their fast and large inspection abilities. The damage presence, location, size, and severity are related to a unique Lamb wave scattering phenomenon (Balageas et al., 2006; Kessler, Spearing, & Soutis, 2002; Su & Ye, 2009). The fundamental \( A_0 \) and \( S_0 \) modes are predominantly utilised in SHM applications (Diamanti & Soutis, 2010; Kessler et al., 2002; Wang, Lu, & Tang, 2008).
Strain sensors based on fibre Bragg gratings (FBG) have been widely used since their discovery in the 1990s (Balageas et al., 2006). FBG sensor is an optical fibre multiplexed with Bragg gratings at different positions along the fibre (Balageas et al., 2006; Giurgiutiu, 2016; Su & Ye, 2009). Gratings are printed into the core as close parallel lines equally spaced, which allows only a narrow bandwidth to be reflected. When the grating is strained, the spacing is shifted and the transmitted wavelengths are shifted as well. Diameters as small as 50 µm can be achieved for improved integration into composite materials (Su & Ye, 2009). FBG sensors glued on the surface of a CFRP structure have been used for sensing of Lamb waves (Tsuda, 2006). Despite their brittleness, they can also be embedded into composite materials. A technique of micro-braiding the optical fibres has been developed to optimise handling and improve strain to failure, without affecting mechanical performance of the composite structure (Rufai, Gautam, Potluri, & Gresil, 2019). FBG sensing sensitivity is mainly

| Mode | α (Np/m) | Frequency (kHz) | Ultrasonic test method | CFRP plate | Ref |
|------|----------|----------------|------------------------|------------|-----|
| A₀ | 10.58 | 500 | Pulse sent; difference of signals received on the top and bottom sides of the plate | 2.2 mm thick [0/+45/−45/90]₂₅ | (Ono & Gallego, 2012) |
| S₀ | 4.25 | 260 | Pulse sent; sum of signals received on the top and bottom sides of the plate | 2 mm thick [−45/−45/0/90]₂₅ | (Lin et al., 2016) |
|     | 1.46 | 500 | 5-count tone burst Hanning-windowed sent and received by PZTs | 2 mm thick [0/45/−45/+45]₂₅ | (Gresil & Giurgiutiu, 2015) |
| A₀ | 5 | 90 | 3-count tone burst Hanning-windowed sent and received by PZTs; values calculated from maximum wave amplitudes or (*) from wave packet energy | 2 mm thick [0/45/+45/0]₂₅ | (Gresil & Giurgiutiu, 2015) |
| S₀ | 6 | 150 | 150 | 300 | 18 * |
| A₀ | 0.5 to 17 | 45 to 300 | 3-count tone burst Hanning-windowed sent by a PZT and received by vibrometer at 0° and (†) 90° directions | 1.8 mm thick [0]₈ | (Mei & Giurgiutiu, 2019) |
| S₀ | 0.5 to 8 | 210 to 300 | 10.5 to 29 | 300 | 16 * |
limited to wave propagation directed along the grating length (Su & Ye, 2009). This high directivity has been used to develop a damage localisation technique in a rosette configuration (Betz, Thursby, Culshaw, & Staszewski, 2007). Distributed fibre optic sensing systems consisting of a single optical fibre with distributed sensitivity along its length can be embedded directly during CFRP manufacturing to monitor the structure not only during fabrication (resin curing) but also during service (mechanical testing) (Chandarana, Sanchez, Soutis, & Gresil, 2017). Distributed optical fibre systems based on Rayleigh scattering have been implemented in large CFRP stiffened aircraft structures such as fuselage skin (Díaz-Maroto, Fernández-López, García-Alonso, Iglesias, & Güemes, 2018) and wing box (Datta et al., 2021) structures to detect local variation of strain.

Piezoelectric transducers can efficiently generate and sense guided waves with rapid acquisition over time and over a large area with detection sensitivity similar to that of conventional ultrasonic NDT (Giurgiutiu, 2016; Lammering et al., 2018; Su & Ye, 2009). The direct effect of piezoelectricity is the generation of an electric charge when under mechanical stress (sensing), whereas the converse effect is the generation of a mechanical strain in response to an electric field (actuation) (Giurgiutiu, 2014; Su & Ye, 2009). Piezoelectric transducers are characterised by their piezoelectric strain and voltage coefficients, \( d_{ij} \) and \( g_{ij} \), corresponding to the actuating and sensing performances, respectively. The double subscripts \( i,j \) indicate the direction of the electric field and the direction of the mechanical strain. A large absolute \( d_{ij} \) coefficient designates a large mechanical strain under a given electric field. In contrast, a large absolute \( g_{ij} \) coefficient designates a large voltage generated under a given mechanical stress. Rectangular transducers will generate Lamb waves with propagation preferentially oriented in the length direction and the wave front parallel to the width, whereas circular transducers will generate omnidirectional (radial) Lamb waves. Piezoelectric transducers surface-mounted on the structure are adhesively bonded, which creates an interface influencing the load transfer between the transducer and the structure, and hence, some attenuation. Certification requirements in terms of temperature, loading or degradation of the adhesive layer might be challenging. Besides, piezoelectric transducers can be used as thickness gauges, detecting damage parallel to the surface directly under their location for monitoring critical hot spot regions (Gresil, Yu, Giurgiutiu, & Sutton, 2012; Zagrai & Giurgiutiu, 2001). Common piezoelectric ceramics are barium titanate (BT), lead titanate (PT), and lead zirconate titanate (PZT) (Giurgiutiu, 2014). Discrete ultrasonic PZT ceramic transducers are the main types of sensors currently used for SHM in aerospace
applications because of their high piezoelectric strain coefficients of about 400 pm/V, electromechanical coupling coefficient, and thermal stability (Balageas et al., 2006; Capsal, David, Dantras, & Lacabanne, 2012; Su & Ye, 2009). However, piezoelectric polymers are easier to fabricate and exhibit a piezoelectric voltage coefficient of about 300 mV m/N, typically 10 to 20 times larger than for piezoceramics (Capsal et al., 2012; Lin & Giurgiutiu, 2006). Poly(vinylidene fluoride) (PVDF) piezoelectric polymer films are used for their greater ease of handling and higher flexibility, which allow better impact resistance than the brittle PZT ceramic transducers (Lin & Giurgiutiu, 2006). But their lower capacitance requires amplifying Lamb wave signals (Bellan et al., 2005; Capsal et al., 2012; Lin & Giurgiutiu, 2006; Tuloup, Harizi, Aboura, & Meyer, 2020).

**Mode selection methods**

**Motivation**

Analysis of signals acquired by ultrasonic transducers can be cumbersome because of the overlapping of multiple dispersive wave modes and complex wave propagation due to scattering. Therefore, methods of Lamb wave mode selection are typically implemented (Giurgiutiu, 2016; Lammering et al., 2018; Su & Ye, 2009; Wang et al., 2008). The ability to select either antisymmetric or symmetric modes is profitable for damage detection and qualification because they undergo different displacements, and hence, respond to damage differently. For instance, the $S_0$ mode is suitable for detection of damage in the thickness such as cracks, whereas the $A_0$ mode is more sensitive to planar damage such as delamination and disbond (Giurgiutiu, 2005; Ihn & Chang, 2008). The $A_0$ mode is selected for its shorter wavelength at a given frequency, larger signal amplitude, and easier mean of activation, whereas the $S_0$ mode is selected for its lower attenuation, faster propagation, and lower dispersion in the low frequency range. The possible mode conversion occurrence due to damage presence would be easily detected if the guided waves are tuned into a specific mode.

Furthermore, it is attractive to select a mode with shorter wavelength (higher frequency) since it is sensitive to smaller damage (Diamanti & Soutis, 2010; Su & Ye, 2009). Theoretically, the half-wavelength of the wave mode used should be shorter than or equal to the damage size to allow strong interaction with damage (Lizé, Rébillat, Mechbal, & Bolzmaccher, 2018; Su & Ye, 2009). However, more Lamb wave modes are simultaneously generated with higher frequencies. Therefore, the choice of a proper combination of frequency and mode on the dispersion curves is essential (Rose, 2011). The mode selected should ideally feature
non-dispersion (stable mode velocity around a narrow frequency bandwidth), low attenuation, high sensitivity to damage, easy excitability, and good detectability (Su & Ye, 2009). A windowed tone-burst sinusoidal signal is frequently used to excite PZT transducers to narrow the frequency.

**Tuning modes**

A wave mode tuning method is the preferential excitation of a single mode. Despite a tuned mode will not completely cancel other modes, a single mode excitation is achieved when using “sweet spots” (Giurgiutiu, 2005; Su & Ye, 2009; Wang et al., 2008). These “sweet spots” are determined by frequencies corresponding to the maximum response amplitude and showing mode separation (Giurgiutiu, 2014). The mode separation can be observed by plotting tuning curves, which are the modes amplitudes versus frequency, as represented in Figure 2. However, it should be noted that PZT transducers excited at resonance frequencies will undergo larger mechanical response than at other frequencies. This could explain the difference between theoretical and experimental tuning curves in Figure 2. Moreover, the A₀ mode is dispersive at low frequency, which can affect its amplitude response.

Because only the fundamental A₀ and S₀ modes exist at low frequency, they are selected by using the frequency corresponding to their highest amplitude response, often linked to the transducer’s length (Giurgiutiu, 2005; Wang et al., 2008). A wavelength tuning occurs when the transducer’s length is an odd multiple of the mode’s half-wavelength (Giurgiutiu, 2005; 2014).

Another well-known technique to tune a mode with PZT transducers is to use two actuators symmetrically bonded on the upper and lower surfaces of the plate. The S₀ and A₀ modes are independently excited by energising both actuators in-phase and out-of-phase, respectively (Su &

![Figure 2. Experimental and theoretical tuning curves identifying a “sweet spot” of the S₀ mode at 300 kHz and of the A₀ mode at 70 kHz (Giurgiutiu, 2014).](image-url)
Ye, 2009). However, this technique is not easily implemented in a real structure for SHM purpose.

**Interdigital transducers and comb electrodes**

Another promising method for mode selection uses electrode design: a comb-shaped electrode is patterned with a periodicity corresponding to the wavelength ($\lambda$) of the desired Lamb wave mode, which can be excited at a specific frequency (Quek, Tua, & Jin, 2007; Schmidt, Sinapius, & Wierach, 2013; Stepinski, Mańka, & Martowicz, 2017). The comb-shaped electrode is made of multiple fingers. The design is shown in Figure 3(b), where the width of the fingers ($W$ in Figure 3) corresponds to the half-wavelength ($\frac{\lambda}{2}$) of the selected mode. The wider the fingers, the higher the resulting amplitudes observed (Lammering et al., 2018). The more fingers in the pattern, the purer the mode selection (Monkhouse, Wilcox, & Cawley, 1997; Su & Ye, 2009). In theory, it requires an infinite number of fingers to generate a pure specific mode, and thus with finite design experimentally, some additional modes may still be generated. A minimum of three fingers are typically required to create an electrode design resembling a “comb” shape. Hence, the electrode dimensions may be relatively large when using large wavelengths.

Moreover, a comb-shaped electrode pattern causes the wave generated to propagate mainly in the direction perpendicular to the fingers (Manka, Rosiek, Martowicz, Uhl, & Stepinski, 2011; Monkhouse et al., 1997). When all fingers of the electrode are excited simultaneously, the selected mode is thus radiated in both directions perpendicular to the fingers.

![Figure 3. Method for selection of a mode with wavelength $\lambda$ using transducers with electrode periodicity of $\lambda$, finger length $L$, and finger width $W$: (a) Interdigital transducer (IDT) and (b) transducer with comb-shaped electrode.](image-url)
The finger length \( (L \text{ in Figure 3}) \) relatively to the wavelength \( (\lambda) \) controls the divergence of this radiated wave propagation (Lammering et al., 2018):

- If \( L \ll \lambda \), the wave propagation is almost non-directional.
- If \( L > \lambda \), the wave propagation exhibits clear directionality.
- If \( \lambda < L < 2\lambda \), the wave propagation exhibits higher directionality with higher number of fingers.
- If \( L > 2\lambda \), the wave propagation exhibits clear directionality whatever the number of fingers.

This feature of wave propagation directivity is very attractive for monitoring critical regions known as hot spots with highly localised stress/strain such as near fastener holes, riveted or bolted joints or stringers (Ataş & Soutis, 2013; Chen et al., 2020). For complex structures with stringers and beams as in aerospace applications, unidirectional wave generation avoids unwanted reflections and focuses damage detection on a precise sensitive location. In a different technique, dual-PZTs made of concentric disk and ring electrodes have been used for creating an optimised network (Lizé et al., 2018).

A similar method is to use interdigital transducers (IDT), also achieving mode selection through the electrode design (Stepinski et al., 2017). IDTs are made of a piezoelectric layer, such as piezoceramic plates or PVDF films, with two comb-shaped electrodes having opposite polarity applied on the surface, as represented in Figure 3(a) (Lammering et al., 2018). The number of fingers in IDT is multiplied compared to comb-shaped electrodes, as shown in Figure 3(b), making IDT mode selection more efficient with amplified signal. However, the fabrication of IDT is more complex.

The issues when using piezoceramic for IDT are the brittleness, the weight penalty, and the difficulty in manufacturing transducers (Schmidt et al., 2013; Stepinski et al., 2017). Due to brittleness, IDT may be damaged during in-service loading and electrical connections may fail. In contrast, thanks to the flexibility and ease of manufacturing, the applications of piezopolymers and piezocomposites (piezoceramic materials embedded in polymers) for IDT are more common (Stepinski et al., 2017). IDT made of PVDF piezoelectric films are the most common and are usually surface-bounded to the composite structure to monitor (Su & Ye, 2009). Indeed, embedded PVDF-based IDT during manufacturing for some composite structure may damage PVDF due to elevated temperatures. Besides, they have been mostly used as sensors only due to relatively smaller piezoelectric strain coefficient.
Monitoring of damage

Passive and active sensing

There are two different ways to perform SHM: passive sensing and active sensing, which can be complementary and combined to greatly benefit SHM applications. For instance, impact damage can be detected by passive or active sensing methods, or by both methods simultaneously (Staszewski, Mahzan, & Traynor, 2009).

Passive approaches rely on measurements of various operational parameters interfering with the structure: strain, acoustic emission (AE), operational loads, etc (Giurgiutiu, 2014, 2016). Some passive sensors used are strain gauges, piezoelectric, and FBG sensors. The elastic waves generated by unknown events such as impact, crack initiation and growth, or delamination, are captured by sensors continuously monitoring a large CFRP structure (Staszewski et al., 2009; Yuan, Ren, Qiu, & Mei, 2016). Impacts can be sensed at frequencies of about tens of kHz, while the potential accompanying AE event would be sensed approximately between 150 and 300 kHz (Giurgiutiu, 2016). In literature, a passive SHM method used four piezoelectric transducers to capture and locate AE produced during an impact on a CFRP plate, with information on possible delamination extend (Dupont, Osmont, Gouyon, & Balageas, 1999). However, this technique capturing signals from unknown events is liable to various noise effects and makes signal interpretation difficult. Moreover, the monitored waves may undergo modifications before reaching the sensors.

Contrastingly, active sensing methods directly interrogate a structure by transmitting controlled signals from actuators to sensors (Balageas et al., 2006; Giurgiutiu, 2016). An actuator generates a diagnostic signal, and different sensors may be used for the signal detection. The generated elastic wave will undergo reflections at structural boundaries and scattering when travelling through structural changes, such as damage. Reflections from boundaries may be reduced by damping edges of the structure with silicone (Lammering et al., 2018). Signals are usually compared with a baseline (signals travelling into the structure in pristine condition), which is typically previously recorded. Any changes in the received signals correspond to changes in the structural integrity. Different methods might be used to interrogate the structure, such as pitch-catch or pulse-echo (Giurgiutiu, 2016). In the former method, the signal is sent by an actuator and received by a sensor across the tested material (Ihn & Chang, 2008). Signal differences compared to the baseline indicate damage. By acquiring signals through different pairs of sensors, damage location is possible with a tomography technique. In the pulse-echo method, the same transducer is used as actuator and sensor. The elastic
wave reflected at the structural boundaries, discontinuities, and damage, travels backward to reach the transducer. New reflections compared to the baseline indicate damage. Phased array is another common method allowing a large area of the structure to be scanned from a single position by an array of transducers (Yan & Rose, 2007). A beam could be constructed from signals simultaneously generated and is steered to different angular positions by arranging the phase delays of each transmitter. Reflections or propagations are received by the array of transducers.

Piezoelectric transducers are widely used for ultrasonic SHM as actuators and sensors. For SHM applications, this opportunity permits flexibility such as alternating roles when using a network of PZT transducers or monitoring non-accessible parts with only one transducer in pulse-echo configuration.

**Signal processing**

To detect and identify damage, signals captured by sensors must be processed and interpreted. A correlation must be established experimentally between the extracted signal characteristics and the damage diagnostic. Signals are usually compared for pristine and damaged structures on a same sensing path. Even though, some baseline-free methods exist based on the reciprocity principle: the comparison of signals on a same sensing path in both directions (PZT actuator becomes sensor) gives reciprocity information (Huang, Zeng, & Lin, 2018; Huang, Zeng, Lin, & Zhang, 2020). However, this method requires the wave packets from reflections to be well separated in the time domain, which is done by optimising the transducers positions for a given structure application. Another baseline-free method focused on this problem and developed a network optimisation solver (Lizé et al., 2018). In the context of challenging EOV in aircraft structures, a straightforward SHM method would be to collect data at different conditions. A more optimised damage-sensitive method using cointegration has been applied for SHM of CFRP structure (Cross, Worden, & Chen, 2011) and proven effective in comparison to other methods (Cross, Manson, Worden, & Pierce, 2012). The cointegration method consists in removing the common trends in data to obtain a stationary residual. With noise, modes superposition and dispersion, digital signal processing can help for signal interpretation through approaches available in time domain, frequency domain, and joint time-frequency domain (Balageas et al., 2006; Su & Ye, 2009).

In the time domain, commonly used features extracted from signals are local amplitude variations corresponding to wave attenuation by damage, wave velocity variations acquired from time-of-flight (ToF)
measurements, energy variations and mode conversions (Ramadas et al., 2011; Wang et al., 2008). Other characteristics such as energy distribution (Ihn & Chang, 2008) or phase shifts (Yan, Royer, & Rose, 2010) may be used for damage identification. The ToF is the time for a wave mode to travel the distance between the actuator and the sensor, which is often measured using the Hilbert transform creating an envelope of the signal (Ramadas et al., 2011).

Signals are transferred into the frequency domain through Fourier transform (FT). Fast Fourier transform (FFT) algorithms computing the discrete FT are preferred for reduced computation. Changes in features, such as energy or frequency magnitude, are used to detect damage (Janarthan, Mitra, & Mujumdar, 2013; Su & Ye, 2009). For instance, the presence of higher harmonics in the Fourier spectrum can indicate micro-crack presence in the structure (Wan, Zhang, Xu, & Tse, 2014). The frequency response function (FRF) is a common feature calculated from the FT of the response divided by the FT of the excitation (Balageas et al., 2006; Banerjee et al., 2007; Su & Ye, 2009). For a more comprehensive damage analysis, the signal can be transferred in a time-frequency space through short-time Fourier transform (STFT), Wigner-Ville distribution, or Wavelet transform (Hua, Cao, Yi, & Lin, 2020; Niethammer, Jacobs, Qu, & Jarzynski, 2001; Prosser, Seale, & Smith, 1999). In literature, impact damage has been identified in a CFRP plate with four PZT transducers using signals processed in the joint time-frequency domain and using ToF information for damage location (Wang & Chang, 2000).

A variety of algorithms for damage identification have been developed, such as time reversal or delay and sum algorithms (Qiu, Liu, Qing, & Yuan, 2013; Su & Ye, 2009; Yan & Rose, 2007). Some other common algorithms are used for damage localisation, such as the ToF-based triangulation (Ihn & Chang, 2008). Considering the damage causes the most significant change in direct path, the damage distribution probability for a given path will be a decreasing elliptical spatial distribution (Zhao et al., 2007). Reconstruction algorithms have been applied in an aircraft wing using eight PZT transducers (Gao, Shi, & Rose, 2005) and in a CFRP plate with the ability to perform damage location inside and outside of the network of 16 PZT transducers (Muller, Soutis, & Gresil, 2019). Another technique called RAPID (reconstruction algorithm for probabilistic inspection of damage) can detect, locate and monitor the growth of damage using relevant signal information, which has been verified for aircraft aluminium wing inspection (Zhao et al., 2007), as well as for damage detection in CFRP (Monaco et al., 2016; Yan et al., 2010) and BVID monitoring in GFRP (Dziendzikowski et al., 2017). However, image reconstructions should implement the skew effects caused
by composite anisotropy (Yan et al., 2010), and the distortion due to inhomogeneity in distribution of sensing paths intersections in noncircular PZTs arrays (Dziendzikowski et al., 2017). Ultimately and eventually, SHM systems can use machine learning techniques as applied for damage location with PZTs on aluminium structures (Dworakowski et al., 2013; Zhang, Li, & Ye, 2021) or on CFRP structures (De Fenza, Sorrentino, & Vitiello, 2015; Qiu & Yuan, 2009).

**Damage index**

Features of Lamb wave modes extracted from signals are used to quantify and evaluate damage severity by developing damage indexes or indices (DI) (Dworakowski et al., 2013; Mechbal & Rebillat, 2017; Memmolo, Monaco, Boffa, Maio, & Ricci, 2018). The comparison of the baseline with a signal corresponding to another structural state can be applied over a precise interval, corresponding to a specific mode, using a window function (Memmolo et al., 2018). The length of the time window would be the duration of the excited signal with a small percentage error, which would be centred over the estimated ToF. However, when the group velocity depends on the direction of propagation, the ToF might not be precisely estimated.

For quantified evaluation, a DI giving a value between 0 and 1 could be introduced, with 0 corresponding to no signal difference (healthy state). The greater the DI, the more serious the damage. A threshold value must be estimated to identify when the signal changes come from identified damage. The baseline allows eliminating noise effects and can be optimised by acquiring signals at different environmental conditions to cover all possible signal disturbances not related to damage (Su & Ye, 2009; Yan et al., 2010). A DI can be developed for a particular type of damage but is hardly optimised to be sensitive to multiple damage types as combinations of damage parameters will be different.

Beyond the common and easily obtained amplitude ratio (Park, Jun, & Lee, 2014; Wan et al., 2014), DI examples comparing a baseline $B(k)$ and a signal $D(k)$ obtained in the damaged state are listed in Table 2. The cross-correlation coefficient is calculated by dividing the covariance by the standard deviations and is effective even for small signal disturbance but can be erroneous for phase shift by giving very high values (Stawiarski & Muc, 2019). Comparing different DIs would be an effective way to cover all types of signal disturbances. A combination (sum, average) of different DIs can be considered (Mechbal & Rebillat, 2017). Good performance of the DI based on correlation or signal energy in the time domain was found for detecting debonding of composite stiffener, unlike
Thus, after first considering the common ratio of difference applied for amplitude of a mode of interest, the cross-correlation coefficient could be considered.

### Ultrasonic-based technologies in applications

#### Monitoring of CFRP structures with PZT transducers

Ultrasonic NDT being a proven method for damage detection, ultrasonic-based SHM is a promising method (Lammering et al., 2018; Ren et al., 2017). Piezoelectric PZT transducers are one of the preferred transducers used for active SHM, often used in pitch-catch configuration (Ihn & Chang, 2008; Muller et al., 2019). Ultrasonic methods have been widely used in metallic materials for damage monitoring but remain more complex for composite materials. The major challenge with SHM methods based on ultrasonic guided waves generated and sensed by PZT transducers is the reproducibility of the technique on different composite materials.
structures. These methods not only depend on the data acquisition system, the sensor type and response, the environmental conditions (temperature, moisture), but also on the material anisotropy and geometry. It is required to understand the complex propagation of guided waves before implementation into a safety-critical structure. Ultrasonic Lamb wave-based inspections of CFRP are much more challenging than in metals because of anisotropy and numerous discontinuities due to CFRP heterogeneity and layered construction (carbon-polymer and plies interfaces) and potentially complex geometry (stringers). In addition, the ultrasonic wave attenuation in composite is higher than in metal, limiting its use at relatively lower frequencies (Gresil & Giurgiutiu, 2015).

Piezoelectric wafer active sensors (PWAS) of thickness 0.2 mm, weight 0.07 g, cost 10 USD each, and typically 7 mm squares or disks, have been developed for Lamb waves-based SHM (Giurgiutiu, 2005, 2014, 2016). PWAS are not more expensive than conventional resistance strain gauges and are cheaper, lighter, and thinner than conventional ultrasonic transducers. An active SHM system using a network of distributed PWAS has been commercialised by Acellent Technologies, Inc, comprising both hardware and software (Giurgiutiu, 2016; Lin, Qing, Kumar, & Beard, 2001). It can be either bonded onto the surface of existing structures through epoxy adhesion or embedded inside composite structures (temperature tolerance above 200 °C) without degrading the integrity of the host structure. This SHM system can be built in different shapes and sizes to fit the host structure and can be applied to composite and metallic structures, such as fuselage panels (Ihn & Chang, 2008).

Besides the commercially available system, the literature counts plenty of studies about SHM with PZT transducers. Some of them were performed on large and complex CFRP structures, such as the ones found in aircraft, and have been largely reviewed (Qing, Li, Wang, & Sun, 2019). For instance, large and complex CFRP structures have been monitored using PZTs such as fuselage panel (Ihn & Chang, 2008; Weiland et al., 2020) or wing box (Qiu et al., 2013; Qiu & Yuan, 2009). The proposed SHM system applied on a wing box was developed with both hardware and software (Qiu & Yuan, 2009), and with improved savings on time consumption and computational resources (Qiu et al., 2013).

While laser systems are not embedded in continuous SHM, they are good candidates for contactless inspection, limiting the consumption of numerous fixed transducers by making use of them (Staszewski et al., 2009; Truong, Kang, Lee, & Farrar, 2015). Laser scanning vibrometer was often used to understand wave propagation, which is of great help for interpreting signals obtained from PZT transducers in a complex
structure, such as T-joint structures, as in Figure 4(a) and (c) (Geetha, Mahapatra, Gopalakrishnan, & Hanagud, 2016; Kapoor et al., 2010; Swenson, Soni, & Kapoor, 2010). This method may be implemented as a scheduled-SHM maintenance or as second stage SHM providing precise damage localisation and characterisation (first stage providing rapid damage detection and localisation using an array of fixed ultrasonic transducers).

Figure 4. (a) GFRP T-joint with a PZT actuator and surface velocity distribution of the \( A_0 \) mode obtained from a laser scanning vibrometer (Geetha et al., 2016). (b) Experimental set-up of the tensile loading of a CFRP T-joint with 9 PZT transducers attached in the red dotted area (Ma et al., 2016). (c) Scans obtained from a laser scanning vibrometer of a CFRP T-joint before (undamaged marked as a \( U \)) and after (damaged marked as a \( D \)) a three-point bending test (Kapoor et al., 2010).

**Mode conversion**

Lamb waves are scattered by discontinuities and may generate new modes. Both \( A_0 \) and \( S_0 \) Lamb wave fundamental modes can exhibit mode conversion when interacting with a discontinuity in aluminium plates (Benmeddour, Grondel, Assaad, & Moulin, 2008; Wandowski, Malinowski, & Ostachowicz, 2014). Mode conversion was also observed in composite structures. In a CFRP plate, mode conversion from \( A_1 \) mode to \( S_0 \) mode was observed when travelling through an artificial delamination (Okabe, Fujibayashi, Shimazaki, Soejima, & Ogisu, 2010). Lamb wave mode conversion was modelled in a complex CFRP structure used in helicopter rotor blades and the interaction with cracks and delamination was explained (Chakrapani, Barnard, & Dayal, 2015).
In a GFRP T-joint structure such as one used for wind turbine blades, the $A_0$ mode travelling through the web generated a new wave mode identified as the $S_0$ mode, which was referred as turning mode (Ramadas et al., 2011). In another GFRP T-joint structure, the $A_0$ mode generated by a PZT transducer bonded to the structure underwent two different mode conversion observed by laser scanning vibrometer: one due to the web and filler region and one due to a delamination created by a Teflon insert under the web-flange interface, as shown in Figure 4(a) (Geetha et al., 2016).

**Applications on T-joint structures**

As damage initiates earlier in critical hot spot regions with highly localised strain, inspection of these regions becomes critical and efficient monitoring is required. Many challenges are faced in monitoring CFRP T-joint structures when using Lamb wave-based methods where thickness variation exists in addition to multiple reflections, and mode conversions. PZT transducers were used to generate and sense Lamb waves in a CFRP panel with two stiffeners for SHM and showed the $S_0$ mode was more strongly attenuated by the presence of stiffener than the $A_0$ mode (Janarthan et al., 2012). A CFRP laminate was compared before and after bonding and screwing a stiffener of same material, the stiffener increased the attenuation of the $S_0$ mode by approximately 60% (Su & Ye, 2009).

Damage detection was performed in CFRP T-joints using PZT transducers in a pitch-catch active SHM approach by considering changes in amplitude responses (Kapoor et al., 2010; Ma, Bian, Lu, & Xiong, 2016; Wu, Gao, Wang, & Rahim, 2015). Fundamental modes $A_0$ and $S_0$ are tuned at respective frequencies 100 kHz and 250-300 kHz according to experiments in CFRP T-joint structures (Kapoor & Soni, 2009; Ma et al., 2016; Truong et al., 2015; Wu et al., 2015). A SHM system was developed, using a network of six PZT transducers on a 200 mm long CFRP T-joint under tensile loading with artificial delamination embedded, and then applied using a network of 57 PZT transducers on a 5 m long full-scale composite aircraft horizontal tail under static load (Wu et al., 2015). The $S_0$ mode was used for rapid monitoring of damage extension and an efficient imaging diagnosis was developed.

In a 200 mm long CFRP T-joint during continuous tensile loading, as in Figure 4(b) (Ma et al., 2016), or after a three-point bending test as shown in Figure 4(c) (Kapoor et al., 2010; Swenson et al., 2010), the $A_0$ mode was generated using PZT actuators. In these studies (Kapoor et al., 2010; Ma et al., 2016; Swenson et al., 2010), BVID in the form of vertically oriented filler cracks blocked Lamb wave propagation and thus
involved a reduction in mode amplitude. Interface debonding or delamination implied shortening in Lamb wave wavelength due to local thickness reduction, which can be interpreted as mode conversion from the A₀ to the S₀ mode. Finally, stress redistribution at ultimate failure caused a sharp drop of mode amplitudes.

When delamination occurs, the laminate is split into two sub-laminates at this region, involving thickness reduction. Because of Lamb waves dispersion, the change in thickness involves a change in mode velocity, and hence, in the time of arrival (Geetha et al., 2016; Ramadas et al., 2011). Most studies on SHM of T-joint structures induced damage under tensile loading (Kesavan, John, & Herszberg, 2008; Ma et al., 2016; Wu et al., 2015) or under three-point bending (Kapoor et al., 2010; Kapoor & Soni, 2009; Swenson et al., 2010), and sometimes with artificial delamination made of Teflon (Geetha et al., 2016; Kesavan et al., 2008; Wu et al., 2015). However, artificial delamination caused by Teflon insert is easier to detect than delamination from BVID in a CFRP plate, because the former creates more significant decrease of the A₀ mode velocity actuated by a PZT transducer and may involve A₀ mode entrapment (Kudela, Radzienski, & Ostachowicz, 2018).

**Development of ultrasonic transducers**

**Emerging lighter transducer solutions**

It remains crucial to improve transducer integration and reliability while maintaining low cost. As previously discussed, SHM networks of numerous heavy distributed transducers and wiring can pose serious problems in aircrafts while adding a significant weight to the structure (Dong & Kim, 2018). Solutions for weight limitations are pursued, such as wireless systems, removing the weight and inconvenience of wires (Su & Ye, 2009; Yuan et al., 2016). However, wireless systems come with an intake of additional weight of power supply (Dong & Kim, 2018).

Less intrusive sensors such as embedded microfabricated sensors are also promising for SHM applications (Kopsaftppoulos et al., 2015; Salowitz et al., 2013). Meanwhile, present concerns about the environment would tend to eliminate the use of lead or any heavy metals. Polymeric transducers are good candidates, adding the benefit of low process temperature (ceramics fabrication demands a lot of energy during sintering at temperatures above 1200°C). In particular, PVDF piezoelectric films have been developed for sensing applications (Lin & Giurgiutiu, 2006; Tuloup et al., 2020); its copolymer P(VDF-TrFE) is even more popular for its spontaneous crystallization into the ferroelectric β-phase (Bae & Chang, 2015; Bellan et al., 2005; Chen, Yao, Tay, & Chew, 2010). While ceramic
brittleness can be an issue in SHM applications, the high flexibility of polymeric transducers allows them to be patterned on curved shapes or limited space. Moreover, the density of PVDF is about 1.78 g/cm\(^3\), which is less than \(\frac{1}{4}\) the density of PZT (7.5 to 8.0 g/cm\(^3\)). Polymers’ deterioration should be considered in applications with extreme environmental conditions such as aircraft structures. P(VDF-TrFE) presents a more stable polarization than PVDF until approaching Curie temperature (110 °C), at which its piezoelectric performance drops (Chen et al., 2010). In contrast, PZT operating temperature range may span from –20 °C to 150 °C. However, earlier degradation of the bonding layer would be expected. Recently, ceramic coatings made of lead-free compositions were developed by thermal spray process without need of adhesive layer and with signal magnitude up to two orders of magnitude higher than PVDF polymer coating (Guo, Zhang, Chen, Tan, & Yao, 2019). These ceramic coatings are promising for ultrasonic SHM applications under high temperature working conditions.

**Solutions using direct-write methods**

Another advantage of using lighter polymeric transducers is that their flexibility offers the potential to be fabricated by using direct-write methods. Since SHM networks using discrete PZT transducers often imply costly and laborious manual installation, there is a desire of developing transducers using direct-write methods, such as spraying or printing. Moreover, the cables could be replaced by printing silver on the structure to reduce weight. Besides the high production efficiency, batch fabrication of direct-write transducers promises for high consistency and enhanced mechanical strain coupling, by reducing misalignments with structures and by eliminating the need for bonding agent, respectively (Capsal et al., 2012; Chen et al., 2020; Elkjaer, Astafiev, Ringgaard, & Zawada, 2013; Shen, Chen, Zhang, Yao, & Tan, 2017). Along with the improved system reliability, direct-write transducers can be patterned on complex structures with minimised weight and profile (less intrusive). Furthermore, direct-write manufacturing is scalable and reproducible. Therefore, direct-write transducers are suitable and very attractive for potential SHM applications. Direct-write methods are increasingly considered in electronics manufacturing, such as by printing strain gauges directly between CFRP plies (Fujimoto et al., 2020; Zhao, Liu, Zhang, Liang, & Wang, 2012). The global printed electronics market is estimated to grow at a compound annual growth rate of 18.3% between 2021 and 2026, reaching USD 23.0 billion by 2026, despite COVID-19 negative impact (MarketsandMarkets, 2021).
Piezoelectric materials such as piezopolymers and piezocomposites can be deposited by direct-write methods to fabricate transducers (Capsal et al., 2012; Elkjaer et al., 2013; Shen et al., 2017). Recently, piezoelectric ultrasonic direct-write transducers have been developed on metallic structures by spraying P(VDF-TrFE): these transducers achieved defect detection (Shen et al., 2017), monitoring of crack growth near fastener holes (Chen et al., 2020) and yielding evaluation with improved reliability (Guo, Chen, Zhang, Chen, & Yao, 2018). Transducers were sprayed on an aluminium plate, which was used as the ground electrode (Shen et al., 2017). To enable mode selection, the top electrode was deposited by gold evaporation in an annular comb array shape with a periodicity of 2 mm, corresponding to the wavelength of the A0 mode at 1.3 MHz. The effective piezoelectric d33 coefficient after electrical poling evaluated with a laser scanning vibrometer was −18 pm/V at 1.5 kHz (refer to Section Lamb waves actuators and sensors). Furthermore, this comb-shaped electrode has been used in structural bonding application (Wong et al., 2021). An epoxy adhesive with inorganic filler could be used for both structural bonding and SHM of the joint. The adhesive showed effective piezoelectric property able to generate and sense Lamb waves.

Direct-write piezoelectric transducers on CFRP structures

Despite the progress made in the field, applications of piezoelectric direct-write transducers on CFRP structures remain rare. Direct-write techniques have been used to deposit piezoelectric coatings on CFRP structure using barium titanate (BT) (Capsal et al., 2012) or PZT particles (Elkjaer et al., 2013) in a polymer matrix. After depositing a conductive coating using silver paint to form the ground electrode, the 100 µm thick piezocomposite layer made of polyurethane and BT particles was sprayed on a 1.6 m large stiffened CFRP structure, as in Figure 5(a) (Capsal et al., 2012). A 15 mm large conductive top electrode was then deposited and a piezoelectric d33 coefficient of 0.7 pC/N was achieved. The sensor centred on the plate was tested for passive impact event detection and quantification. Four piezocomposite sensors made of PZT particles and polymer matrix were screen-printed on a 13.5 mm thick CFRP honeycomb sandwich structure, as shown in Figure 5(b) (Elkjaer et al., 2013). The 10 mm electrodes were made of silver paste. The network integration was improved by printing electrical connections with silver ink. The impact locations of the 14 impact tests were estimated with an error under 50 mm.

Both directly written piezoelectric sensors successfully detected AE from impact events (Capsal et al., 2012; Elkjaer et al., 2013). In contrast, direct-write piezoelectric transducers have been developed for Lamb
wave-based active monitoring and applied on a CFRP plate by in-situ depositing, crystallizing, and patterning a 25 µm thick piezoelectric P(VDF-TrFE) coating (Philibert et al., 2021). Unlike for the design employed on metallic structures (Shen et al., 2017), a bottom electrode was implemented (Philibert et al., 2021). Mode selection was achieved through top electrode design, as shown in Figure 5(c).

Figure 5. (a) A piezocomposite sensor made of BT particles sprayed on a large stiffened CFRP structure and amplitude responses of AE measured by the sensor for different impact energies and for different distances from the sensor (Capsal et al., 2012) (hal.archives-ouvertes.fr/hal-00852836). (b) Four piezocomposite sensors made of PZT particles screen-printed on CFRP honeycomb sandwich structure and the impact location estimation compared to actual impact location (Elkjaer et al., 2013). (c) Tuning curves representing $A_0$ mode amplitudes according to the frequency of transmitted input signal for direct-write transducers (DWT) of different electrode patterns (periodicity of 12 mm, 10 mm, and 8 mm) (Philibert et al., 2021). The bottom figure shows theoretical phase velocity of $A_0$ mode with dashed lines indicating some wavelengths of interest. These lines are used to determine the frequencies to select a mode for a fixed electrode periodicity in DWT. (d) CFRP Plate highlighting two paths: Path A and Path B, each path includes two PZTs and two DWTs (Philibert et al., 2021). DWTs with electrode periodicity of 10 mm and 12 mm on Path A and Path B, respectively.
The characteristics and performance of the novel transducers were benchmarked with the state-of-the-art devices, discrete PZT ceramic transducers surface-mounted on the same CFRP plate in Figure 5(d). The direct-write transducers exhibited single-mode excitation of the fundamental Lamb wave $A_0$ or $S_0$ modes and enhanced directivity due to the comb-shaped electrode design, which allowed improved mode identification reliability despite the smaller signal amplitude (up to about two orders of magnitude due to relatively smaller piezoelectric strain coefficient of P(VDF-TrFE) compared to PZT). In contrast, influences on wave propagation of complex modes by multiple parameters such as misalignment, bonding agent, and position on the plate were observed with the manually bonded PZTs, requiring extensive signal processing and analysis. Thus, the use of mode selection for SHM applications promises simpler signal analysis and damage interpretation. The combination of direct-write sensor with PZT actuator could achieve balanced improvements in mode selection and signal amplitude (Philibert et al., 2021). These direct-write transducers were tested to detect damage introduced by a 31 J impact (Philibert et al., 2022). Direct-write transducers as receivers combined with PZT as actuators showed the highest signal amplitude change of $A_0$ or $S_0$ mode. A damage index based on amplitude change thus allowed efficient detection of the impact damage. The combination of the broadband laser excitation with the direct-write transducers as sensors was also considered and showed consistent results.

**Concluding remarks**

The increased use of polymer composites in aircraft construction has motivated the community to develop cost-effective and reliable methods for monitoring their structural integrity. Of upmost importance is the effectiveness to detect and monitor BVID in CFRP, which substantially reduces fatigue life and runs the risk of growing during service. The high demand for early detection merits investigation, as it would improve safety and reduce the significant cost due to major repair and unplanned down time. Real time SHM techniques are desired, but their implementation remains challenging. A dense network of piezoelectric ultrasonic transducers can generate and sense guided waves, particularly including Lamb waves travelling into large complex CFRP structures and carrying valuable information about structural integrity. Multiple Lamb modes unavoidably overlap in the signals acquired by ultrasonic transducers that require complex signal analysis and translation to physical damage. Therefore, methods of mode selection have been implemented in ultrasonic SHM that can collect the targeted signals, improving the identification of a mode of interest and simplifying associated damage analysis.
For instance, as only fundamental $A_0$ and $S_0$ Lamb wave modes exist at low frequency, they are often preferably selected at the frequencies corresponding to their highest amplitude response, which are typically linked to the transducers’ dimensions. Furthermore, the ability to select either $A_0$ or $S_0$ mode is profitable for damage detection and characterization qualification because they undergo different displacements, and hence respond distinctively to different damage. Ultrasonic-based SHM of CFRP is much more challenging than in metals because of anisotropy and numerous discontinuities due to their layered construction and higher wave attenuation. The use of Lamb wave in SHM of CFRP is often limited to relatively lower frequency range.

Moreover, it remains crucial to improve transducers integration and reliability maintaining low cost for ultrasonic SHM implementation. SHM networks of numerous distributed transducers and wiring can pose serious problems for aircraft application while adding a consequent weight to the structure. Less intrusive lightweight polymeric transducers eliminate the use of heavy metals, adding the benefit of low processing temperature. Their high flexibility allows them to be patterned on curved shape or limited space. In particular, PVDF and P(VDF-TrFE) polymer sensors have been developed for ultrasonic Lamb wave applications.

Since SHM networks using bulky discrete PZT transducers often imply costly and laborious manual installation, there is a desire of developing piezoelectric coating transducers using direct-write methods such as spraying or printing process. Besides the high production efficiency, batch fabrication of direct-write transducers promises for high consistency and enhanced mechanical strain coupling, by respectively reducing misalignments with structures, eliminating the need for bonding agent and other human factors. Along with the improved system reliability, direct-write transducers can be patterned on complex structures with minimised weight and profile. Recently, direct-write transducers have been fabricated on both metallic and composite structures by spraying piezoelectric P(VDF-TrFE) polymer coating, and even ceramic coating. Thanks to the freedom in design, comb-shape electrodes are used to simplify Lamb wave mode selection by matching the periodicity of the finger electrodes with the wavelength at a specific frequency, achieving in addition improved wave propagation directivity.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Ataş, A., & Soutis, C. (2013). Subcritical damage mechanisms of bolted joints in CFRP composite laminates. Composites Part B: Engineering, 54(1), 20–27. doi:10.1016/j.compositesb.2013.04.071

Bae, J.-H., & Chang, S.-H. (2015). Characterization of an electroactive polymer (PVDF-TrFE) film-type sensor for health monitoring of composite structures. Composite Structures, 131, 1090–1098. doi:10.1016/j.compstruct.2015.06.075

Balageas, D., Fritzen, C., & Güemes, A. (2006). Structural health monitoring. London: ISTE Ltd.

Banerjee, S., Ricci, F., Monaco, E., Lecce, L., & Mal, A. (2007). Autonomous impact damage monitoring in a stiffened composite panel. Journal of Intelligent Material Systems and Structures, 18(6), 623–633. doi:10.1177/1045389X06067942

Bellan, F., Bulletti, A., Capineri, L., Masotti, L., Yaralioglu, G. G., Degertekin, F. L. … Rosi, E. (2005). A new design and manufacturing process for embedded Lamb waves interdigital transducers based on piezopolymer film. Sensors and Actuators A: Physical, 123-124, 379–387. doi:10.1016/j.sna.2005.05.013

Benmeddour, F., Grondel, S., Assaad, J., & Moulin, E. (2008). Study of the fundamental Lamb modes interaction with asymmetrical discontinuities. NDT & E International, 41(5), 330–340. doi:10.1016/j.ndteint.2008.01.004

Betz, D. C., Thursby, G., Culshaw, B., & Staszewski, W. J. (2007). Structural damage location with fiber Bragg grating rosettes and Lamb waves. Structural Health Monitoring, 6(4), 299–308. doi:10.1177/1475921707081974

Capsal, J.-F., David, C., Dantras, E., & Lacabanne, C. (2012). Piezoelectric sensing coating for real time impact detection and location on aircraft structures. Smart Materials and Structures, 21(5), 055021. doi:10.1088/0964-1726/21/5/055021

Chakrapani, S. K., Barnard, D., & Dayal, V. (2015). Finite element simulation of core inspection in helicopter rotor blades using guided waves. Ultrasonics, 62, 126–135. doi:10.1016/j.ultras.2015.05.009

Chandarana, N., Sanchez, D. M., Soutis, C., & Gresil, M. (2017). Early damage detection in composites during fabrication and mechanical testing. Materials, 10(7), 685. doi:10.3390/ma10070685

Chen, S., Wong, Z. Z., Zhang, L., Wong, V.-K., Yao, K., Safai, M., … Georgeson, G. E. (2020). Monitoring of cracks near fastener holes using direct-write ultrasonic transducers. Engineering Research Express, 2(1), 015019. doi:10.1088/2631-8695/ab6b69

Chen, S., Yao, K., Tay, F. E. H., & Chew, L. L. S. (2010). Comparative investigation of the structure and properties of ferroelectric poly(vinylidene fluoride) and poly(vinylidene fluoride-trifluoroethylene) thin films crystallized on substrates. Journal of Applied Polymer Science, 116(5), 3331–3337. doi:10.1002/app.31794

Cohades, A., Branfoot, C., Rae, S., Bond, I., & Michaud, V. (2018). Progress in self-healing fiber-reinforced polymer composites. Advanced Materials Interfaces, 5(17), 1800177. doi:10.1002/admi.201800177

Cross, E. J., Manson, G., Worden, K., & Pierce, S. G. (2012). Features for damage detection with insensitivity to environmental and operational variations. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 468(2148), 4098–4122. doi:10.1098/rspa.2012.0031
Cross, E. J., Worden, K., & Chen, Q. (2011). Cointegration: A novel approach for the removal of environmental trends in structural health monitoring data. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 467(2133), 2712–2732. doi:10.1098/rspa.2011.0023

Datta, A., Augustin, M. J., Gaddikeri, K. M., Viswanurthy, S. R., Gupta, N., & Sundaram, R. (2021). Damage detection in composite aircraft wing-like test-box using distributed fiber optic sensors. *Optical Fiber Technology*, 66, 102651. doi:10.1016/j.yofte.2021

Díaz-Maroto, P. F., Fernández-López, A., García-Alonso, J., Iglesias, M., & Güemes, A. (2018). Buckling detection of an omega-stiffened aircraft composite panel using distributed fibre optic sensors. *Thin-Walled Structures*, 132, 375–384. doi:10.1016/j.tws.2018.08.024

Dong, T., & Kim, N. (2018). Cost-effectiveness of structural health monitoring in fuselage maintenance of the civil aviation industry. *Aerospace*, 5(3), 87. doi:10.3390/aerospace5030087

Dupont, M., Osmont, D., Gouyon, R., & Balageas, D. (1999). Permanent monitoring of damaging impacts by a piezoelectric sensor based integrated system. Structural Health Monitoring 2000, Stanford, USA.

Dworakowski, Z., Ambroziński, Ł., Packo, P., Dragan, K., Stepinski, T., & Uhl, T. (2013). Application of artificial neural networks for damage indices classification with the use of Lamb waves for the aerospace structures. *Key Engineering Materials*, 588, 12–21. doi:10.4028/www.scientific.net/KEM.588.12

Dziendzikowski, M., Dragan, K., & Katunin, A. (2017). Localizing impact damage of composite structures with modified RAPID algorithm and non-circular PZT arrays. *Archives of Civil and Mechanical Engineering*, 17(1), 178–187. doi:10.1016/j.acme.2016.09.005

Monaco, E., Boffa, N. D., Memmolo, V., Ricci, F., Testoni, N., De Marchi, L., ... Koen, V. D. A. (2016). Methodologies for guided wave-based SHM system implementation on composite wing panels: Results and perspectives from SARISTU scenario 5. In P. Wölcken & M. Papadopoulos (eds.), *Smart Intelligent Aircraft Structures (SARISTU)* (pp. 495–527). Cham: Springer International Publishing.

Elkjaer, K., Astafiev, K., Ringgaard, E., & Zawada, T. (2013). *Integrated Sensor Arrays based on PiezoPaint for SHM applications* [Paper presentation]. In Annual Conference of the Prognostics and Health Management Society, New Orleans, USA.

Fujimoto, K. T., Watkins, J. K., Phero, T., Litteken, D., Tsai, K., Bingham, T., ... Estrada, D. (2020). Aerosol jet printed capacitive strain gauge for soft structural materials. *npj Flexible Electronics*, 4(1), 32. doi:10.1038/s41528-020-00095-4

Gao, H., Shi, Y., & Rose, J. L. (2005). Guided wave tomography on an aircraft wing with leave in place sensors. *American Institute of Physics*, 760, 1788–1794. doi:10.1063/1.1916887

Geetha, G. K., Mahapatra, D. R., Gopalakrishnan, S., & Hanagud, S. (2016). Laser Doppler imaging of delamination in a composite T-joint with remotely
located ultrasonic actuators. *Composite Structures*, 147, 197–210. doi:10.1016/j.compstruct.2016.03.039

Giurgiutiu, V. (2005). Tuned lamb wave excitation and detection with piezoelectric wafer active sensors for structural health monitoring. *Journal of Intelligent Material Systems and Structures*, 16(4), 291–305. doi:10.1177/1045389X05050106

Giurgiutiu, V. (2014). *Structural health monitoring with piezoelectric wafer active sensors* (2nd ed.). Waltham, MA: Elsevier.

Giurgiutiu, V. (2016). *Structural health monitoring of aerospace composites*. Waltham, MA: Elsevier, Academic Press.

Graff, K. F. (1975). *Wave motion in elastic solids*. New York: Dover Publications.

Gresil, M., Giurgiutiu, V., Shen, Y., & Poddar, B. (2012). Guidelines for using the finite element method for modeling guided Lamb wave propagation in SHM processes. In *Proceedings of the 6th EWSHM*, Dresden, Germany, Vol. 1.

Gresil, M., Yu, L., Giurgiutiu, V., & Sutton, M. (2012). Predictive modeling of electromechanical impedance spectroscopy for composite materials. *Structural Health Monitoring*, 11(6), 671–683. doi:10.1177/1475921712451954

Gresil, M., & Giurgiutiu, V. (2015). Prediction of attenuated guided waves propagation in carbon fiber composites using Rayleigh damping model. *Journal of Intelligent Material Systems and Structures*, 26(16), 2151–2169. doi:10.1177/1045389X14549870

Guo, S., Chen, S., Zhang, L., Chen, Y. F., & Yao, K. (2018). Plastic strain determination with nonlinear ultrasonic waves using in situ integrated piezoelectric ultrasonic transducers. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 65(1), 95–101. doi:10.1109/TUFFC.2017.2768238

Guo, S., Zhang, L., Chen, S., Tan, C. K. I., & Yao, K. (2019). Ultrasonic transducers from thermal sprayed lead-free piezoelectric ceramic coatings for in-situ structural monitoring for pipelines. *Smart Materials and Structures*, 28(7), 075031. doi:10.1088/1361-665X/ab1e88

Hua, J., Cao, X., Yi, Y., & Lin, J. (2020). Time-frequency damage index of broadband Lamb wave for corrosion inspection. *Journal of Sound and Vibration*, 464, 114985. doi:10.1016/j.jsv.2019.114985

Huang, L., Zeng, L., Lin, J., & Zhang, N. (2020). Baseline-free damage detection in composite plates using edge-reflected Lamb waves. *Composite Structures*, 247, 112423. doi:10.1016/j.compstruct.2020.112423

Huang, L., Zeng, L., & Lin, J. (2018). Baseline-free damage detection in composite plates based on the reciprocity principle. *Smart Materials and Structures*, 27(1), 015026. doi:10.1088/1361-665X/aa9cc1

Ihn, J.-B., & Chang, F. (2008). Pitch-catch active sensing methods in structural health monitoring for aircraft structures. *Structural Health Monitoring*, 7(1), 5–19. doi:10.1177/1475921707081979

Irving, P., & Soutis, C. (2020). *Polymer composites in the aerospace industry* (2nd ed.). Duxford, UK: Elsevier. Matthew Deans.

Janarthan, B., Mitra, M., Mujumdar, P. M. (2012). Damage detection in stiffened composite panels using Lamb wave. In *Proceedings of the 6th EWSHM*, Dresden, Germany, Vol. 2.

Janarthan, B., Mitra, M., & Mujumdar, P. M. (2013). Lamb wave based damage detection in composite panel. *Journal of the Indian Institute of Science*, 93(4), 715–733.
Kapoor, H., Blackshire, J. L., & Soni, S. R. (2010). Damage detection in z-fiber reinforced, co-cured composite Pi-Joint using pitch-catch ultrasonic analysis and scanning laser vibrometry. *Tech Science Press*, 3(3), 221–238.

Kapoor, H., & Soni, S. R. (2009, March). *Experimental structural health monitoring of Z-fibre reinforced co-cured composite pi-joints using Lamb wave propagation* [Paper presentation]. Proceedings of the SPIE – Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security (Vol. 7294, p. 72941C). San Diego, USA. doi:10.1117/12.817800

Katafiasz, T. J., Greenhalgh, E. S., Allegri, G., Pinho, S. T., & Robinson, P. (2021). The influence of temperature and moisture on the mode I fracture toughness and associated fracture morphology of a highly toughened aerospace CFRP. *Composites Part A: Applied Science and Manufacturing*, 142, 106241. doi:10.1016/j.compositesa.2020.106241

Kesavan, A., John, S., & Herszberg, I. (2008). Strain-based structural health monitoring of complex composite structures. *Structural Health Monitoring*, 7(3), 203–213. doi:10.1177/1475921708090559

Kessler, S. S., Spearing, S. M., & Soutis, C. (2002). Damage detection in composite materials using lamb wave methods. *Smart Materials and Structures*, 11(2), 269–278. doi:10.1088/0964-1726/11/2/310

Kim, H. C., & Park, J. M. (1987). Ultrasonic wave propagation in carbon fibre-reinforced plastics. *Journal of Materials Science*, 22(12), 4536–4540. doi:10.1007/BF01132059

Kopsaftppoulos, F., Nardari, R., Li, Y.-H., Wang, P., Ye, B., & Chang, F.-L. (2015). Experimental identification of structural dynamics and aeroelastic properties of a self-sensing smart composite wing [Paper presentation]. In Proceedings of the 10th IWSHM (pp. 1–13). Stanford, USA. doi:10.12783/SHM2015/163

Kudela, P., Radziencki, M., & Ostachowicz, W. (2018). Impact induced damage assessment by means of Lamb wave image processing. *Mechanical Systems and Signal Processing*, 102, 23–36. doi:10.1016/j.ymssp.2017.09.020

Lammering, R., Gabbert, U., Sinapius, M., Schuster, T., & Wierach, P. (2018). *Lamb-wave based structural health monitoring in polymer composites*. Cham: Springer International Publishing.

Lee, B. C., & Staszewski, W. J. (2007). Sensor location studies for damage detection with Lamb waves. *Smart Materials and Structures*, 16(2), 399–408. doi:10.1088/0964-1726/16/2/019

Lin, B., & Giurgiutiu, V. (2006). Modeling and testing of PZT and PVDF piezoelectric wafer active sensors. *Smart Materials and Structures*, 15(4), 1085–1093. doi:10.1088/0964-1726/15/4/022

Lin, J., Gao, F., Luo, Z., & Zeng, L. (2016). High-resolution lamb wave inspection in viscoelastic composite laminates. *IEEE Transactions on Industrial Electronics*, 63(11), 6989–6998. doi:10.1109/TIE.2016.2582735

Lin, M., Qing, X., Kumar, A., & Beard, S. J. (2001). *SMART Layer and SMART Suitcase for structural health monitoring applications* [Paper presentation]. Smart Structures and Materials 2001: Industrial and Commercial Applications of Smart Structures Technologies (Vol. 4332, pp. 98–106). Newport Beach, USA. doi:10.1117/12.429646

Lizé, E., Rébillat, M., Mechbal, N., & Bolzmac, C. (2018). Optimal dual-PZT sizing and network design for baseline-free SHM of complex anisotropic composite structures. *Smart Materials and Structures*, 27(11), 115018. doi:10.1088/1361-665X/aad534
Lowe, M. J. S. (1995). Matrix techniques for modeling ultrasonic waves in multilayered media. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, 42*(4), 525–542. doi:10.1109/58.393096

Ma, X., Bian, K., Liu, H., Wang, Y., & Xiong, K. (2020). Numerical and experimental investigation of the interface properties and failure strength of CFRP T-Stiffeners subjected to pull-off load. *Materials & Design, 185*, 108231. doi:10.1016/j.matdes.2019.108231

Ma, X., Bian, K., Lu, J., & Xiong, K. (2016). Experimental research on detection for interface debond of CFRP T-joints under tensile load. *Composite Structures, 158*, 359–368. doi:10.1016/j.compstruct.2016.09.006

MarketsandMarkets. (2020a, July). *Aerospace composites market*. Retrieved from https://www.marketsandmarkets.com/Market-Reports/aerospace-composites-market-246663558.html?gclid=CjwKCAjwoP6LBhBlEiwAvCcthKGtT43_PnTs5o-lgs6vyvyeOo3hYk1SIVWUGatCZed-YlewUbLQwxoC0-UQAvD_BwE

MarketsandMarkets. (2020b, August). *Structural health monitoring market*. Retrieved from https://www.marketsandmarkets.com/Market-Reports/structural-health-monitoring-market-101431220.html

MarketsandMarkets. (2020c, November). *NDT and inspection market*. Retrieved from https://www.marketsandmarkets.com/Market-Reports/non-destructive-testing-ndt-equipment-services-market-882.html

MarketsandMarkets. (2021, October). *Printed electronics market*. Retrieved from https://www.marketsandmarkets.com/Market-Reports/printed-electronics-market-197.html?gclid=CjwKCAjwoP6LBhBlEiwAvCcthA61IyvmmwFTNEk93sU3qi_SYKAutoDMcP9TLaWiDLBj8Tq3XzjleBoCX2QQAvD_BwE

Marks, R., Clarke, A., Featherston, C., Paget, C., & Pullin, R. (2016). Lamb wave interaction with adhesively bonded stiffeners and disbands using 3D vibrometry. *Applied Sciences, 6*(1), 12. doi:10.3390/app6010012

Mechbal, N., & Rebillat, M. (2017). Damage indexes comparison for the structural health monitoring of a stiffened composite plate [Paper presentation]. VIII ECCOMAS Thematic Conference on Smart Structures and Materials SMART, Madrid, Spain.

Mei, H., & Giurgiutiu, V. (2019). Guided wave excitation and propagation in damped composite plates. *Structural Health Monitoring, 18*(3), 690–714. doi:10.1177/1475921718765955

Memmolo, V., Monaco, E., Boffa, N. D., Maio, L., & Ricci, F. (2018). Guided wave propagation and scattering for structural health monitoring of stiffened composites. *Composite Structures, 184*, 568–580. doi:10.1016/j.compstruct.2017.09.067

Monkhouse, R. S. C., Wilcox, P. D., & Cawley, P. (1997). Flexible interdigital PVDF transducers for the generation of Lamb waves in structures. *Ultrasonics, 35*(7), 489–498. doi:10.1016/S0041-624X(97)00070-X

Muller, A., Soutis, C., & Gresil, M. (2019). Image reconstruction and characterisation of defects in a carbon fibre/epoxy composite monitored with guided waves. *Smart Materials and Structures, 28*(6), 065001. doi:10.1088/1361-665X/ab1359

Nietherammer, M., Jacobs, L. J., Qu, J., & Jarzynski, J. (2001). Time-frequency representations of Lamb waves. *The Journal of the Acoustical Society of America, 109*(5 Pt 1), 1841–1847. doi:10.1121/1.1357813

Okabe, Y., Fujibayashi, K., Shimazaki, M., Soejima, H., & Ogisu, T. (2010). Delamination detection in composite laminates using dispersion change based
on mode conversion of Lamb waves. *Smart Materials and Structures*, 19(11), 115013. doi:10.1088/0964-1726/19/11/115013

Ono, K., & Gallego, A. (2012). Attenuation of Lamb waves in CFRP plates. *Journal of Acoustic Emission*, 30, 109–123.

Ooijevaar, T., Rogge, M. D., Loendersloot, R., Warnet, L., Akkerman, R., & Tinga, T. (2016). Vibro-acoustic modulation–based damage identification in a composite skin–stiffener structure. *Structural Health Monitoring*, 15(4), 458–472. Jul. doi:10.1177/1475921716645107

Park, I., Jun, Y., & Lee, U. (2014). Lamb wave mode decomposition for structural health monitoring. *Wave Motion*, 51(2), 335–347. doi:10.1016/j.wavemoti.2013.09.004

Philibert, M., Chen, S., Wong, V.-K., Liew, W. H., Yao, K., Soutis, C., & Gresil, M. 2022. Direct-write piezoelectric coating transducers in combination with discrete ceramic transducer and laser pulse excitation for ultrasonic impact damage detection on composite plates. *Structural Health Monitoring*, 21(4), 1645–1660. doi:10.1177/14759217211040719

Philibert, M., Chen, S., Wong, V.-K., Yao, K., Soutis, C., & Gresil, M. (2021). Direct-write piezoelectric transducers on carbon-fiber-reinforced polymer structures for exciting and receiving guided ultrasonic waves. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 68(8), 2733–2740. doi:10.1109/TUFFC.2021.3073131

Philibert, M., Soutis, C., Gresil, M., & Yao, K. (2018). Damage detection in a composite T-joint using guided Lamb waves. *Aerospace*, 5(2), 40. doi:10.3390/aerospace5020040

Prosser, W. H., Seale, M. D., & Smith, B. T. (1999). Time-frequency analysis of the dispersion of Lamb modes. *The Journal of the Acoustical Society of America*, 105(5), 2669–2676. doi:10.1121/1.426883

Qing, X., Li, W., Wang, Y., & Sun, H. (2019). Piezoelectric transducer-based structural health monitoring for aircraft applications. *Sensors*, 19(3), 545. doi:10.3390/s19030545

Qiu, L., Liu, M., Qing, X., & Yuan, S. (2013). A quantitative multidamage monitoring method for large-scale complex composite. *Structural Health Monitoring*, 12(3), 183–196. doi:10.1177/1475921713479643

Qiu, L., & Yuan, S. (2009). On development of a multi-channel PZT array scanning system and its evaluating application on UAV wing box. *Sensors and Actuators A: Physical*, 151(2), 220–230. doi:10.1016/j.sna.2009.02.032

Quek, S. T., Tua, P. S., & Jin, J. (2007). Comparison of plain piezoceramics and inter-digital transducer for crack detection in plates. *Journal of Intelligent Material Systems and Structures*, 18(9), 949–961. doi:10.1177/1045389X06071435

Ramadas, C. (2014). Three-dimensional modeling of lamb wave attenuation due to material and geometry in composite laminates. *Journal of Reinforced Plastics and Composites*, 33(9), 824–835. doi:10.1177/0731684413518254

Ramadas, C., Balasubramaniam, K., Joshi, M., & Krishnamurthy, C. V. (2011). Interaction of Lamb mode (Ao) with structural discontinuity and generation of “Turning modes” in a T-joint. *Ultrasonics*, 51(5), 586–595. doi:10.1016/j.ultras.2010.12.014

Ramadas, C., Balasubramaniam, K., Joshi, M., & Krishnamurthy, C. V. (2011). Sizing of interface delamination in a composite T-joint using time-of-flight of Lamb waves. *Journal of Intelligent Material Systems and Structures*, 22(8), 757–768. doi:10.1177/1045389X11407943
Ren, H., Chen, X., & Chen, Y. (2017). *Reliability based aircraft maintenance optimization and applications*. London, UK: Elsevier

Rose, J. L. (2011). The upcoming revolution in ultrasonic guided waves. In *Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security* (Vol. 7983, p. 798302). San Diego, USA. doi:10.1117/12.897025

Rufai, O., Gautam, M., Potluri, P., & Gresil, M. (2019). Optimisation of optical fibre using micro-braiding for structural health monitoring. *Journal of Intelligent Material Systems and Structures*, 30(2), 171–185. doi:10.1177/1045389X18810805

Salowitz, N., Guo, Z., Li, Y.-H., Kim, K., Lanzara, G., & Chang, F.-K. (2013). Bio-inspired stretchable network-based intelligent composites. *Journal of Composite Materials*, 47(1), 97–105. doi:10.1177/0021998312442900

Schmidt, D., Sinapius, M., & Wierach, P. (2013). Design of mode selective actuators for lamb wave excitation in composite plates. *CEAS Aeronautical Journal*, 4(1), 105–112. doi:10.1007/s13272-012-0059-3

Shen, Z., Chen, S., Zhang, L., Yao, K., & Tan, C. Y. (2017). Direct-write piezoelectric ultrasonic transducers for non-destructive testing of metal plates. *IEEE Sensors Journal*, 17(11), 3354–3361. doi:10.1109/JSEN.2017.2694454

Staszewski, W. J., Mahzan, S., & Traynor, R. (2009). Health monitoring of aerospace composite structures – Active and passive approach. *Composites Science and Technology*, 69(11-12), 1678–1685. doi:10.1016/j.compscitech.2008.09.034

Stawiarz, A., & Muc, A. (2019). On transducers localization in damage detection by wave propagation method. *Sensors*, 19(8), 1937. doi:10.3390/s19081937

Stepinski, T., Mańka, M., & Martowicz, A. (2017). Interdigital lamb wave transducers for applications in structural health monitoring. *NDT & E International*, 86, 199–210. doi:10.1016/j.ndteint.2016.10.007

Su, Z., & Ye, L. (2009). *Identification of damage using Lamb waves: From fundamentals to applications* (Vol. 48). Berlin, Germany: Springer Science & Business Media.

Swenson, E. D., Soni, S. R., & Kapoor, H. (2010). *Lamb wave propagation in Z-pin reinforced co-cured composite pi-joints* [Paper presentation]. Proceedings of the SPIE - Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security (Vol. 7649, p. 76490D). San Diego, USA. doi:10.1117/12.848787

Truong, C. T., Kang, D.-H., Lee, J.-R., & Farrar, C. R. (2015). Comparative study of laser Doppler vibrometer and capacitive air-coupled transducer for ultrasonic propagation imager and the new development of an efficient ultrasonic wavenumber imaging algorithm. *Strain*, 51(4), 332–342. doi:10.1111/str.12144

Tsuda, H. (2006). Ultrasound and damage detection in CFRP using fiber Bragg grating sensors. *Composites Science and Technology*, 66(5), 676–683. doi:10.1016/j.compscitech.2005.07.043

Tuloup, C., Harizi, W., Aboura, Z., & Meyer, Y. (2020). Integration of piezoelectric transducers (PZT and PVDF) within polymer-matrix composites for structural health monitoring applications: New success and challenges. *International Journal of Smart and Nano Materials*, 11(4), 343–369. doi:10.1080/19475411.2020.1830196
Wan, X., Zhang, Q., Xu, G., & Tse, P. (2014). Numerical simulation of nonlinear lamb waves used in a thin plate for detecting buried micro-cracks. Sensors, 14(5), 8528–8546. doi:10.3390/s140508528

Wandowski, T., Malinowski, P., Ostachowicz, W. (2014). Investigations on guided wave interaction with various discontinuities. Proceedings of the 9th International Conference on Structural Dynamics (pp. 2165–2171). Porto, Portugal.

Wang, C. S., & Chang, F.-K. (2000). Diagnosis of impact damage in composite structures with built-in piezoelectrics network [Paper presentation]. Proceedings of SPIE Smart Structures and Materials 2000: Smart Electronics and MEMS (Vol. 3990, pp. 13–19). Newport Beach, USA. doi:10.1117/12.388893

Wang, X., Lu, Y., & Tang, J. (2008). Damage detection using piezoelectric transducers and the lamb wave approach: I. System analysis. Smart Materials and Structures, 17(2), 025033. doi:10.1088/0964-1726/17/2/025033

Wandowski, T., Malinowski, P., Ostachowicz, W. (2014). Investigations on guided wave interaction with various discontinuities. Proceedings of the 9th International Conference on Structural Dynamics (pp. 2165–2171). Porto, Portugal.

Weiland, J., Hesser, D., Xiong, W., Schiebahn, A., Markert, B., & Reisgen, U. (2020). Structural health monitoring of an adhesively bonded CFRP aircraft fuselage by ultrasonic Lamb Waves. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 234(13), 2000–2010. doi:10.1177/0954410020950511

Williams, G., Trask, R., & Bond, I. (2007). A self-healing carbon fibre reinforced polymer for aerospace applications. Composites Part A: Applied Science and Manufacturing, 38(6), 1525–1532. doi:10.1016/j.compositesa.2007.01.013

Wong, Z. Z., Chen, S., Liu, M., Lim, S. H., Cui, F., & Yao, K. (2021). Piezoelectricity in structural adhesives and application for monitoring joint integrity via guided ultrasonic waves. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 68(3), 777–783. doi:10.1109/TUFFC.2020.3017760

Worden, K. (2001). Rayleigh and Lamb waves – Basic principles. Strain, 37(4), 167–172. doi:10.1111/j.1475-1305.2001.tb01254.x

Wu, Z., Gao, D., Wang, Y., & Rahim, G. (2015). In-service structural health monitoring of a full-scale composite horizontal tail. Journal of Wuhan University of Technology-Materials Science Edition, 30(6), 1215–1224. doi:10.1007/s11595-015-1298-z

Yan, F., Royer, R. L., & Rose, J. L. (2010). Ultrasonic guided wave imaging techniques in structural health monitoring. Journal of Intelligent Material Systems and Structures, 21(3), 377–384. doi:10.1177/1045389X09356026

Yan, F., & Rose, J. L. (2007). Guided wave phased array beam steering in composite plates [Paper presentation]. Proceedings of the SPIE - Health Monitoring of Structural and Biological Systems (Vol. 6532, p. 65320G). San Diego, USA. doi:10.1117/12.716109

Yuan, S., Ren, Y., Qiu, L., & Mei, H. (2016). A multi-response-based wireless impact monitoring network for aircraft composite structures. IEEE Transactions on Industrial Electronics, 63(12), 7712–7722. doi:10.1109/TIE.2016.2598529

Zagrai, A. N., & Giurgiutiu, V. (2001). Electro-mechanical impedance method for crack detection in thin plates. Journal of Intelligent Material Systems and Structures, 12(10), 709–718. doi:10.1109/HHXL-TLM8-8CM5-6OAK

Zhang, S., Li, C. M., & Ye, W. (2021). Damage localization in plate-like structures using time-varying feature and one-dimensional convolutional neural network. Mechanical Systems and Signal Processing, 147, 107107. doi:10.1016/j.ymssp.2020.107107
Zhao, D., Liu, T., Zhang, M., Liang, R., & Wang, B. (2012). Fabrication and characterization of aerosol-jet printed strain sensors for multifunctional composite structures. *Smart Materials and Structures, 21*(11), 115008. doi:10.1088/0964-1726/21/11/115008

Zhao, X., Gao, H., Zhang, G., Ayhan, B., Yan, F., Kwan, C., & Rose, J. L. (2007). Active health monitoring of an aircraft wing with embedded piezoelectric sensor/actuator network: I. Defect detection, localization and growth monitoring. *Smart Materials and Structures, 16*(4), 1208–1217. doi:10.1088/0964-1726/16/4/032