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Guided Lamb waves for identification of damage in composite structures: A review

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Abstract

The guided Lamb wave is widely acknowledged as one of the most encouraging tools for quantitative identification of damage in composite structures, and relevant research has been conducted intensively since the 1980s. The main aim of this paper is to provide a comprehensive review on the state of the art of Lamb wave-based damage identification approaches for composite structures, addressing the advances and achievements in these techniques in the past decades. Major emphasis is placed on the unique characteristics and mechanisms of Lamb waves in laminated composites; approaches in wave mode selection, generation and collection; modelling and numerical simulation techniques; signal processing and identification algorithms; and sensor network technology for practical utility. Representative case studies are also briefly described in terms of various experimental validations and applications.

1. Introduction

Discovered by Horace Lamb in 1917, Lamb waves can exist in plate-like thin plate with parallel free boundaries. A comprehensive theory for such a wave was established by Mindlin in 1950 [1], in parallel with experimental work conducted by Schoch in 1952 and Frederick in 1962 [2]. The development of such a topic was driven essentially by its applications in medical industry during World War II. Subsequently in 1961, Worlton [3] introduced Lamb waves as a means of damage detection. All these pilot studies established the fundamentals of the utilisation of Lamb waves as a prominent non-destructive evaluation (NDE) tool.

With a high susceptibility to interference on a propagation path, e.g. damage or a boundary, Lamb waves can travel over a long distance even in materials with a high attenuation ratio, such as carbon fibre-reinforced composites, and thus a broad area can be quickly examined. The entire thickness of the laminate can also be interrogated by various Lamb modes, affording the possibility of detecting internal damage as well as that on surface. The potential damage types that a Lamb wave-based inspection can provide are summarised by Rose [4]. In general, a Lamb wave-based damage detection approach features (1) the ability to inspect large structures while retaining coating and insulation, e.g. a pipe system under water; (2) the ability to inspect the

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entire cross sectional area of a structure (100% coverage over a fairly long length); (3) the lack of need for complicated and expensive insertion/rotation devices, and for device motion during inspection; (4) excellent sensitivity to multiple defects with high precision of identification; and (5) low energy consumption and great cost-effectiveness [4]. At a sophisticated level, a Lamb wave-based identification should hierarchically perform, with increasing levels of difficulty, (1) qualitative indication of the occurrence of damage; (2) quantitative assessment of the position of damage; (3) quantitative estimation of the severity of damage; and (4) prediction of structural safety, e.g. residual service life [5].

However, the propagation of Lamb waves in anisotropic viscoelastic media is notoriously complicated. With a very fast velocity, waves reflected from boundaries may easily conceal damage-scattered components in the signals. To ensure precision, the structure under inspection may have to be relatively large, and with a relatively small area for detection. Multiple wave modes usually exist, and their dispersive properties throughout the thickness of the medium are not identical, even for the same mode but in different frequency scopes. For its sophistication in damage detection for advanced composites, substantial efforts have been directed to Lamb wave study, especially in the past decade.

There is no shortage of achievements for Lamb wave-based identification techniques. This paper presents a comprehensive review on the state of the art of damage identification techniques using Lamb waves for fibre-reinforced composite structures. Specifically, the unique dispersion characteristics and mechanisms of Lamb waves in composite laminates, mode selection, generation and collection, modelling and simulation, signal processing/interpretation and sensor network technology are addressed, and some challenging topics are also proposed for further research.

2. Fundamentals of Lamb wave

Lamb waves, made up of a superposition of longitudinal and shear modes, are available in a thin plate, and their propagation characteristics vary with entry angle, excitation and structural geometry. A Lamb mode can be either symmetric or anti-symmetric (Fig. 1), formulated by [6]

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2qp}{(k^2-q^2)^2} \quad \text{for symmetric modes,} \tag{1a}$$

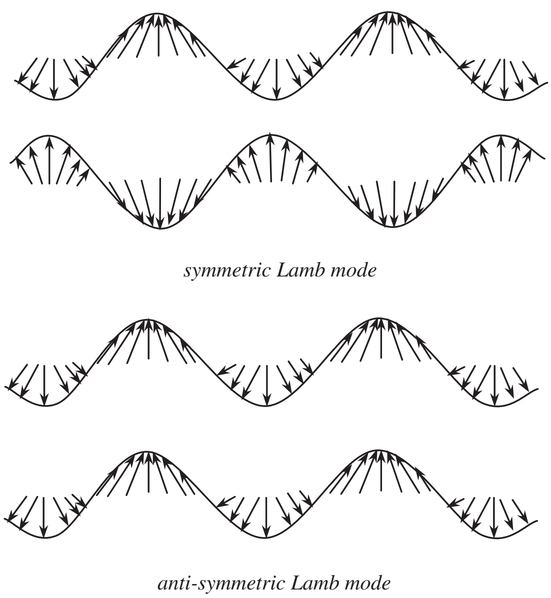

Fig. 1. Symmetric and anti-symmetric Lamb wave modes.

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{(k^2-q^2)^2}{4k^2qp} \quad \text{for anti-symmetric modes,} \tag{1b}$$

$$p^2 = \frac{\omega^2}{c_L^2} - k^2, \quad q^2 = \frac{\omega^2}{c_T^2} - k^2 \quad \text{and} \quad k = \omega/c_p,$$

where h, k, c_L, c_T, c_p, ω are the plate thickness, wavenumber, velocities of longitudinal and transverse modes, phase velocity and wave circular frequency, respectively. Eq. (1), correlating the propagation velocity with its frequency, implies that Lamb waves, regardless of mode, are dispersive (velocity is dependent on frequency).

In addition to Lamb modes, a transverse (shear) motion, different from normal shear waves (vertical shear mode), was detected between layers of laminate by Love in 1911. This observation has also been confirmed by finite element simulation [7] and experimental study [8]. Perpendicular to the plane of wave travel (see Fig. 2), such a mode was accordingly named the *shear horizontal* (SH) mode (*Love* wave) [9]. In some identification schemes [10,11], Love mode is employed together with Lamb modes.

Anisotropic properties of composite structures introduce many interesting but somewhat complex phenomena in wave propagation, such as direction-dependent speed, and difference between phase and group velocities. In an N-layered composite laminate, the Lamb wave can be generally described using its displacement field, u, by satisfying Navier's displacement equations within each layer [9]

$$\mu^n \nabla^2 u^n + (\lambda^n + \mu^n)\nabla(\nabla \cdot u^n) = \rho^n \frac{\partial^2 u^n}{\partial t^2} \quad (n = 1, 2, \ldots, \mathrm{N}), \tag{2}$$

where ρ^i and λ^i, μ^i are density, Lamé constants for the ith layer, respectively. Attenuation in magnitude, variation in propagating velocity and change in wavenumber are commonly observed, referred to as *dispersion*.

Table 1 details experimentally measured attenuation coefficients of Lamb waves in different composite structures [12]. Also tabulated is the distance of propagation before decaying to 10% of its original amplitude. It is clear that in general Lamb waves are able to propagate a relatively long distance even in the composites. A longer propagation distance is normally observed in the carbon fibre-based materials than in the glass fibre-reinforced materials. The introduction of stiffening members (such as T-stringers) can increase the attenuation but not substantially. The most serious effect on attenuation is the presence of surface coating materials which may cause very significant damping [12].

On the other hand, applying boundary conditions at $N-1$ interfaces and free surfaces to Eq. (2) leads to a comprehensive *dispersion* equation [9]

$$\left|A(\omega, k, \lambda^n, \mu^n, h_n)\right| = 0, \tag{3}$$

where Lamb wave frequency ω is related to the wavenumber k and plate geometry (h_n), for a given material (λ^n, μ^n). In an implicit expression, the dispersion equation has infinite roots, corresponding to the dispersive

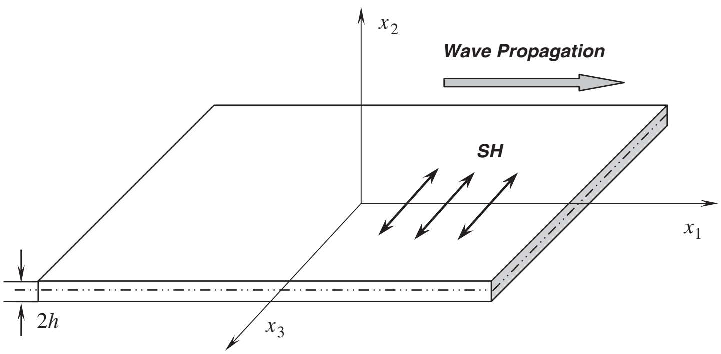

Fig. 2. Horizontal shear (SH) mode in composite laminate [9].

Table 1
Attenuation coefficients of Lamb waves in various composite materials [12]

Materials	Lamb mode	Excitation frequency (kHz)	Attenuation coefficient (mm^{-1})	10% amplitude distance (mm)
CFRP woven 8-ply	S_0	250	0.0014	1700
CFRP woven 10-ply	A_0	285	0.027	85
CFRP woven 10-ply with T-stringers				
Parallel to stringers	S_0	250	0.00078	3000
Perpendicular to stringers	S_0	250	0.0016	1500
GFRP random	S_0	220	0.0035	660
CFRP/GFRP hybrid (RTM) sandwich foam core	S_0	250	0.013	182
CFRP/GFRP hybrid (RTM) sandwich honeycomb core	S_0	250	0.0036	640
	S_0	150	0.0015	1600
GFRP filament would pipe	S_0	250	0.015	150
	S_0	150	0.011	210

curves of infinite Lamb modes, respectively. Dispersion often leads to some specific concerns for implementing Lamb wave-based damage identification, which are detailed in the following sections.

3. Generation of Lamb waves

3.1. Actuator/sensor for Lamb waves

Lamb waves can be actively excited and collected by a variety of means, roughly grouped under five categorises, summarised in Table 2 and compared with other NDE transducers.

3.1.1. Ultrasonic probe

Notable for excellent precision and controllability, ultrasonic probes coupled with angle-adjustable perspex wedges [13–15] or Hertzain contact transducer [16] have been widely used to actively generate and collect a pure Lamb wave, in accordance with Snell's law. Without the complexity of multi-mode, it permits explicit signal interpretation. During manipulation, couplant, directionality and contact are issues that may influence effectiveness. Non-contact innovations, such as air-coupled [17,18], and fluid-coupled [19] transducers and electro-magnetic acoustic transducers (EMATs) [20,21] have therefore been introduced. In particular, EMAT is an effective way to generate shear horizontal mode [22], although their applications were normally limited to metallic structures. However, these transducers can suffer from the large difference in mechanical impedance between air/fluid and objects under detection, resulting in low precision. Downtime of the system to be inspected is usually required and the system must be accessible from both sides. Moreover, such methods may be less efficient for detecting near-surface damage, where reflections from a defect are limited within the wavelength of the transmitted ultrasonic pulse [22]. In addition, the non-negligible mass/volume of the probe and limited access to complex geometry often reduce the practical applications.

3.1.2. Laser

Non-contact excitation of Lamb waves via *laser-based ultrasonics* (LBU) and acquisition using *laser interferometer* are reputable methods for high precision [20,23–27]. *Fabry–Perrot* and heterodyne interferometers are the devices most frequently employed to this purpose. A LBU can be flexibly designed to be broadband or narrowband depending on an actual application, to satisfy different spatial resolution requirements. The exact detection that LBU can offer ranges from apparent defects to small cracks. Such an approach is also exceptionally effective for curved surfaces or complicated geometry, where access is unfeasible. Additionally, by using a short laser pulse it is possible to excite a broad bandwidth signal with

Table 2
Comparison of Lamb wave transducers with other NDE transducers

Sensor	Applications/features	Available style
Ultrasonic probe	Flaw, distance and thickness detection, exact and efficient	Contact, air/ fluid-coupled
Laser interferometer	Derivation or displacement measurement, high precision, expensive	Contactless
Piezoceramics	Active sensor, vibration detection, high-frequency response, low driving force, cheap	Attaching, embedding
Piezoelectric paint and PVDF	Vibration and/or crack detection, easy application for non-flat shapes, cheap	Attaching, embedding
EMAT	Narrow band, avoidance of physical contact	Contact, attaching
Accelerometer	Acceleration detection, high-frequency response	Attaching
Shape memory alloy	Active sensor, deformation detection, active control, large force, low-frequency response	Attaching, embedding
Magnetic sensor	Crack or large deformation with magnetic leakage, soft magnetic piece, magnetic field required	Contact, attaching
Optical fibre	Deformation, temperature and location detection, line sensing, high precision, conformable, expensive	Embedding
AE sensor	Changes in physical property only, location detection, passive sensor	Attaching, embedding
Eddy-current transducer	Electromagnetic impedance detection, good for composites, too complicated, expensive	Attaching
Strain gauge	Deformation detection, low-frequency response, possible to use in hostile environments, cheap	Attaching

several Lamb modes in a single measurement, providing more opportunities to selectively generate the desired modes [28]. Nevertheless, the cost of equipment can limit broad application.

3.1.3. Piezoelectric element

Piezoelectric lead zirconate titanate (PZT) elements deliver excellent performance in Lamb wave generation and acquisition, and are particularly suitable for integration into a host structure as an in-situ generator/sensor, for their neglectable mass/volume, easy integration, excellent mechanical strength, wide frequency responses, low power consumption and acoustic impedance, as well as low cost. Applications to Lamb wave generation for damage detection purpose are numerous [29–31] (particularly detailed in the forthcoming section). An optimal criterion for designing a disc-like PZT wave actuator has been proposed [32], aimed at minimising geometric effects and consequently avoiding uneven wave propagation,

$$2R = \frac{v_{\mathrm{wave}}}{f}\left(n + \tfrac{1}{2}\right) = \lambda_{\mathrm{wave}}\left(n + \tfrac{1}{2}\right) \quad (n = 0, 1, 2, \ldots), \tag{4}$$

where R is the radius of PZT disk; v_{wave}, f and λ_{wave} are the wave velocity, frequency and wavelength of a concerned Lamb mode, respectively. With regard to thickness selection, it has also been observed that the maximum voltage applied on a PZT, without depolarising it, is 250–300 V/mm [33].

PZT-generated Lamb waves unavoidably contain multiple modes. Sophisticated signal processing is accordingly required. Moreover, a PZT element usually reveals certain nonlinear behaviour and hysteresis under large strains/voltages or at high temperature. Small driving force/displacement, brittleness, low fatigue life, etc., may be some other concerns limiting application [34].

3.1.4. Interdigital transducer

Novel interdigital transducers, such as polyvinylidene fluoride (PVDF) piezoelectric polymer film, have been increasingly introduced to accommodate more versatile applications with reduced cost [35–37]. Compared with piezoelectric ceramics, PVDF features better flexibility, higher dimensional stability, more stable piezoelectric coefficients over time and greater ease of handling [38]. PVDF is able to produce Lamb waves with controllable wavelength by adjusting the space between interdigital electrodes [36]. Soft and flexible, it can be variously shaped to cope with curved surfaces. PVDF is mainly used as a sensor due to its weak driving force, though it has been used as an actuator in a few studies [39,40], to find that PVDF actuators work in a very low frequency range only (up to 500 Hz).

3.1.5. Optical fibre

With light weight, immunity to electromagnetic interference, wide bandwidth, good compatibility, long life and low power consumption and cost, optical fibre sensors have been increasingly adopted in damage identification [41]. In most approaches, fibre optic devices are used for capturing static or quasi-dynamic strain, with the capacity to measure strain at two-to-three orders of magnitude better resolution than conventional electrical resistance strain gauges [42]. However, applications as a sensor to monitor dynamic Lamb wave signal in the ultrasonic range are rare [43–48], because of the low sampling rate of the normal optical spectrum analyzer (OSA). One solution to accommodate this concern is the use of a fibre Bragg grating (FBG) filter connected with a photodetector [49], with which the light intensity induced by the Lamb wave, rather than strain itself, can be recorded at a high sampling rate. It has been demonstrated [50] that the amplitude of a Lamb wave captured by a FBG sensor perpendicular to the wave propagation can be 100 times less than that measured by a FBG sensor paralleling the propagation, indicating strong directivity of FBG sensors in collecting Lamb wave signal. In another study [51] on the effectiveness of surface-bonded and embedded FBG sensors in acquiring Lamb waves, it was concluded that an embedded FBG sensor is 20 times more sensitive to Lamb waves than a surface-bonded FBG sensor, although the surface-bonded sensor is more practical because embedding an optical fibre into composite materials often lowers structural mechanical properties, with consequent difficulty in repair and replacement [52].

3.2. Lamb mode selection

A proper Lamb mode for damage detection should feature (1) non-dispersion, (2) low attenuation, (3) high sensitivity, (4) easy excitability, (5) good detectability and (6) toilless selectivity [53]. Based on these criteria, different modes with various frequencies in large thick and thin plates (aircraft skin) were examined [53], and it was found that a narrow bandwidth input signal is able to effectively prevent wave dispersal. For this reason, windowed toneburst, rather than pulse, is frequently adopted as the diagnostic Lamb signal. The selectable frequency range $[f_{\min}, f_{\max}]$ with toneburst cycle number n and excitation frequency f_0 can be related by [53]

$$f_{\min} = f_0(1 - k/n), \tag{5a}$$

$$f_{\max} = f_0(1 + k/n), \tag{5b}$$

where k is a constant depending on the bandwidth used. Eq. (5) indicates that increasing the number of cycles can reduce the bandwidth, leading to less dispersion. However, it is noteworthy that different wave components, such as reflected and incident waves, can overlap each other when a large cycle number is used for a small coupon.

Alternatively, the most suitable cycle number and frequency for a Lamb mode can also be determined by the *minimum resolvable distance* (MRD) approach [54],

$$\mathrm{MRD} = \frac{v_0}{d}\left[l\left(\frac{1}{v_{\min}} - \frac{1}{v_{\max}}\right) + T_{\text{initial}}\right]\Bigg|_{\min}, \tag{6}$$

where l and d are the wave propagation distance and plate thickness concerned; v_0, $v_{\min}$ and $v_{\max}$ are the group velocity at the central frequency of the input wave-packet, minimum and maximum velocities in the wave-packet to travel through the distance of l; while T_{initial} is the initial time duration of the wave-packet. It was found that the smaller a MRD value, the better the resolution, and the more suitable the current frequency and cycle number. Modes S_0 and A_0 are usually observed to possess very low MRD values. It was also concluded that S_0 exhibits reasonable sensitivity to defects anywhere in the thickness, while A_0 is more sensitive to surface cracks or corrosion, but the latter may not be suitable for long-distance propagation because of its high attenuation ratio (also referring to Table 1). Another study based on the use of power-spectral-densities (PSD) [55] suggested that, for a certain structure and damage type, the best frequency should be determined by watching the maximum response amplitude for a range of potential frequencies. Also, for waveform selection, pure sinusoidal shapes appear to excite Lamb wave harmonics more efficiently than parabolic shapes, and a windowed sinusoidal signal can help to narrow the bandwidth and centralise energy. Researchers [56,57] have found that if the stress level due to existence of a defect is higher for a certain wave mode than others, this mode is most effective in identifying the type of defect. Further, the modes which produce large shear stress at the interface position are most sensitive to the change in shear stiffness of the interface.

The basic symmetric mode, S_0, and anti-symmetric mode, A_0, are normally used in practice. Although S_0 is preferred in the majority of studies [10,58], utilisation of A_0 is increasing due to its short wavelength, in recognition of the fact that the wavelength of the selected mode must be lower than or equal to the size of the damage. In particular, it has been shown that A_0 is highly effective for detecting delamination and transverse ply cracks [16,35,36,59,60].

To implement the Lamb mode selection, a multi-element transducer set-up was proposed [60] to dominantly generate mode A_0. A theoretical relationship between Lamb wave displacement and the distance of two PZT elements on the surface of a composite laminate was established under a perfect condition, as displayed in Fig. 3. It was observed that the distance of two PZT elements at 17 mm, twice its corresponding A_0 wavelength under the excitation frequency of 180 kHz, gave the maximum normal displacement of A_0 mode and the minimum displacement of S_0 mode, shown in Fig. 4, providing a way to produce pure A_0 mode by appropriately choosing the distance between two PZTs. With the same purpose but a different approach, a pair of PZT actuators were symmetrically bonded on the upper and lower surfaces of a composite laminate [61] (see Fig. 5), with which symmetric and anti-symmetric modes could be generated individually under in-phase and out-of-phase excitation, respectively. As also pointed out in these studies, these mode selection approaches based on interdigital strategy cannot cancel a mode completely.

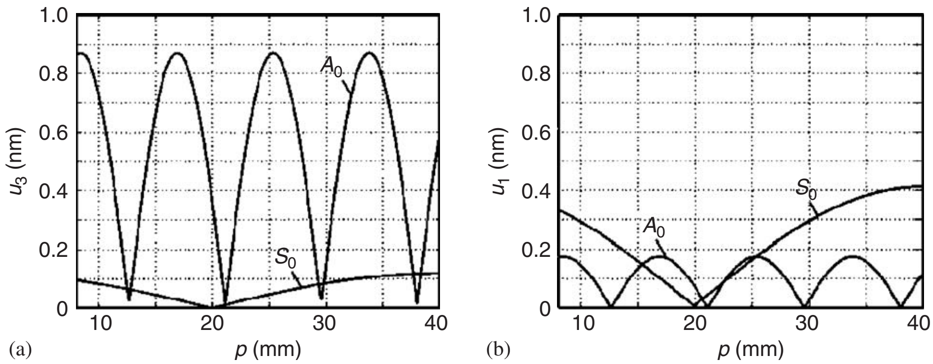

Fig. 3. Relationship of *inter-element distance* with (a) normal (u_3) and (b) tangential displacement of S_0 and A_0 modes [60].

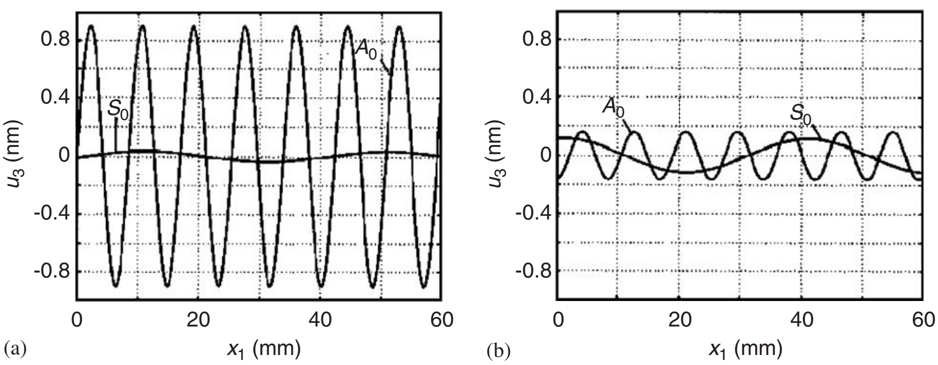

Fig. 4. (a) Normal (u_3) and (b) tangential displacement of S_0 and A_0 modes under an *inter-element distance* of 17 mm [60].

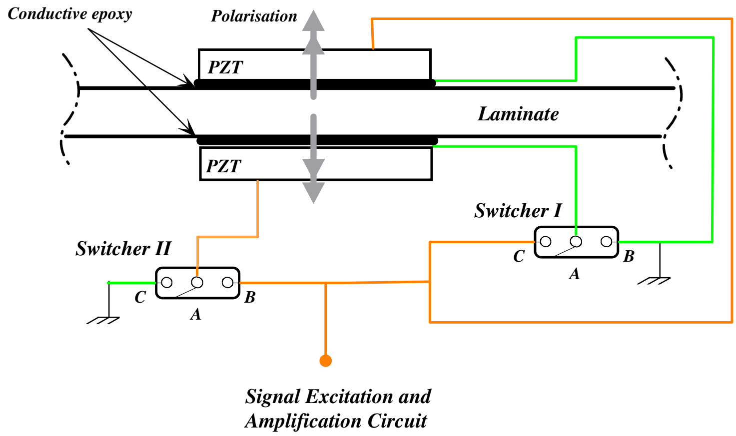

Fig. 5. Configuration of PZT actuators for selective generation of Lamb mode [61].

4. Analysis and simulation of Lamb waves

The mechanisms of Lamb waves have been rigorously examined over the years for their application to damage identification. Unique dispersive characteristics make Lamb waves intriguing but complex.

4.1. Analytical study of Lamb wave characteristics

Analytical studies on dispersion nature of Lamb wave are in a large quantity. For a given frequency, infinite wavenumbers mathematically satisfying Eqs. (1) and (3) can be obtained by an iterative root-finding method (such as Newton–Raphson) [9], where the dispersive curves of different modes are the root loci of the equation. Major analytical tools for this purpose are *transfer matrix* approach (Thomson–Haskell method), *global matrix* approach [1], and some other more specific methods, such as one based on homogenisation (*effective elastic constant*) [62].

The transfer matrix method assumes that, for a N-layer composite laminate, four waves exist at each layer, all of which must share the same frequency and spatial properties at each interface [1]. With such a scenario, the equations for intermediate interfaces are eliminated, and a relation between wave frequency and wavenumber is established in the form of a matrix regarding the boundary conditions. Dispersion curves can be further obtained by solving such a matrix [1]. A set of dispersive curves for a composite laminate obtained by this method are shown in Fig. 6 [1]. However, such a method becomes ill-conditioned and unstable when the plate thickness (d) is large and the frequency (f) is high (so-called '*large fd problem*'). Knopoff developed an improved method, the *global matrix* approach [1], to directly assemble a single matrix to seek for root loci. This method remains numerically robust for any range of fd values, but has a relatively slow convergence.

Assuming a composite laminate to behave as a homogeneous orthotropic plate, the nature of dispersion can be studied [8] using the *effective elastic constants* method. Other more specific methods for analytically studying the propagation characteristics of Lamb waves in composites are also widely reported [63–65].

4.2. Modelling and simulation

Analytical studies of Lamb waves in composites are usually complex. FEM simulation has been developed in parallel for the purpose of damage identification.

4.2.1. Characteristics of Lamb waves

As a representative example, FEM models which allow particle displacement to vary as cubic polynomials in the z-direction and to vary harmonically in the x-direction were developed to evaluate the dispersion nature of Lamb waves in carbon fibre/resin composite laminates [7,8]. The models are able to simulate horizontal

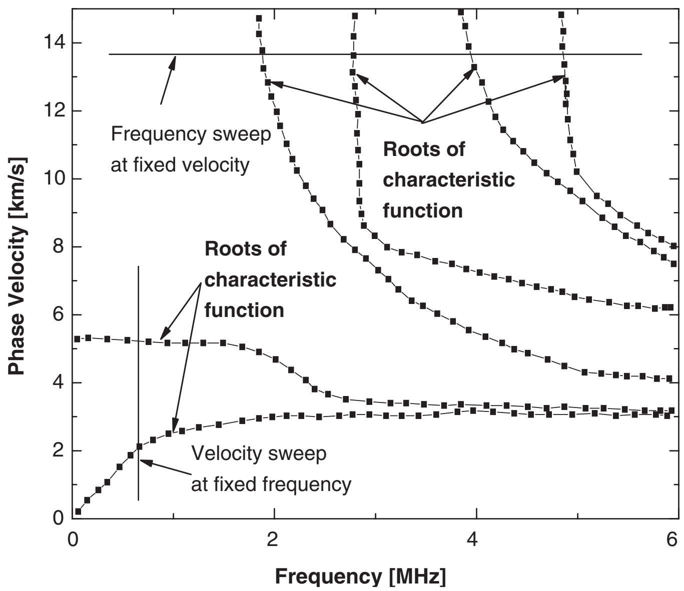

Fig. 6. Dispersion curves for composite laminate obtained by *transfer matrix* method [1].

shear mode (Love wave). Dispersion curves for several typical CF/EP composite laminates as well as for aluminium plate are displayed in Fig. 7, compared with those based on the *effective elastic constants* method described previously [8]. Distinct propagation behaviour can be observed for different laminate layouts, such as different wave velocities (compared in Table 3).

In another FEM model [14,66], a uniform in-plane displacement was applied on FEM nodes across the thickness of a laminate beam end to excite symmetric Lamb mode. The simulation is capable of capturing dynamic responses of Lamb waves by individually measuring vertical displacement [14,67] or horizontal displacement [66], as illustrated in Fig. 8. This model works particularly well for one-dimensional (1D) composite laminates. Three-dimensionally, a FEM model was established to study Lamb wave propagation in $[45/-45/0/90]_s$ CF/EP laminate [68], which simulated Lamb waves that matched experimental observation well. Additionally, Lamb waves in beam- and plate-like structures under different excitations and boundary conditions have also been evaluated using shell elements [69], where different wave modes were excited by transient nodal rotations or translations, or using a strip element method [70].

Hybrid techniques have been introduced for characterising Lamb waves for the purpose of damage identification, by combining analytical methods with numerical simulations, so as to avoid the problems encountered in the sole use of FEM. Cho and Rose [71] combined the boundary element method (BEM) with the normal-mode expansion method to study the edge reflection of Lamb wave and mode conversion with thickness variation. Liu [72] examined the Lamb wave scattering by crack and inclusion in the composite laminates using a combined finite element–strip element approach. Galan and Abascal [73] evaluated the Lamb wave propagation characteristics in sandwich plates in terms of an absorbing boundary condition derived from a truncated normal mode expansion technique. Moulin et al. [74] established a hybrid modelling technique using a coupled finite element-normal-mode expansion, validated by simulating the mechanical excitation from a piezoceramic transducer. Expanding Moulin's work, Grondel et al. [60] built a FEM model for surface-bonded PZT using a hybrid technique, leading to an optimal configuration for generating A_0 mode.

4.2.2. Lamb wave scattering by damage

Lamb wave scattering in 1D composite beams with through-width delamination parallel to the beam surfaces in the span direction has been intensively examined using various FEM models [14,66,75–78], identifying the high sensitivity of Lamb waves to the occurrence of damage. The reflection and transmission

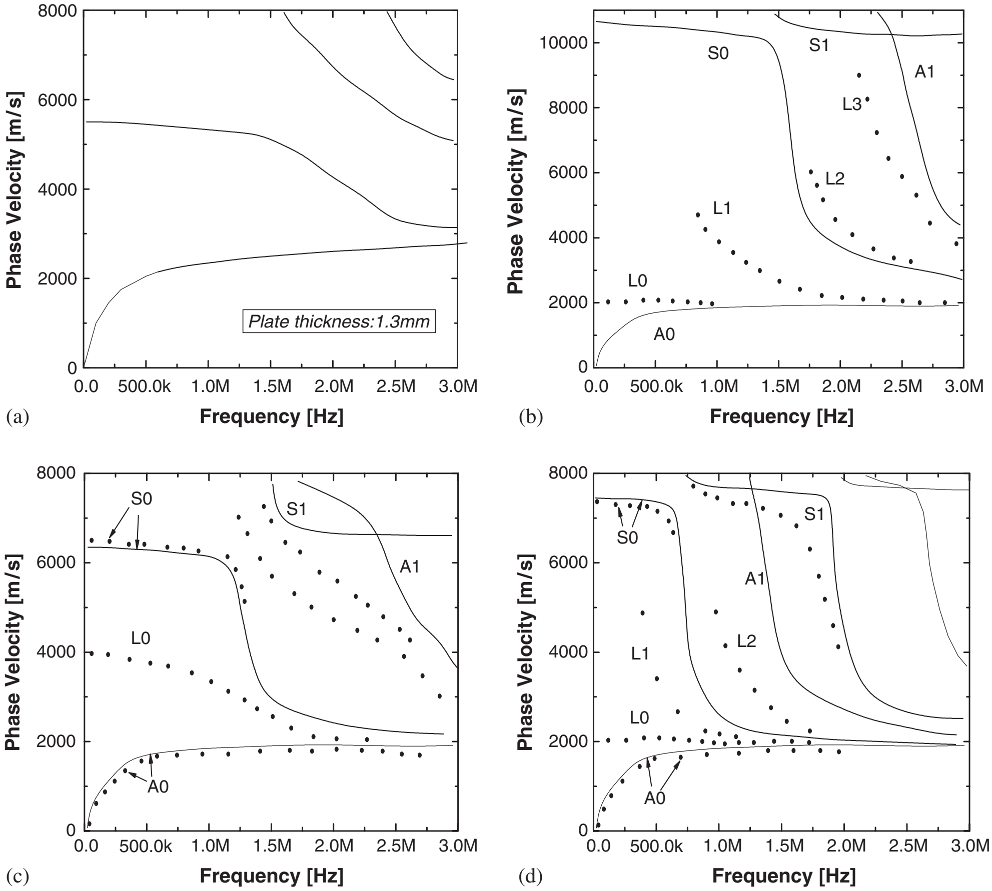

Fig. 7. Dispersion curves for (a) aluminium plate; (b) 8-ply unidirectional laminate; (c) 8-ply $[45/-45/0/90]_s$ quasi-isotropic laminate; (d) 16-ply $[0/90]_{4s}$ cross-ply laminate (solid line: effective elastic constant model; dotted line: FEM model) [8].

ratios strongly depend on the frequency of the incident Lamb waves and the size of the damage [78]. To interrogate the scattering characteristics of waves two-dimensionally, a FEM model with absorbing boundary conditions was developed [79], able to simulate complex mode conversion when the wave interacts with crack-like flaws and cylindrical/spherical holes. The study highlighted the fact that if the scattering object is a void, such as a delamination, part of the incident wave energy is converted to radiate energy in all directions, and surface wave 'creep' occurs around the cavity. Using a more complex approach a 3D model was developed for CF/EP composite laminates containing elliptic delamination, to evaluate the interaction between damage and S_0 mode [80].

In these studies, to exactly characterise Lamb wave scattering by damage, a fine FEM mesh is usually required. It has been demonstrated that at least 10 nodes per wavelength of the Lamb wave can guarantee good precision [13,81]. However such a requirement becomes impractical for structures which are meters in size. For such applications, transition elements have been adopted to connect 3D 20-node solid elements (for a plate area containing surface-bonded PZT) with nine-node shell elements (other plate area) [82]. Further, a parameterised modelling technique (PMT) using multi-point constraints was introduced for large composite panels [83], to harmonise different degrees of freedom (dofs) between the damage zone (multi-layer 3D brick elements) and distant zones (single consolidated layer with 3D brick elements), allowing the combination of model parts with different mesh densities.

In addition, based on the study on Lamb wave scattering by damage, Tang and Henneke [84] and Toyama et al. [85] adopted Lamb waves to quantify the axial stiffness reduction in composite plates attributable to fibre fracture and transverse crack, respectively. Seale et al. [86] verified the efficiency of Lamb waves in detecting

Table 3
Comparison of measured and calculated Lamb wave group velocities for some typical laminate layouts [8]

Lay-up	Propagation direction	Calculated S_0 group velocity (mm/μs)	Measured S_0 group velocity (mm/μs)	Measured A_0 group velocity (mm/μs)
$[0]_8$ 8-ply	0	10.25	9.9 ± 0.7	1.7 ± 0.1
	±45			
	90		2.9 ± 0.2	1.4 ± 0.1
$[0/90]_{4s}$ 8-ply	0	6.77	6.8 ± 0.3	1.6 ± 0.1
	±45		5.3 ± 0.2	1.6 ± 0.1
	90		6.9 ± 0.3	1.5 ± 0.1
$[45/-45/0/90]_s$ 8-ply	0	6.27	6.1 ± 0.2	1.6 ± 0.1
	±45		5.9 ± 0.2	1.6 ± 0.1
	90		6.0 ± 0.2	1.5 ± 0.1
$[0/90]_{8s}$ 16-ply	0	6.67	6.8 ± 0.3	1.6 ± 0.1
	±45		5.1 ± 0.2	1.7 ± 0.1
	90		6.9 ± 0.3	1.6 ± 0.1
$[45/-45/0/90]_{2s}$ 16-ply	0	6.07	6.0 ± 0.2	1.6 ± 0.1
	±45		6.0 ± 0.2	1.6 ± 0.1
	90		6.0 ± 0.2	1.6 ± 0.1

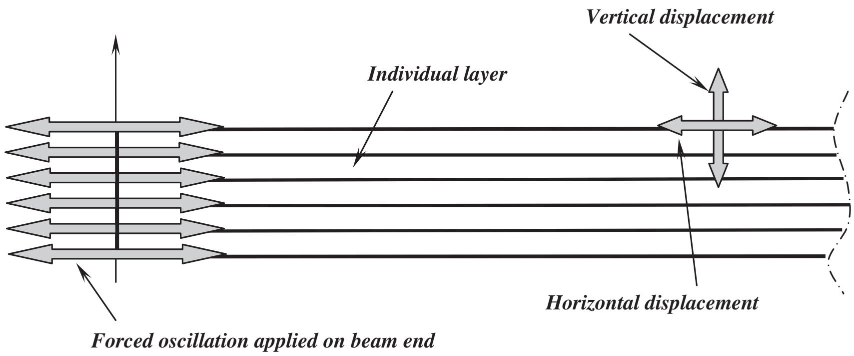

Fig. 8. Lamb wave generation and monitoring [14,66,67].

fatigue and thermal damage in composites. Lamb waves have also been extended to applications in more complex composite structures, such as sandwich structures [87–89], honeycomb structures [90], and lap-splice joint panels in real aircraft [91].

4.2.3. Generator/sensor-coupled system

Modelling of Lamb waves for damage identification is often associated with the simulation of a structure coupled with a wave actuator and senor. A quasi-3D model using iso-parametric elements for a piezo layer embedded-composite laminate containing a delamination has been developed, as shown in Fig. 9 [92], and wave distribution in the structure as well as the electric response of the piezo layer were simulated. By considering the coupling effect between the surface-bonded PZT disc and host structure, Lin and Yuan [93] established a model for studying the propagation of mode A_0 in a plate. One pair of PZT discs symmetric with regard to the plate neutral plane as actuators and another PZT disc as sensor were modelled. The generated Lamb wave in the form of electric voltage was then evaluated. Taking into account the transverse shear deformation and nonlinear longitudinal displacement, a composite beam with delamination and attached PZT actuator was modelled to evaluate wave propagation [94]. To investigate the PZT-generated wave scattering

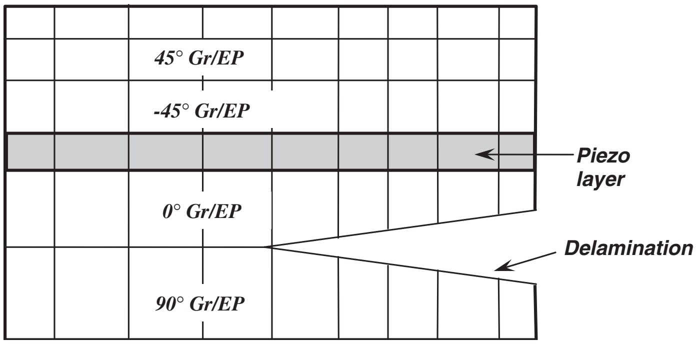

Fig. 9. Modelling of piezo layer-embedded composite laminate containing delamination [92].

by a cylindrical inhomogeneity, Mindlin plate theory was applied in a wave propagation model [95], with which the Lamb wave generated by circular or rectangular piezoelectric actuators was examined. Three-dimensionally, a FEM model was created for both symmetrically bonded dual PZT actuators and a non-symmetrically bonded single actuator coupled with CF/EP composites, and the equivalent radial displacement along the PZT disc circumference was related to the applied electric field, for symmetric and non-symmetric excitations, respectively [61]. Such a method also contributed to the active generation of symmetric mode, S_0, and anti-symmetric mode, A_0. Other modelling techniques for studying PZT-generated Lamb waves have also been reported for surface-bonded [96,97] or embedded cases [98].

More specifically, the influence of dimension, position and excitation delay of bonded or embedded PZT on the generation of Lamb waves was rigorously evaluated by Moulin et al. [74]. Wave generation by PZTs of different shapes, including rectangular, triangular, circular, elliptic, *etc*., was discussed by Sonti et al. [99]. Tan et al. [100] experimentally investigated the sensitivity of Lamb wave probes to delaminations of various sizes. A general review of the modelling technique for generator-coupled systems can be found elsewhere [101].

5. Processing of Lamb wave signals and feature extraction

Lamb wave-based damage identification is essentially subject to interpretation of the captured wave signals. However, the extraction of key features useful for damage identification from the collected Lamb wave signal usually involves a number of confounding problems, such as contamination from diverse noise, interference from natural structural vibration, confusion of multiple modes and bulkiness of sampled data. Accordingly, various signal processing and identification techniques have been introduced, in particular *time-series analysis*, *frequency analysis* and *integrated time–frequency analysis*.

5.1. Time domain analysis

The direct time domain analysis of a signal can detect damage both globally and locally. Valdes and Soutis [102] located a delamination in a composite beam by measuring the *time of flight* (ToF) in the acquired Lamb signal. Sohn and Farrar [103] presented a time-series analysis and applied it to wave signals to detect damage with the aid of a two-stage prediction model, to find that the difference in the signals in the time domain between defective structure and benchmark, defined as *residual error*, would be maximised for the sensors near the damage. An approach to detect structural damage based on combining independent component analysis (ICA) in the time domain and artificial neural networks (ANN) was recently presented by Zang et al. [104], able to capture the essential features from measured vibration signals. However, except for a few successful applications in locating damage, direct time-series analysis is normally incapable of isolating defect-scattered information appropriately from noise in different frequency bands. Additionally, a benchmark signal is essential for comparison.

5.2. Frequency domain analysis and its variants

It is more usual to examine a dynamic signal in the frequency domain via *Fourier transform* (FT). FT mathematically transforms a time-dependent Lamb wave signal, $f(t)$, into the frequency space [105] by

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)\,\mathrm{e}^{-\mathrm{j}\omega t}\,\mathrm{d}t, \tag{7}$$

where ω and j are the angular frequency and unit complex, respectively. $F(\omega)$ is the Fourier counterpart of $f(t)$.

Originating from FT but with enhanced ability, *fast Fourier transform* (FFT) and its 2D form (2D-FFT) are able to speed up this transform, and are widely used for Lamb wave signal analysis [106–109]. By measuring the response of the plate at a series of equally spaced positions on the surface and applying 2D-FFT, different modes at different frequencies can be isolated in the frequency–wavenumber domain, facilitating an explicit analysis of multi-mode Lamb waves [67]. For example, a laser ultrasonic set-up was designed to generate Lamb waves in the direction perpendicular to the laser beam, and the laser line source position was monitored by a mirror translation [27]. 2D-FT was then applied to signals collected from different positions using a Michelson interferometer along the scanning path, and the dispersion curves could be obtained. On the same principle, a pair of grease-coupled transducers was used to measure signals at 64 equally spaced positions [67]. Upon application of 2D-FT analysis, symmetric and anti-symmetric Lamb modes were easily separated, as seen in the Lamb wave spectrum in frequency–wavenumber domain (Fig. 10), where multiple modes are apart, even for those in the same frequency band.

However, since both 2D-FT and 2D-FFT need a significant volume of signals captured from different positions, a great number of transducers or dense measuring points must be ensured to scan the whole structural surface. Laser ultrasonic can be an alternative that avoids huge consumption of transducers, but it entails high expenditure. Most importantly, the sole frequency domain analysis of Lamb wave signals leads to the loss of temporal history.

5.3. Integrated time–frequency domain analysis

To overcome the deficiencies of either time- or frequency-domain analysis of the dynamic Lamb wave signal, the combination of time information with frequency data is introduced. Most time–frequency algorithms can be generalised as [110]

$$P(t,\omega) = \frac{1}{2\pi}\int_{\delta}\int_{\tau}\int_{\theta} \mathrm{e}^{-\mathrm{i}\theta t - \mathrm{i}\tau\omega - \mathrm{i}\theta\delta}\phi(\theta,\tau) f^{*}\left(\delta - \frac{\tau}{2}\right) f\left(\delta + \frac{\tau}{2}\right)\mathrm{d}\delta\,\mathrm{d}\lambda\,\mathrm{d}\theta, \tag{8}$$

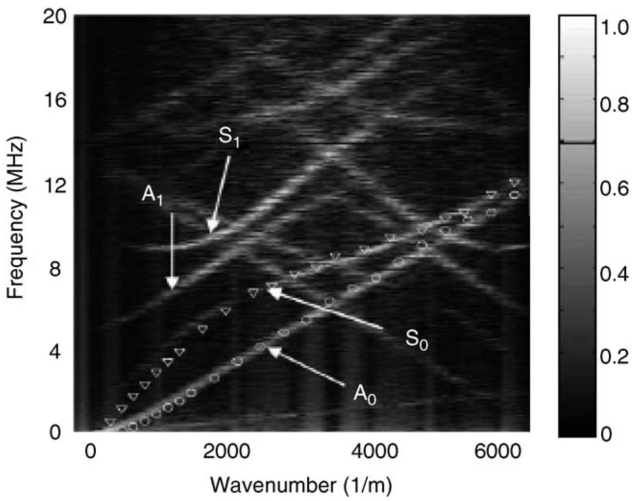

Fig. 10. Lamb wave spectrum by 2D-FT [67].

where $P(t,\omega)$ is the energy intensity at time t and frequency ω, f^* denotes the complex conjugate of Lamb wave signal f and $\phi(\theta,\tau)$ is a function depending on $f(t)$. Widely employed for failure detection in rotating machinery, such a signal processing technique has been increasingly applied to Lamb wave signal analysis. In practice, rather than direct time–frequency analysis, some variants of Eq. (8) are more popular, e.g. *short-time Fourier transform* (STFT), *Winger-Ville distribution* (WVD), and *wavelet transform* (WT).

5.3.1. Short-time Fourier transform (STFT) analysis

Introduced by Dennis Gabor in 1946, STFT was developed to improve the efficiency of FT or FFT transforms for non-stationary signals [110], by applying the basic FT to a small piece of signal around a specific time window ('*short time*'). Continuously moving this short time interval along the time axis, STFT can map a time-dependent wave signal into a 2D representation. With success in detecting damage of rolling bearings, Kim and Kim [111] applied such an algorithm to crack detection in a structural beam, and concluded that STFT compromises information well in both the time and frequency domains, but satisfactory precision along time and frequency axes cannot be obtained simultaneously with its fixed time window size.

5.3.2. Winger-Ville distribution (WVD) analysis

With a flexible transform window size, the WVD transform can offer a better resolution than STFT. The effectiveness of WVD in analysing Lamb waves was compared with other time–frequency methods [25], and it was concluded that the sole use of WVD may not be sufficient for full Lamb wave analysis. Normally, a WVD analysis is performed at the cost of a very high sampling rate (at least four times higher than the highest frequency of the signal) to avoid aliasing [112,113]. Additionally, WVD my lose sensitivity when applied directly to raw wave signals, and alterations of a short duration or low magnitude in a wave signal may not be detected. Although some variants of WVD analysis have been developed to overcome these disadvantages, e.g. *Choi-Williams* analysis [111,114], such a technique is still not generally suitable for wave-based quantitative damage identification [115].

5.3.3. Wavelet transform (WT) analysis

From a historical perspective, WT is a fresh tool for signal processing. Unlike STFT or WVD, WT uses a *wavelet*, a piece of waveform with limited duration whose average amplitude equals zero, also mapping a time-dependent signal into a 2D representation with *scale* and *time*, rather than a direct time–frequency view [112], but the *scale* can be connected with *frequency* by determining the scale value at which a scalogram reaches its maximum [116]. Via WT analysis, a dynamic wave signal can be interrogated using a localised fragment to display hidden characteristics fully, such as trends, breakdown points or discontinuities, and self-similarity. *Continuous wavelet transform* (CWT) and *discrete wavelet transform* (DWT) are two typical forms of WT. For a Lamb wave signal, generally, CWT is particularly effective for analysis and visualisation, while DWT is more useful in signal de-noising, filtration, compression and feature extraction.

Fundamentally, applied with a basic orthogonal WT function, $\Psi(t)$, a Lamb wave signal, $f(t)$, acquired from a sensor, can be converted into a quadratic expression using the dual parameters *scale*, a, and *time*, b [117]:

$$W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t)\, \Psi^*\left(\frac{t-b}{a}\right) \mathrm{d}t, \tag{9}$$

$W(a,b)$ is the *CWT coefficient*. $\Psi^*(t)$ denotes the complex conjugate of $\Psi(t)$. The wave energy allocation in the time-scale domain is accordingly yielded as [112]

$$E = \int_{-\infty}^{+\infty} \int_{a \geqslant 0}^{+\infty} \left|W(a,b)\right|^2 \mathrm{d}a\, \mathrm{d}b, \tag{10}$$

where $\left|\mathrm{CWT}(a,b)\right|^2$ is referred to as *scalogram*. By way of illustration, the energy spectrum via CWT for a Lamb wave signal captured by a PZT sensor on a CF/EP composite laminate containing a delamination is shown in Fig. 11 [80].

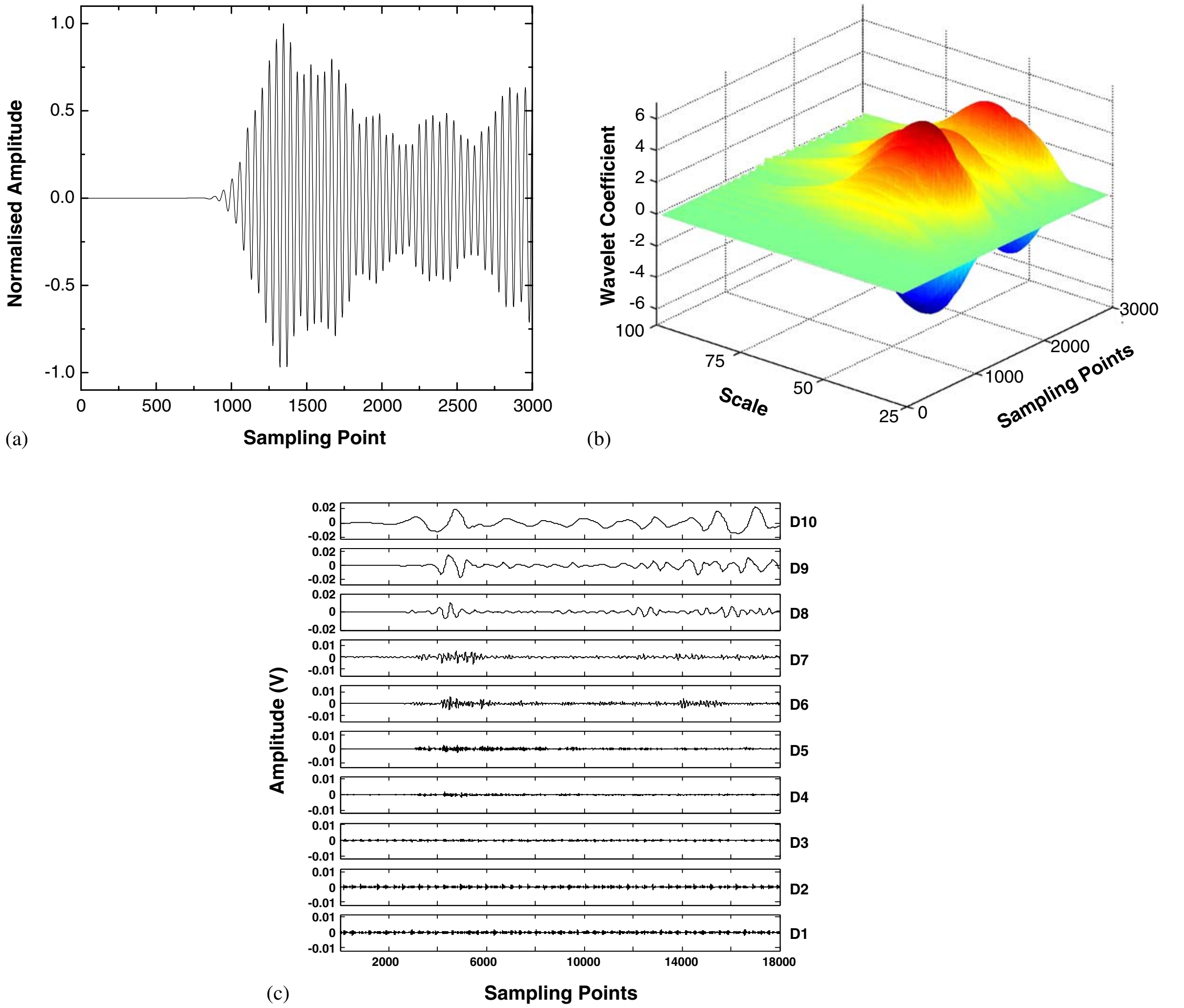

Fig. 11. WT-based signal analysis: (a) raw Lamb wave signal; (b) CWT-based energy spectrum and (c) DWT-based decomposition [80].

To calculate wavelet coefficients at every scale point is computationally expensive. For simplification, Eq. (9) can be executed at discretised *scale* and *time* using dyadic variables m and n, i.e. DWT [105]

$$a = a_0^m \quad \text{and} \quad b = n a_0^m b_0, \quad m, n \in Z, \tag{11a}$$

$$\mathrm{DWT}(m,n) = a_0^{-m/2} \int f(t)\, \Psi(a_0^{-m} t - n b_0)\, \mathrm{d}t, \tag{11b}$$

where a_0 and b_0 are constants determining sampling intervals along the *time* and *scale* axes, respectively. Eq. (11) decomposes a signal into bands of relatively higher and lower frequencies. Successively for the above example signal, components of different frequencies are separated into ten levels upon application of DWT, as displayed in Fig. 11(c).

It was probably Daubechies [118] and Newland [119] who firstly introduced WT into the study of vibrational signals in the early 1990s. Its advantages for the detection of singularity, especially for condition monitoring of rotating machines, have been widely demonstrated [120–124]. With the aid of WT, Lemistre and Balageas [10] and Su et al. [11] located delamination in CF/EP composite laminates. Paget et al. [125] designed a new wavelet transform base and applied it to Lamb signals in a composite panel subjected to impact, with which the impact energy could be predicted by calibrating changes in the wavelet coefficient. Kessler et al. [59] applied WT to PZT-generated A_0 mode acquired from a sandwich beam, for the detection of delamination. The effectiveness of WT analysis for studying wave dispersion was evaluated by Kim and Kim [111]. In particular, Yan and Yam [126] demonstrated that a CWT-based spectrographic analysis can detect 0.01–0.1% variation in selected parameters for the identification of delamination, while such a value is normally over 10% for modal-based methods. In addition to the analysis of Lamb waves generated by PZT, WT also has utility in processing Lamb wave signals produced by EMAT [21,28], by laser [28] or collected by fibre optic sensors [43].

Other signal processing tools that can potentially be used for analysing Lamb wave signals also include reassigned spectrographic analysis [26], cepstrum investigation [127], blind deconvolution [128] and cyclostationary processes [129], or statistical modelling [130] and probability analysis [131].

6. Algorithms for Lamb wave-based damage identification

As the pivotal step in overall damage identification, the interpretation of preliminarily processed Lamb wave signals can be either *forward* or *inverse*. A *forward* analysis is conduced logically, and in most cases the solution is unique. In contrast, an *inverse* problem is difficult to solve by rational means, and the solution can be ambiguous. Quantitative damage detection is known as a typical and highly complicated *inverse* pattern recognition problem [132].

6.1. Forward (direct) algorithm

For few simple cases, logical analysis of signals may be sufficient. *Time of flight* (ToF), defined as the time lag from the moment when a sensor catches the damage-reflected signal to the moment when the same sensor catches the incident signal, can be a straightforward method for damage triangulation [59,102].

As a 2D expansion of such a concept to composite structures, a series of PZT sensors was employed to cover the area of interest and ToFs were extracted from signals captured from each possible actuator-sensor path upon denoise [10,11,133]. For example, four PZT sensors, each serving as both actuator and sensor, were attached to the four corners of a CF/EP plate (500 mm × 500 mm) [11]. ToFs were extracted from signals captured from each possible actuator-sensor path upon denoise. When transducer P_1 acts as an actuator and simultaneously the origin of its coordinate system,

$$\frac{L_{A-D}}{V_{S_0}} + \frac{L_{D-S}}{V_{S'_{0\,\mathrm{Damage}}}} - \frac{L_{A-S}}{V_{S_0}} = T_{1-i} \quad (i = 2, 3, 4), \tag{12}$$

where $V_{S'_{0\,\mathrm{Damage}}}$ and V_{S_0} are the velocities of damage-induced shear mode $S'_{0\,\mathrm{Damage}}$ and incident symmetric mode S_0, respectively. T_{1-i} denotes the acquired ToF via path P_1–P_i. L_{D-S}, L_{A-D} and L_{A-S} represent distances between the damage centre (x, y) and the ith sensor, P_1 and the damage centre, P_1 and the ith sensor, respectively, i.e.

$$L_{D-S} = \sqrt{(x - x_i)^2 + (y - y_i)^2}, \quad L_{A-D} = \sqrt{x^2 + y^2}, \quad L_{A-S} = \sqrt{x_i^2 + y_i^2} \qquad (i = 2, 3, 4), \tag{13}$$

where (x_i, y_i) represents the coordinates of the ith transducer in the present coordinate system. Analogously, a nonlinear system consisting of four equation sets was established when each PZT actuator in turn acted as the actuator based on its own reference systems, whose mathematical solution led to the damage location (see Fig. 12).

Also by exploiting ToF, time-reversal imaging was introduced for wave-based damage detection [134,135]. The governing equations for Lamb waves in an ideal (lossless, time-independent) structure contain only the second-order derivatives with respect to time. For any waves radiating from a source which are subsequently scattered, reflected and refracted by damage, there exists a set of waves that can precisely retrace all the paths and converge in synchrony at the original source, as if time were going backwards [135]. Considering an inhomogeneity in a plate, its scattered Lamb waves, measured by different actuator-sensor paths, can thus be time-reversed with such a scenario, by oppositely changing the roles of actuator and sensor, i.e., the wave is

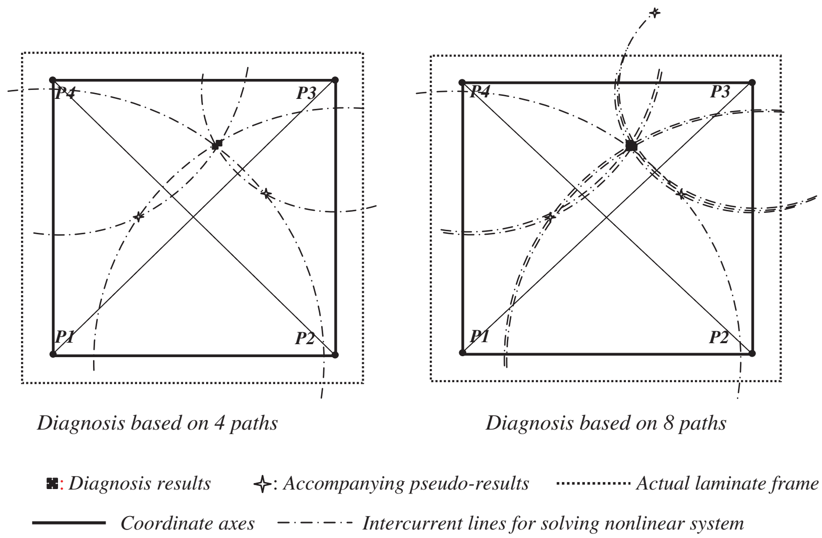

Fig. 12. Detection of delamination location via direct algorithm [11].

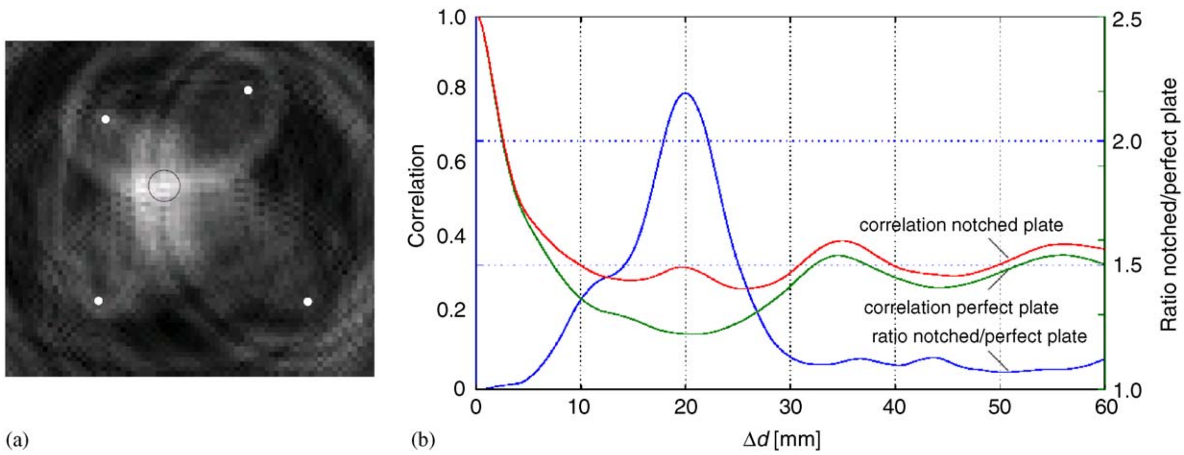

Fig. 13. (a) Damage identification using time-reversal imaging approach [134]. (b) Correlation curves for perfect, notched plate and ratio of them [136].

supposed to propagate from sensor to actuator. All these time-reversed wave signals, each exhibiting a time delay due to the existence of damage, will simultaneously converge at one point, namely the scatter (damage). For validation, damage (simulated by added mass) was introduced to a large panel (500 mm × 500 mm). By applying time-reversal, the location of damage was graphically determined [134] (see Fig. 13(a), where four sensors are highlighted by white dots while the back circle indicates the actual location of the simulated damage).

Correlation or benchmarking is another effective identification tool recently reported for Lamb wave-based damage location. Hurlebaus et al. [136] transformed laser-generated Lamb signals in a notched plate into the velocity-frequency domain using STFT, to obtain the auto-correlation curves for intact and notched plates, as well as the correlation coefficient curve based on the ratio of intact to notched. Correlation coefficient of their ratio (curves of perfect to notched) was then associated with the damage location (Δd), as shown in Fig. 13(b). Singularity in the curve (poor correlation) was corresponding to the location where damage occurred. This method is able to detect notch right located along the actuator-sensor path.

6.2. Inverse algorithm

6.2.1. General inverse approaches

Quantitative damage identification, an *inverse* pattern recognition problem, can only be effectively achieved through appropriate *inverse* algorithms. Tremendous efforts have been directed to this issue over the years. Statistical modelling, syntactic method and artificial intelligence are some of the major approaches. Relying on probabilistic and stochastic theories, the principle of statistical modelling and the syntactic method is an iterative comparison between theoretical results and experimentally captured signals, to pursue the case that fits best [137–142].

6.2.2. Artificial intelligence

With advances in neuroscience and high capability computing devices since the 1990s, artificial intelligence (AI), defined as the simulation of human intelligence toward solving a problem [80], has rapidly emerged as one of the promising alternatives for handling complex *inverse* problems, represented by *expert systems* (knowledge-based system), *fuzzy logic*, *inductive learning*, *genetic algorithms* and *artificial neural networks* [143]. In particular, an ANN operates as a parallel computational model to authentically explore the connection between a series of reasons (*inputs*) and consequences (*outputs*) for a given system. A well-trained ANN can predict outcomes under an unknown stimulus according to pre-accumulated knowledge, while avoiding interrogating intricate constitutive relations.

Study [144] has shown out that any continuous system with an *m*- to *n*-dimensional mapping can be smoothly portrayed by an ANN with two hidden processing layers, with the *i*th (ov_i) output in the ANN being defined by [80]

$$ov_i = T_3\left(\left(\sum_{q=1}^{K} w_{q-i}^{3}\, T_2\left(\left(\sum_{r=1}^{J} w_{r-q}^{2}\, T_1\left(\left(\sum_{p=1}^{m} w_{p-r}^{1}\, im_p\right) + b_r^1\right)\right) + b_q^2\right)\right) + b_i^3\right) \quad (i = 1, 2, \ldots, n), \tag{14}$$

where m, n, J and K are numbers of elements in input and output layers, and neurons in two neural layers, respectively. im_p denotes the pth input element, w_{p-q}^{r} ($r = 1, 2, 3$) represents the weight joining the pth input element/neuron in the rth layer with the qth neuron/output variable in the next layer. Similarly, b_q^i is the bias for the qth element in ith layer ($q = 1, 2, \ldots, J/K/n$ for the first/second-processing/output layer), while T_i is the transfer function to bridge different layers in the neural network.

In most approaches using ANN for damage identification, various structural features in the single time or frequency domain, or static parameters, are commonly employed for network training for the sake of simplicity. These features include mode shape [145,146] and natural frequencies [97,147–150] or combined modal information [151]; acceleration spectra [152] or combined parameters of displacement, velocity and acceleration [153]; applied force [154], or deformation parameters, such as displacement [23,155,156], strain [157], as well as strain history [158], impedance [159], etc.

Lamb waves have a much higher sensitivity to damage than other structural responses, e.g. modal shape, frequency, etc., and their combination with ANN technique is able to lead to precise identification. Bork [160] and Bork and Challis [161] developed an identification technique for debonding in adhesively bonded joints using ANN-interpreted Lamb wave signals. Yam et al. [89] analytically related crack location and length with percentage change in structural energy. Twenty-seven different crack lengths at four locations in a PVC sandwich panel were numerically simulated and the percentage shifts in energy were used to train a single-layer ANN. Good identification precision was achieved for another 12 numerically simulated damage cases. However, parallel verification using in-field measured signals did not predict the damage well. This was attributed to the noise disturbance and the difference between the model and actual structure. Su and Ye [80] presented an ANN-based damage identification technique for composite structures. The spectrographic characteristics of Lamb signals from a PZT sensor network were extracted, defined as *digital damage fingerprints* (DDF). DDF serves as a series of digitalised symptoms of a defective structure, and accordingly a particular damage case is uniquely defined with one set of DDF. By way of illustration, the extracted DDF for the example signal in Fig. 11(a) is displayed in Fig. 14. In this approach, a damage parameters database (DPD) containing DPD for various damage cases from numerical simulation was employed to train the ANN, which

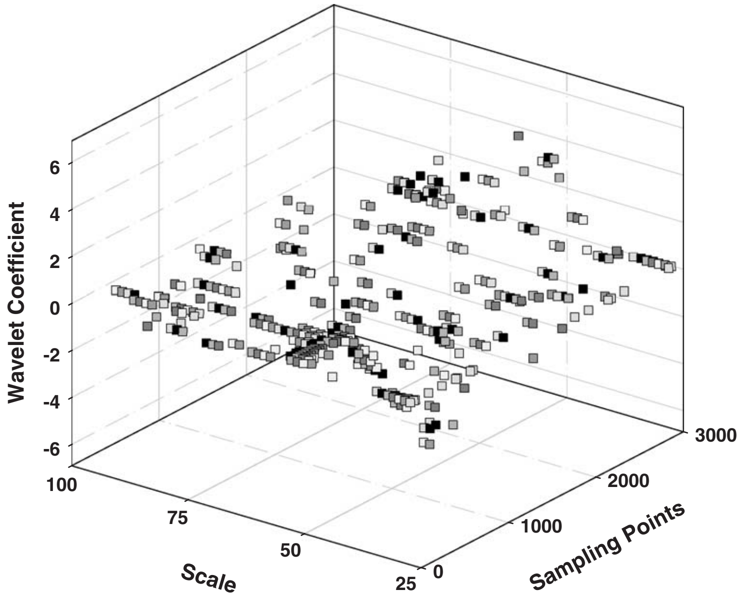

Fig. 14. Extracted DDF in the time-scale domain for signal in Fig. 11(a) [80].

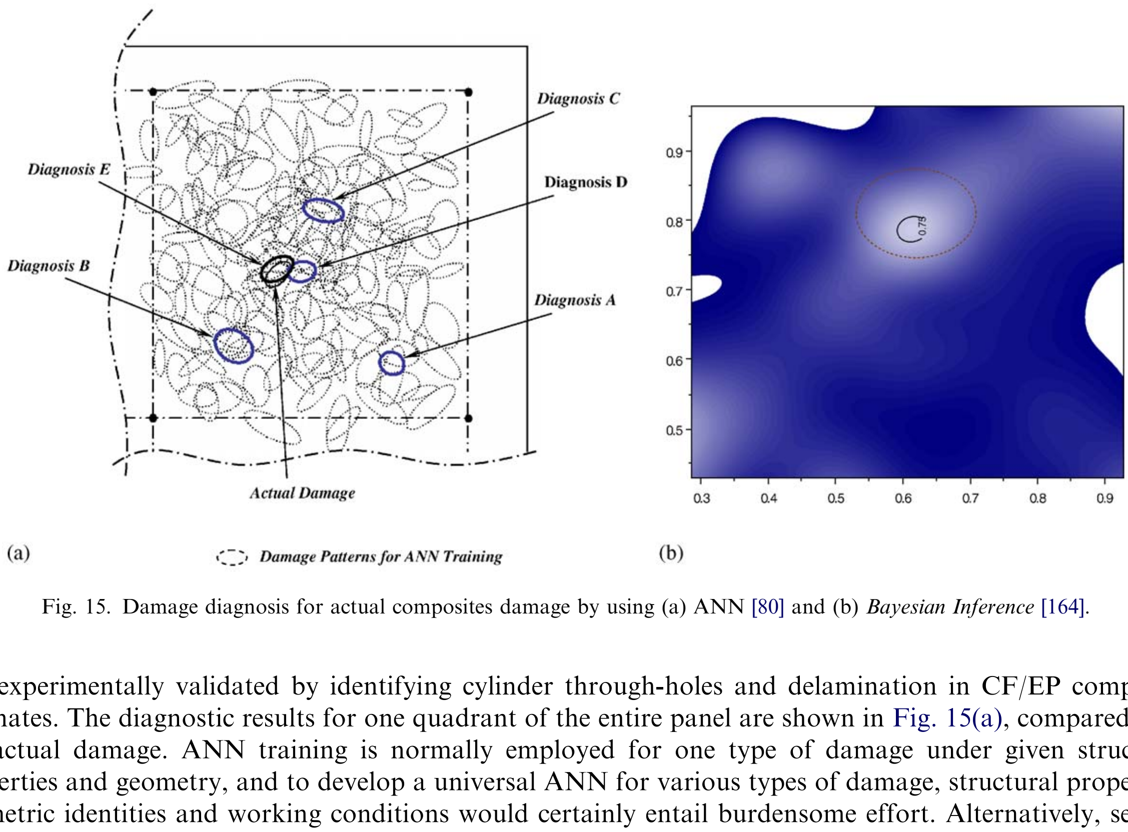

Fig. 15. Damage diagnosis for actual composites damage by using (a) ANN [80] and (b) *Bayesian Inference* [164].

was experimentally validated by identifying cylinder through-holes and delamination in CF/EP composite laminates. The diagnostic results for one quadrant of the entire panel are shown in Fig. 15(a), compared with the actual damage. ANN training is normally employed for one type of damage under given structural properties and geometry, and to develop a universal ANN for various types of damage, structural properties, geometric identities and working conditions would certainly entail burdensome effort. Alternatively, several ANNs, exclusively contributing to the identification of one kind of damage, may be a solution.

In addition to ANN in the AI category, genetic algorithms (GAs) have also been introduced for damage identification [162,163]. However, GA-based detection requires repeated searching from among numerous damage parameters to find the optimal solution of the objective function, and efficiency is quite low when the measured data or the structural damage parameters are multitudinous [89]. Moreover, to design an objective function for a complicated structure is always problematic. On the other hand, a two-level information fusion technique in terms of a knowledge database-based AI algorithm, *Bayesian Inference*, has been proposed [164]. The level-one decision fusion was implemented using Lamb wave features extracted from individual actuator-sensor paths to create perceptions of damage status and a knowledge database. Subsequently, the perceptions from each sensor were integrated to represent decision fusion at a higher level, to determine the possible damage. The assessment results for through-hole damage in a composite laminate via such a method are displayed in Fig. 15(b), where lighter colour represents a higher possibility of damage.

6.2.3. Tomography

Application has recently been found for tomography in Lamb wave-based signal processing, working in such a way that if Lamb wave measurements are made for a number of relative transducer positions (projections), an image of a large region can be reconstructed tomographically using a simultaneous iterative reconstruction technique (SIRT) [165]. Tomography yields an easily interpretable quantitative map of the parameter of interest, such as thickness loss due to delamination. Aided by tomography, with Lamb waves it is possible to rapidly interrogate a large area, putting Lamb wave ultrasonography in the same league as rapid full-field techniques such as thermography and photoelasticity. Early Lamb wave tomography studies [166,167] usually adopted a standard *parallel-projection* geometry with the velocity or attenuation of Lamb waves as input for the reconstructions, while recent studies [168,169] have introduced a '*crosshole*' tomographic scheme. The Lamb wave signal measurement scheme for parallel-projection tomography as well as the scanning system to realise such a measurement are shown in Figs. 16(a) and (b), respectively, where the ToF for each individual transmitter-receiver path is captured. As an example, diagnostic results, for hammer-inflicted invisible impact damage located at the centre of a multi-layer woven graphite epoxy plate, are exhibited in Figs. 16(c) and (d) for the two above-mentioned approaches [165]. Normally, crosshole tomography has more flexibility, allowing any geometry and incomplete data sets. In contrast, the parallel projection algorithm is very sensitive to incompleteness or noise in the experimental data. It is noteworthy that both of them require a large number of sensors to scan the entire area carefully for image construction, which may limit their applications for quick damage identification.

7. Sensor and sensor network technology

Sensor technology is an integrated element in the overall development of damage identification techniques, inter-disciplinarily spanning areas of physics, chemistry, materials, molecular biology, fabrication, electronics and signal processing. Basically, a sensing device for damage identification must meet requirements of (1) endurance for general environmental service, (2) a life of at least 5–10 years, and (3) simple and easy handling and attachment [170]. For higher performance, such devices should be small in size, light in mass, with high sensitivity, low cost/power consumption, and high reliability. To accommodate field applications, consideration should also be given to remote control and data transmission, robustness for vibration and noise, little deterioration due to aging, and reduced wire or even wireless features.

A single sensor, embedded in or bonded on the host structure, can perform only local data acquisition. Sensor networks have therefore been developed. In this regard, PZT can be wired cost-effectively into sensor arrays or wireless communicators, to realise multi-point Lamb wave excitation and measurement. Many studies have been focused on the optimisation of transducer location in networks [171] to pursue the most effective signal generation and acquisition, although increasing effort is being directed to the development of a standard sensor unit technique for general application regardless of the optimal location of individual sensors.

SMART Layer® (*Stanford Multi-Actuator-Receiver Transduction Layer*), developed by Stanford University and commercialised by Acellent® Technologies, Inc. [172], integrates a certain number of distributed PZT elements into a dielectric film to configure a network. As a thin and flexible layer, a SMART Layer® can either be embedded into a composite structure or bonded onto a surface to excite and collect Lamb wave signals, without noticeable degradation of host structural integrity. Unlike SMART Layer® that generates and measures stress waves, HELP Layer® (*Hybrid Electromagnetic Performing Layer*), developed by the French Aeronautics and Space Research Center (ONERA) [173], is based on the interaction between electromagnetic

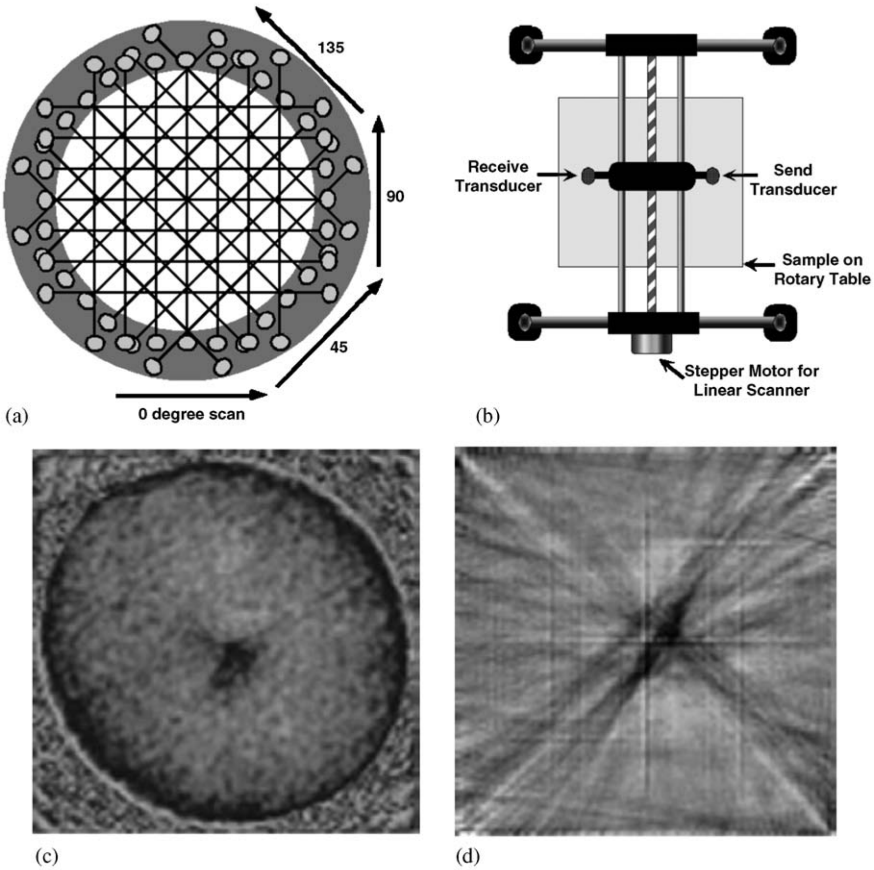

Fig. 16. (a) Signal measurement scheme for parallel-projection tomography; (b) tomography scanning system; [168,169] (c) reconstruction of damage by using parallel-projection tomography; and by using (d) crosshole tomography [165].

fields and structural abnormalities. Such a layer allows the detection of variations in local electric conductivity and dielectric permittivity induced by mechanical or thermal damage. In addition, to simplify the transducer network design for Lamb waves, four PZT disks are collocated to encircle a square area controlled by a signal excitation/acquisition circuit [80], defined as a *standard sensor unit* (SSU). As the basic component in an active sensor network, SSUs are collocable, and diverse networks can be tailored by assembling a set of SSUs, flexibly accommodating different geometries and boundaries.

As a valuable approach in parallel with sensor networks, the patch repair technique using Lamb waves for debonding monitoring has also been explored [38,97,174,175]. In particular, smart patch techniques were intensively developed by Chiu et al. [176] and Koh et al. [107]. In their studies, a piece of boron/epoxy patch 0.6 mm in thickness, named a '*perceptive repair*', was manufactured and bonded onto a host plate to generate Lamb wave signals. The PZT elements in the patch measured the shift in structural mechanical impedance, and it was thus possible to detect debonding in an adhesive layer between the adherend and parent structure. These studies also indicated that the impedance-based technique could not find debonding in areas distant from the patch.

8. Concluding remarks and some challenging issues

Although increasingly employed in various engineering communities, composite structures still run a high risk of losing effectiveness under abrupt impact or sequential accumulation of defects during their operation. For enhancement of the overall integrity and reliability of composite structures, damage identification techniques have been studied intensively over the past decades. With excellent propagation capability, high sensitivity to damage and convenience of generation/collection, Lamb waves exhibit excellent performance in offering high-precision damage detection, serving as a competitive substitute for traditional tools.

With this survey on the major body of related studies, the state of the art of Lamb wave-based damage identification techniques since the 1990s has been reviewed. Some of the most representative studies and fruitful achievements have been addressed and commented upon. The following summary remarks are offered, together with some challenging issues for future development:

(1) Active piezoelectric actuator/sensors are capable of generating and capturing Lamb waves most cost-effectively for damage identification purposes, compared with other techniques. Large-scale integrated or embedded sensor networks can be customised using a certain number of distributed PZT elements. However, PZT-generated Lamb waves unavoidably create difficulty in signal interpretation. Sophisticated signal processing with interpretation software is an integrated part of the approach.
(2) Appropriate Lamb modes may have to be selected in terms of identification of individual types of damage. The excitation frequency, waveform, cycle number and other signal characteristics should be comprehensively considered during mode selection and diagnostic waveform design.
(3) Although some methods are available, it is very difficult to generate pure Lamb mode using a PZT element. Undesired modes can only be suppressed rather than completely eliminated. The purification of multi-mode is an intriguing but challenging issue.
(4) Damage identification is normally a typical yet complex *inverse* pattern recognition problem and cannot be effectively solved by traditional logic approaches. Artificial intelligence, particularly the ANN technique, can be an encouraging approach. But some limitations exist, such as the need for preparation of vast input training data. For practical uses these limitations need to be addressed.
(5) Detection of multiple damage is another issue worthy of investigation. The use of Lamb waves seems more viable than other tools for its exclusive responses to different damage status. But more complex scattering phenomena complicate the interpretation of Lamb wave signals, and distinguishing such signals remains problematic.

In comparison with mature NDE techniques developed over 50 years, Lamb wave-based quantitative damage identification and its applications to engineering practices are still in a very early stage. Intensive investigation and improvement are matters for further research. It is an intention of the present paper to promote wide consideration and mature application of Lamb waves in cost-effective NDE and structural health monitoring techniques.

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