Health monitoring of aerospace composite structures – Active and passive approach

W.J. Staszewski a,*, S. Mahzana, R. Traynorb

a Dynamics Research Group, Department of Mechanical Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, United Kingdom
b Lambda Photometrics Ltd., The UK Division of Polytec, Lambda House, Batford Mill, Harpenden, Herts AL5 5BZ, United Kingdom

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A B S T R A C T

Impact damage is one of the major concerns in maintenance of aircraft structures built from composite materials. Damage detection in composite materials can be divided into active and passive approaches. The active approach is usually based on various non-destructive techniques utilizing actuators and/or receivers. In contrast passive approaches do not involve any actuators; receivers are used to “sense” and/or hear any perturbations caused by possible hidden damage. Often strain data are used to localize impacts and estimate their energy. The assumption is that damage occurs above well-defined energy of impacts. The paper illustrates one active and one passive method recently developed for impact damage detection. The first method, based on guided ultrasonic waves, utilises 3-D laser vibrometry and does not require any signal processing. Simple laser scans, revealing the change in Lamb wave response amplitudes, have been used to locate delamination and estimate its severity in a composite plate. In contrast, the second method does not require any sophisticated instrumentation but relies on advanced signal processing. An array of piezoceramic sensors has been to detect strain waves transmitted from an impact applied to the composite aircraft structure. The modified multilateration procedure with Genetic Algorithms has been used to locate impact position.

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1. Introduction

Composite materials have been widely used in many aircraft structures due to their high specific strength, light weight, resistance to fatigue/corrosion and flexibility in design. Application examples include the newly-designed Boeing 787 aircraft, which is composed of 50% composites, and the latest Airbus A380 aircraft, which uses 25% of composite materials [1]. It appears that Airbus will be the first manufacturer to build an aircraft with an all-composite wing in their latest model A350-XWB which is currently under design. The entire structure will be composed of 45% composite materials.

The susceptibility of composite materials to incur impact damage is well known and creates a major concern related to structural integrity. Low velocity impacts are often caused by bird strikes, tool drops during manufacturing and servicing or runway stones during take off. Such impacts may result in various forms of damage such as indentation, delamination, or fibre/matrix cracking, leading to severe reduction in strength and integrity of composite structures. Although structures designed with safe-life principles can withstand in theory catastrophic failures, impact damage detection is an important problem in maintenance of aircraft and space structures [2]. Visible damage can be clearly detected and remedial action taken to maintain structural integrity. However, a major concern to end-users is the growth of undetected, hidden damage caused by low velocity impacts and fatigue. This undetected, hidden damage is also known in aerospace applications as Barely Visible Impact Damage (BVID). Failure to detect BVIDs may result in a catastrophe.

Damage detection in composite materials can be divided into active and passive approaches. The active approach needs actuation (or excitation) of monitored structures and then measurements of resulting responses. Various Non-Destructive Testing/Evaluation (NDT/E) techniques have been developed in this area. Examples include ultrasonic testing, X-rays, vibration/modal analysis and numerous optical methods such as shearography or holography, as described in [2]. It appears that ultrasonic testing is the most widely used technique for damage detection in composite materials. The method requires point-by-point measurements which are time-consuming and labour expensive particularly when large surfaces need to be inspected. Guided ultrasonic waves (e.g. Lamb waves) can be used to obtain on-line monitoring and to reduce maintenance costs in plate-like structures, as reviewed in [3,4]. However, the propagation complexity of these waves (often associated with difficult analysis and interpretation), requirements for baseline measurements and temperature-dependence often limit current applications to laboratory developments [3].

Passive damage detection approaches in composite structures do not involve any actuation. Transducers are used to monitor
perturbations directly caused by damage (e.g. rapid release of acoustics energy or heat) or to record/monitor structural responses (e.g. ambient vibration, loads, impact events). Acoustic Emission (AE) is the best known example of a passive technique used for damage detection. However, it is more often used for damage detection in metallic rather than composite structures. Passive approaches often require various mapping techniques to obtain information about usage or possible structural damage from signal responses. Flight parameters and/or strains are mapped to loads and information about usage in Operational Load Monitoring (OLM) systems, as explained in [2]. However, this is often associated with significant errors in estimated structural usage, as reported in [2]. Impact strain data are used to obtain information about location and energy of impact events assuming that damage occurs above well-defined energy level. Impact detection monitoring has a great potential for damage detection in composite structures. However, the majority of methods in this area often require substantial data for training and additionally these methods have been tested for relatively simple plate-like structures.

This paper demonstrates one active and one passive technique recently developed for damage detection in composite aircraft structures. In the active approach a three-dimensional (3-D) laser vibrometer, previously used for fatigue crack detection in metallic structures [5], is applied to sense Lamb wave responses and detect delamination in a composite plate. The method avoids major difficulties associated with guided ultrasonic waves when used for damage detection. In the passive approach, a modified multilateration procedure with Genetic Algorithms (GAs) is employed to locate impacts events. In contrast to other techniques used for impact location, the method does not require substantial data for training. This recently developed approach, reported in [6], is tested on a complex aircraft structure. Both approaches used in the current paper demonstrate their great potential for impact damage detection in aircraft/space applications.

2. Impact damage detection – active approach

The first example of impact damage detection in composite structures demonstrates the application of the active method which is based on Lamb waves. The 3-D laser vibrometer is used to scan Lamb wave responses in order to reveal delamination in the composite plate. This section briefly describes the methodology, experimental arrangements and damage detection results.

2.1. Introduction – Lamb waves for damage detection

Elastic waves propagating in bounded media are often called guided waves. Guided waves are governed by the same wave equa-
tions as bulk waves. However, in contrast to bulk waves, they have an infinite number of modes associated with propagation. Lamb waves are waves propagating in thin plates. These waves have a complex mechanism of propagation. The equations governing their propagation can be solved using the method of potentials [7] or the partial wave techniques [8]. For finite ratios the wavelength $\lambda$ and thickness $b$, Lamb waves are dispersive. For a given thickness $b$ and frequency $f$, the number of propagating modes and the variation of Lamb wave velocities can be established from dispersion curves obtained from Rayleigh-Lamb relations. Small values of the product $f \cdot b$ lead to two fundamental modes propagating in the plate. These are the symmetric $S_0$ and antisymmetric $A_0$ modes.

Lamb waves are the most widely used ultrasonic guided waves for structural damage detection.

However, despite the extensive literature on the subject – as reviewed in [3–4] – commercial applications of Lamb waves for damage detection are largely limited. There are many reasons for this. The subtleties of Lamb waves with complicated physics require some experience related to monitoring strategy, as discussed in [3]. Often single mode excitation (i.e. the excitation leading to fundamental modes propagating in the plate, with the amplitude of one of these modes suppressed to a minimum value) is used to reduce the complexity. However, the application of these modes requires dispersion characteristics for monitored structures. These characteristics are not easy to obtain for composite materials and complex geometries. Also, when fundamental modes propagate only in the plate, lower frequencies of excitation are required. This leads to small wavelengths and reduced sensitivity to small damage. Lamb wave responses used for damage detection need to be compared with baseline measurements taken for undamaged structures. Current inspection techniques based on Lamb waves utilize wave attenuation and/or mode conversion for damage detection. Previous work in this area clearly shows that such features are often unreliable (when analysed over long time periods) due to additional effects such as temperature, loading or bad coupling between the transducer and the structure, as reported in [3]. There exist different types of transducers used for Lamb wave excitation and sensing [3]. Recent sensing example in this area include applications of fibre Bragg grating sensors [9–12], capacitive transducers [13] and laser vibrometers [14–18]. The later applications have demonstrated great potential of laser vibrometry for fatigue crack detection in metallic structures.

2.2. Experimental set-up and procedure

This section describes the experimental work undertaken for active impact damage detection in composite structures. A rectangular 530 \times 225 \times 7 \text{mm} composite plate (Fig. 1), fabricated from
the T300/914 carbon/epoxy unidirectional prepreg, was used in the experiment. The plate’s lay-up was made up from 32 plies, each with a nominal thickness of 0.15 mm/ply with exception of 48 plies near the area at the root. The lay-up sequences of the composite were [+45, −45, 04, +45, −45, 04, +45, −45, 02, 902, 02, −45, +45, 02], and [−45, +45, 03, −45, +45, 02, +45, −45, 902, −45, +45, 03]. A ply build-up region was fabricated to simulate reinforcement. The specimen used was originally manufactured for impact damage detection tests in aircraft composite structures [2,19]. The plate was designed to be mechanically fastened to a stiffening aluminium sub-frame using screws. Also, a composite stiffener was bonded to the root side of the panel in those tests to allow for disbond to be investigated. Therefore, the screw holes around the bond to be investigated. Therefore, the screw holes around the edges of the plate and the shaded area in the left part of the composite panel, originally marked for the stiffener to be bonded, can be seen in Fig. 1. This actuator was used for Lamb wave generation. A series of burst signals comprising five cycles of sine wave with the Hann window envelope was introduced to the plate. The peak-to-peak amplitude of excitation was equal to 20 V. The 100-kHz frequency of excitation used was very close to the first resonance of the piezoceramic actuator to maximize the signal-to-noise ratio and increase the wave propagation range. This excitation signal was generated using the TTI-TCA-1230, arbitrary waveform generator. The excitation burst signals were triggered every 50 ms to minimise the overlapping of the oncoming and reflected waves. In theory two combined S0 and A0 Lamb wave modes co-exist for the thickness of the plate and selected frequency of excitation.

The scanning Polytec PSV-400-3D laser vibrometer was used to acquire Lamb wave responses from the analysed plate. The scanned area was a 182 × 139 mm square around the impact position, as indicated in Fig. 1. Altogether 567 points were used on this scanned area to acquire Lamb wave responses. The maximum 2.56 MHz acquisition frequency bandwidth of the laser system was used. The data were low-pass filtered to a frequency of 1.5 MHz. The data acquisition process utilised 150 averages for each measuring point in order to improve the signal-to-noise ratio. The acquired Lamb wave responses included 2048 data samples. The entire acquisition process took less than a few minutes for the area and parameters applied. This time can be reduced significantly if smaller number of measuring points, signal averages and lower sampling frequency were used.

### 2.3. Damage detection results

The 3-D Lamb wave data gathered from the damaged composite plate were analysed automatically by the PSV software. Firstly, the separation into in-plane and out-of-plane vector components was performed for all Lamb wave responses. Then the peak-to-peak amplitude was calculated for all components. Fig. 2 shows the in-plane (x and y directions) and out-of-plane (z direction) components of Lamb wave propagation taken from the animated sequential images obtained from the scanning vibrometer software, with all points phase-referenced to the triggered piezoceramic actuator burst. The sequential images were obtained for the Lamb responses exhibiting the maximum peak-to-peak amplitudes for the relevant components. The results in Fig. 2c exhibit large values of peak-to-peak amplitudes in the vicinity of the delamination area for the out-of-plane component, which is dominated by the A0 Lamb wave mode. The in-plane components in Fig. 2a and b do not show any significant amplitude changes due to damage.

Fig. 3 shows the contour plot for the results presented in Fig. 2c. Here the peak-to-peak amplitude profiles for the indicated A-B and C-D paths are also presented. The amplitude is increased between 55 and 100 mm. Both amplitude profiles can be used to estimate the area of delamination. It is important to note that the location of damage and its severity coincided with the results obtained by ultrasonic testing.

### 3. Impact damage detection – passive approach

The second example illustrates the passive method of impact damage detection in composite structures. The modified multilateration procedure with the GA-based optimisation scheme is used to locate impact positions in an aircraft composite structure. This section describes the composite specimen, presents the methodology used and gives details related to the experimental tests performed and presents impact location results.
3.1. Introduction – impact detection in composites

Passive impact damage detection has been the subject of many investigations over the last fifteen years [20]. The algorithms presented can be classified into three major categories. The first group of methods involves trigonometric location techniques such as triangulation and multilateration, as reviewed in [21,22]. These techniques use appropriate distances angles and arrival times to establish impact location. The procedures are trivial for isotropic materials. More recently a modified multilateration procedure for anisotropic materials has been proposed [6]. The method, implemented for simple plate structures, uses experimental velocity characteristics and the GA optimization scheme for impact location. The second group of methods is based on system modelling (e.g. [23]). Structural models are used to obtain dynamic responses for simulated impact locations. These responses are then compared with measured sensor outputs. The entire process is repeated iteratively until both results converge. The major drawback of the method is the fact that system modelling is not easy for complex structures. Therefore impact detection results have lead to significant location errors even for simple structures such as beams and plates. The third group of methods involves various machine learning procedures and mapping techniques to locate impacts. This includes artificial neural networks, case-based reasoning methods and multivariate statistical process control techniques, as reviewed in [21–22]. Previous work in this area demonstrates that machine learning techniques are capable of modelling extremely complex relationships between input and output data and produce impressive impact location results even in complex structures. However, these methods require a significant amount of impact data for learning and this is not always possible. In summary, the modified multilateration procedure, presented in [6], has a potential for impact damage detection in composite structures.

3.2. Impact location algorithm

For the sake of completeness this section briefly describes the modified multilateration procedure for impact location in anisotropic materials. The method uses deflection signals measured by three different sensors \( S_1, S_2, \text{ and } S_3 \) positioned on the monitored structure, as illustrated in Fig. 4. These deflections come from propagating strain waves as a result of impact. Since the impact position is unknown, three different angles (namely \( \alpha_1, \alpha_2 \) and \( \alpha_3 \)) for wave propagation directions are assumed (Fig. 4). For every transducer \( S_i \) and assumed wave propagation angle, the distance \( d_i \) between the transducer and unknown impact position can be calculated as

\[
d_i = v_i t_i \quad (i = 1, 2, 3)
\]

where \( t_i \) and \( v_i \) are arrival times and velocities of the propagating strain waves. The arrival times can be estimated from the experimental strain data for all relevant transducers. The major difficulty is the velocity \( v_i \) which depends on the wave propagation direction for anisotropic materials and complex geometries. These velocity characteristics \( v_i = f(\alpha_i) \) can be estimated a priori for monitored composite structures using experimental analysis for all possible angles of wave propagation. For the assumed wave propagation directions \( \alpha_i \) and estimated distance \( d_i \), the analysis of strain data from three different transducers results in three estimated impact

![Fig. 3. Contour plot and amplitude profiles of the Lamb wave response for the out-of-plane z direction of propagation.](image)

![Fig. 4. Illustration of modified triangulation impact location procedure.](image)
positions, i.e. A₁, A₂, and A₃. These positions can be considered as the vertices of a triangle. The GA can be used to minimise the area of this triangle. Finally, the estimate for x and y coordinates of the unknown impact position can be obtained as

\[ x = \frac{1}{3}(x_{A_1} + x_{A_2} + x_{A_3}) \quad \text{and} \quad y = \frac{1}{3}(y_{A_1} + y_{A_2} + y_{A_3}) \]  

where \(x_{A_i}, y_{A_i}\) are the x and y coordinates for the \(A_i\) \((i = 1, 2, 3)\) vertices, respectively. The entire procedure, presented graphically in Fig. 4, can be implemented for any configuration of three sensors.

3.3. Composite structure and experimental impact tests

The test specimen used in the experimental work performed for impact location was a composite section from the wing flap of a commercial aircraft. Fig. 5 gives photographs of the entire structure. The flap had a complex geometry, various structural features and was manufactured from different materials. The composite skin was curved at the top. The interior of the component below the leading and trailing edges were filled with aramid fibre and aluminium honeycombs, respectively. The underside of the central area had numerous stringers attached. Vertical and horizontal lines of rivets can be observed at the top curved surface of the structure in Fig. 5. These lines also indicate positions where underside ribs and spars were attached.

Due to the geometry involved, the structure was divided into four different zones. The analysed zones were: the upper part of the central area (zone 1), the lower part of the central area (zone 2), the trailing edge (zone 3) and the leading edge (zone 4), as illustrated in Fig. 5.

The composite structure was instrumented with nine Sonox-P5 piezoceramic sensors bonded on the top surface. The diameter and thickness of each sensor was equal to 6.5 and 0.25 mm, respectively. Two sensors were bonded on the leading edge (zone 4); two on the trailing edge (zone 3) and five in the central area (zones 1 and 2), as shown in Fig. 5.

A series of 41 low-velocities, low-energy impacts were performed at various positions on the structure in order to obtained wave velocity characteristics. The impact strain data were acquired using the Waverunner LeCroy LT-264 oscilloscope by sensors S4 and S7 in zone 1, sensors S3 and S6 in zone 2, sensors S1 and S2 in zone 3 and finally sensors S8 and S9 in zone 4. The sampling frequency used was equal to 5 kHz. Fig. 6 gives examples of strain signals acquired by two different sensors. The strain data were used to obtain the wave velocity characteristics. Firstly, the arrival time...
was estimated for all recorded signals. Two different methods are used in impact detection studies for arrival time estimation. These are thresholding and arrival of the signal maximum peak. The later approach was used in the current paper as it has provided good estimation in previous investigations [20–22]. Once the arrival time was estimated then, for known distances between impact and sensor positions, the velocity was calculated from Eq. (1) for the 0–180° range of wave propagation angles. Polynomial functions were then curve-fitted to the experimental data. Finally, the wave velocity characteristics for the 0–180° angle range were mirrored (due to the symmetry of the structural layout) to produce the final characteristics for the 0–360° angle range. The final results, presented in Fig. 7 for all analysed zones, were used for further impact location studies based on the modified triangulation procedure.

3.4. Impact location results

The algorithm described in Section 3.2 was used for impact location. This algorithm involves the GA optimisation scheme [24]. The integer encoding was used to represent three unknown values of wave propagation angles. Three random integer numbers were chosen to represent angle values. For \( i = 1 \) (sensor \( S_1 \)) and \( i = 3 \) (sensor \( S_3 \)) the actual angle values from the velocity characteristics were taken as \( x = x_1 + 180° \) and \( x = x_3 + 270° \), respectively (see Fig. 4). Once a population of chromosomes was selected randomly, the experimental wave velocity characteristics were used to estimate impact positions. The GA was then performed to evolve the initial population and optimise the final impact positions. The entire procedure was coded in C and run under Solaris v.8 operational system. A Sun grid computer was used in all calculations. Since there is very little guidance in the literature regarding the choice of GA parameters, a trial and error approach was used for selection. The parameters selected are summarised in Table 1. The natural fitness measure was introduced as the inverse of the total length comprising of lengths \( A_1A_2, A_1A_3 \) and \( A_2A_3 \) (see Fig. 4)

\[
f = \frac{1}{A_1A_2 + A_1A_3 + A_2A_3}
\]  

(4)

The GA procedure was run for 500 generations. However, the convergence was obtained after 40 generations. Fig. 8 gives an example of impact location results for the four analysed zones. The results, given as the comparison between the actual and estimated impact locations, show that the overall trends of the actual location curves are followed by the estimated location curves. The discrepancies in \( x \) and \( y \) coordinate estimates were monitored as percentage errors expressed in terms of the overall surface area of the monitored structure. A summary of impact location estimation errors are given in Table 2. This clearly shows that the errors obtained were smaller than 2% for all analysed structural zones. Thus the procedure used has led to good estimates for impact locations. The study also shows that the zones 3 and 4 have produced worse results than zones 1 and 2. This is probably due to fact that both structural edges (i.e. zones 3 and 4) were filled with honeycombs leading to extra damping of the propagating waves. The curvature of the leading edge (zone 4) could contribute additionally to inaccurate impact location estimates.

4. Conclusions

The application of two various methods used for impact damage detection in composite structures have been demonstrated. Firstly, the active approach utilized Lamb waves and a 3-D laser vibrometer. This has allowed for separation of in-plane and out-of-plane Lamb wave components. Simple laser scans of Lamb wave amplitude have been used to locate delamination and estimate its

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**Table 1**

Summary of GA parameters used for the optimisation scheme

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of chromosomes per population</td>
<td>16</td>
</tr>
<tr>
<td>No. of generations</td>
<td>500</td>
</tr>
<tr>
<td>No. of genes per chromosome</td>
<td>3</td>
</tr>
<tr>
<td>Probability of crossover</td>
<td>0.6</td>
</tr>
<tr>
<td>Probability of mutation</td>
<td>0.01</td>
</tr>
<tr>
<td>No. of elite chromosomes</td>
<td>3</td>
</tr>
<tr>
<td>No. of new blood chromosomes</td>
<td>5</td>
</tr>
</tbody>
</table>
severity in a composite plate. The method allows for non-contact measurements that cannot be achieved with a small number of currently used contact transducers. It is important to note that damage detection has not involved any studies of complex Lamb wave propagation in the monitored structures, neither any baseline measurements for undamaged structures, nor any signal post-processing performed to extract damage-related features. The analysis and interpretation of the results is very straightforward.

The second investigated method represented a passive approach to impact damage detection in composite structures. The impact location in the aircraft composite structure was performed using the modified triangulation procedure with the GA optimisation scheme. The procedure did not require substantial data for training and resulted in good impact location estimates.

The active approach presented in the paper requires sophisticated instrumentation in order to obtain straightforward damage detection results. In fact very little signal processing was used for damage detection. In contrast, the passive approach involves more complex signal processing but does not need any sophisticated instrumentation for damage detection. It is important to note that both approaches can be used together in real applications. The passive approach can be used to estimate impact location. Then the active approach can be applied to reveal possible impact damage and its severity.

Although both methods offer a good solution to the impact detection problem further tests are required to establish the methods.

**Table 2**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Integer encoding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>0.45</td>
</tr>
<tr>
<td>Zone 2</td>
<td>1.48</td>
</tr>
<tr>
<td>Zone 3</td>
<td>1.32</td>
</tr>
<tr>
<td>Zone 4</td>
<td>1.97</td>
</tr>
</tbody>
</table>

**Fig. 8.** Impact Location results for zones 1 and 3; x-coordinate – left column; y-coordinate – right column.

**References**


