Effect of Delta-T Grid Resolution on Acoustic Emission Source Location in GLARE

John P. MCCRORY, Rhys PULLIN, Matthew R. PEARSON, Mark J. EATON, Carol A. FEATHERSTON, Karen M. HOLFORD

Cardiff School of Engineering, Cardiff University, Cardiff, Wales; Phone: +442920875924 email: mccroryjp@cardiff.ac.uk, pullinr@cardiff.ac.uk, pearsonmr@cardiff.ac.uk, eatonm@cardiff.ac.uk, featherstonca@cardiff.ac.uk, holford@cardiff.ac.uk

Abstract:

Ever increasing international political pressure regarding the emissions from aircraft is pushing the aerospace industry to make continuous improvements to aircraft fuel efficiency through the use of lighter structural materials. This paper investigates the applicability of Acoustic Emission (AE) to accurately locate damage occurring in the fibre metal laminate GLARE, a composite material which has seen increasing use on aircraft in recent years due to its weight saving properties. The source locations of pencil lead breaks on a GLARE specimen were determined using the conventional Time of Arrival (TOA) technique and a novel approach called delta-T Mapping. Furthermore, a review of the impact of the delta-T grid density on the accuracy of the calculated source locations in the complex specimen was performed. A comparison of the results from the two techniques showed a slight improvement in the location capabilities of delta-T over the conventional TOA approach for fine grid resolutions. In addition, delta-T location accuracy deteriorated when the grid subset size increased to beyond twice the maximum defect size in the specimen.

Keywords: acoustic emission (AE), AE source location, composite, aerospace, fibre metal laminate (FML), GLARE, delta-T, time of arrival (TOA)

1. Introduction

The International Air Transport Association’s most recent technological report [1] states that the year 2020 will see aircraft emissions reduce to between 20 to 35% below 2005 levels. A significant proportion of that reduction will be attributed to the use of lighter structural, composite materials such as the fibre metal laminate (FML) GLARE. Of course, the introduction of new materials into such a safety critical application requires the operators to possess the ability to assess the working condition of these materials during use and thus a reliable structural health monitoring (SHM) system must be suggested. This study investigates the use of Acoustic Emission (AE) monitoring as a two-dimensional damage location tool by identifying the locations of pencil lead breaks in a test on a GLARE panel.

AE source location has seen considerable academic interest in recent years. A summary of the most used and investigated location techniques can be seen in the overview by Eaton et al [2]. With regards to two-dimensional source location, the conventional time of arrival (TOA) method makes use of the concept of triangulation to determine the origin of a source and is explained in detail by Miller et al [3] in the NDT Handbook. In short, it reasons that if the arrival time of a wave caused by an event is known at each sensor in an array along with the velocity of the wave produced by that event then the source location can be identified by comparing the difference in times of arrival of the wave at pairs of sensors. Inserting the information for any sensor pair into Eq. (1) will describe a parabola on which the source must lie to produce the apparent difference in TOA between that sensor pair.
\[ R = \frac{D^2 - dT^2 C_{AE}^2}{2dT C_{AE} + D \cos \theta} \]  

Where \( D \) is the distance between the sensor pair, \( dT \) is the difference in the time of arrival of the signal between the sensor pair, \( C_{AE} \) is the wave speed and \( \theta \) is the angle made from the straight line connecting the sensor pair to any position on the parabola. Once this has been completed for all sensor pairs in an array then the parabolas can be overlaid and the mutual crossing point used to indicate the source location. Of course, this method assumes a uniform wave speed in all directions which is grossly inaccurate for orthotropic composite materials, which have been observed to exhibit differences in wave speeds of up to a factor of three in orthogonal propagation directions [4] and so alternative location methods have been suggested.

Among the most promising of these alternative locating algorithms are mapping techniques. Scholey et al [5] describe the ‘best-matched point’ method which consists of creating a computational model of the test specimen’s geometry from points, which are defined in reference to a global coordinate system, and highlighting the positions of the sensors that form the sensor array, also in reference to the global coordinate frame. Using simple vector manipulation it is possible to determine the propagation direction and distance from any given point in the geometry to any sensor in the array and thus, with known wave speeds, calculate the time of flight from a point to any sensor. With this known the difference in arrival times between a pair of sensors for a wave travelling from any point in the geometry to those sensors is known for all sensor pairs and all points and hence a map of location contours is generated which can then be used to locate physical sources generating AE in a test of the specimen.

Of course, accurate wave propagation speeds must first be calculated in all directions before any time of flight values can be computed and the very nature of using a simulation to determine these values will introduce errors to the method since simulations are based on models which make simplifying assumptions about the behaviour of waves. Furthermore, the technique has difficulties when faced with specimens that have hidden features or that have unknown levels of damage or imperfections contained within them before experimentation, since these will not be represented in the wave simulation.

A novel technique developed by Baxter et al [6] called delta-T mapping improves on this approach. Instead of computationally simulating the propagation of waves in the structure, a grid, referred to as a training grid, is instead overlaid onto the physical structure itself. A repeatable AE source, in the form of a Hsu-Nielsen (H-N) pencil lead break [7, 8], is then generated at each grid point several times and recorded by the sensor array. This physical measurement provides the times of flight from any grid point to any sensor and so, similar to the best-matched point method, the difference in time of arrival between sensor pairs and hence a map of constant delta-T contours for sensor pairs is generated and subsequently used as part of the delta-T location program [6] to locate sources of AE in a test. Note that since the grid resolution is typically in the range of 2x2 cm the time of flights for any analogous point in the grid area is obtained by linearly interpolating the time of flights calculated at the surrounding grid points.

Since the training grid data is created using the test specimen itself it automatically takes into account the effect of defects, thickness changes and complex geometries ensuring accurate time of flight data. It also means that velocity or dispersion information about the material
being tested need not be obtained. It is believed that the resolution of the training grid used has a bearing on the accuracy of the results of the location calculation, since to obtain the \(dT\) values between a sensor pair for any point in the area of interest using data collected from a coarse training grid requires interpolation across a larger spatial distance. However, previous experimentation investigating this grid resolution effect [9] were carried out using relatively simple geometries, thus no significant improvement was seen in accuracy upon increasing the training grid resolution.

Accurate first arrival time data for a wave reaching a sensor is paramount to the accuracy of any location calculation. Kurz et al [10] highlight a method of utilizing an Akaike Information Criterion (AIC) to calculate more accurate TOA values with greatest improvements in accuracy occurring when dealing with waveforms that have a low signal-to-noise ratio (SNR). Ziola and Gorman [11] look at using a cross correlation technique to highlight an individual frequency component of a wave to calculate a more accurate time of arrival for that frequency component and Jeong [12] used a Gabor wavelet transform to the same effect. This said, the use of a H-N source for this experiment ensured that the signal had a significantly large amplitude and thus the faster moving, symmetrical \(S_o\) wave mode had a magnitude sufficient enough to trigger a hit from the sensors using the conventional threshold crossing method of determining the first arrival time and it was not necessary to implement any of the more advanced methods described above.

Literature shows that FMLs have seen less exposure to AE testing than other composite materials and, to the author’s knowledge, the GLARE layup used in this study has never been tested before. FMLs consist of alternating fibre reinforced polymer and metal layers and NDT is regarded as challenging when compared to the testing of monolithic structures [13] due to the increased complexity brought about by the interaction of the different layers and their anisotropic material properties. AE could provide a monitoring solution for this complex material due to its ability to detect plate waves travelling through the entire structure; this study aims to help determine the extent of its applicability. Further adding to the intricacy of their NDT, Woo et al. [14] suggest that the surface wave velocity in FML’s may display peculiar dispersive behaviour due to the interaction of the waves in the surface and inner layers, however the extent of this is unknown. Thus, gaining further information on the manner in which the AE waves travel in GLARE is of interest to researchers in order to understand what techniques may be utilised in subsequent source characterisation studies.

This paper explores the use of the delta-T mapping location method on a GLARE specimen in an attempt to determine the effect of the training grid resolution on the accuracy of the calculated location. The results are also compared with those calculated using the TOA approach to determine the improvement, if any, delta-T posses over this conventional method. Finally, a broader understanding of the behaviour of AE in the GLARE is desired.

2. Experimental Methods

The GLARE panel, obtained from Airbus, measures at approximately 1200mmx700mm and once formed part of the fuselage of an aircraft, Figure 1. The area of interest chosen for testing on the panel was selected as it appeared to be the most geometrically challenging, including rivets, holes and supporting structural members on the underside. The panel is 3.1mm thick and consists of alternating layers of glass fibre reinforced epoxy (GFRE) and 2024-T3 aluminium alloy, Figure 1, and is referred to by Airbus as ‘Glare 3 -5/4 - .4’.
Sensors were acoustically coupled to the surface using grease and affixed at arbitrary positions around the area of interest using a pair of magnets on the top and bottom surfaces. Nano 30 sensors were chosen due to their relatively broad band response within the frequency range of 125–750 kHz. The 1x1cm training grid was drawn onto the upper surface of the specimen over the area of interest as shown in Figure 2, the grid spanned an area of 15x35cm.

Figure 1: a) GLARE panel specimen and b) schematic representation of GLARE layup (not drawn to scale)

Figure 2: GLARE panel with delta-T training grid
Signals were amplified by 40dB using Physical Acoustics Corporation (PAC) preamplifiers and recorded at 4MHz using a Physical Acoustics Ltd. (PAL) PCI-2 acquisition system. To create the training grid data file necessary to run the delta-T location program a H-N source was generated five times at each grid point. The output display from the PCI2 system was monitored throughout to verify that each event registered just once on each of the six sensors. The data collected from these events was converted to the appropriate format and processed using the algorithms designed by Baxter [6] to produce a delta-T grid data file containing the information on the contours of constant dT between sensor pairs. The raw data collected was then manipulated to remove the events necessary to mimic the data that would have been collected from grids with resolutions of 2x2cm, 3x3cm, 4x4cm, 5x5cm and 7x7cm and these too were processed to obtain delta-T grid data files for each. Fourteen locations inside the delta-T grid were then selected based on their surrounding geometrical features for use in the location test and ten pencil lead breaks were recorded at each of them. The events recorded from the experiment were then processed along with each of the delta-T grid files individually using the delta-T location program to obtain location estimates for each event at each grid resolution.

In order to conduct TOA location calculations using PALs AEwin software the average velocity of the wave travelling through the tested medium must be known and so a velocity test was conducted on the GLARE specimen. This consisted of placing two sensors, sensor 1 and sensor 2, in a line at 0, 45 and 90 degrees to the x-axis of the delta-T grid in turn at 275, 160 and 160 mm respectively and exciting ten H-N sources 30 mm behind sensor 2 at each configuration to determine the average time of flight (TOF) for the S_0 mode between the sensors in these three directions, Figure 3.

![Figure 3: Velocity test configuration](image)

The distance between the sensors, d_0, d_{45} and d_{90}, were then divided by the average time of flight in that direction to obtain the velocity, and these velocities were used to estimate the average velocity for the material, Table 1.
Table 1: Velocity of H-N source wave in GLARE panel

<table>
<thead>
<tr>
<th>Orientation (degrees)</th>
<th>( S_0 ) wave mode velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4918</td>
</tr>
<tr>
<td>45</td>
<td>4719</td>
</tr>
<tr>
<td>90</td>
<td>4870</td>
</tr>
<tr>
<td>Average</td>
<td>4836</td>
</tr>
</tbody>
</table>

3. Results and Discussion

The locations of the fourteen selected test points as well as the results of the location calculations using both the TOA and 1x1 cm delta-T methods can be seen in Figure 4. It is apparent, even by eye that both sets of locations are in reasonable agreement with the actual source locations but with the TOA results appearing more erroneous than those calculated by delta-T.

Figure 4: Comparison of locations calculated using TOA and delta-T against actual source location
To obtain a clearer representation of the accuracies of the two techniques, and to compare the results of the data processed using the coarser grids, the average error between the calculated and actual source locations was determined for each solution method, Figure 5.

It is observed that both TOA and delta-T accurately locate the artificial sources in the geometry to within 1cm of their true position. However it should be noted that since a H-N source was utilised, the signals have a large amplitude and hence clear arrival times whereas in real monitoring situations, signals arising from damage in GLARE would be more problematic to detect. Acknowledging this it is suggested that the improvement in accuracy seen by high resolution delta-T over TOA would be much more apparent in a practical application.

The error for the delta-T results stay reasonably constant for the 1x1, 2x2 and 3x3 cm grids and only noticeably increase when using the 4x4 cm grid or greater. An inspection of the tested GLARE panel reveals that the largest imperfections in the surface are the 1.8 cm diameter holes. Thus it is observed that when the training grid subset dimension increases to beyond double the largest defect size dimension, the error increases substantially. Whilst mostly true in this scenario further investigation would be needed to declare this as a ‘rule of thumb’ when planning future delta-T experiments as there is not enough supporting evidence from just one test and the 7x7 cm grid was capable of calculating accurate results.

The error of the TOA results is lower than expected for such a complex, composite specimen. Table 1 shows that the $S_0$ wave velocity exhibits little variation with propagation direction in GLARE which would help explain this. Furthermore, whilst abundant on the specimen, the holes and rivets are relatively small, meaning they have little impact on the accuracy. Finally, a sensor array of six sensors is excessive for the area of interest tested and had the locations been calculated using the data from fewer sensors then the accuracy would likely drop.

Since the $S_0$ mode velocity is linked to the in-plane stiffness of the material, the uniform velocity with propagation direction suggests that the signal generated is travelling in an isotropic material leading to the hypothesis that the majority of the AE wave energy may be travelling in the upper most, isotropic, aluminium layer. To investigate further, PAC
Dispersion Curves software was used to calculate the $S_0$ mode wave speed in a 0.4 mm thick aluminium plate as 5400 m/s. Furthermore, work by Toyama et al. [15] records the velocity of the $S_0$ wave mode in GFRE to vary from 4682 m/s along the fibre orientation to 2594 m/s orthogonal to the fibre orientation and measure at 3205 m/s for a mixed layup. Bearing in mind that the GFRE layer orientations vary in the GLARE specimen, the velocity measured in this study, 4836 m/s, is closer to that calculated for an aluminium plate than to GFRE. Thus it is a possibility that the majority of the AE wave energy is travelling in the upper most aluminium layer of the GLARE and the drop in velocity from that of pure aluminium could be accounted for by the dispersive effects reported by Woo et al. [14] due to the interaction with the GFRE layer below.

Future work will consist of conducting a more thorough velocity test, using more propagation directions, and investigating the through-thickness propagation of AE in GLARE with the aim of probing the validity of the above hypothesis. The difference in accuracy between the varying delta-T grid resolutions as well as the TOA method when using fewer sensors will also be examined.

4. Conclusion

A range of different delta-T training grid resolutions were used to calculate the locations of H-N sources generated on a geometrically complex GLARE FML panel specimen as a means of determining the significance of the grid resolution on the accuracy of the results. Furthermore the results from delta-T were compared against those determined using the conventional TOA location method. It was found that the error produced by delta-T was uniform up to the 3x3 cm grid after which point it increased significantly. Linking grid resolution to geometrical features highlighted that using a grid subset size more than two times the dimension of the largest defect in the geometry lead to a significant increase in error. Both delta-T and TOA were found to be capable of locating a source to within 1cm of its true position, with delta-T offering a larger accuracy when a fine grid was used. A velocity test revealed the average velocity of the $S_0$ wave mode in the GLARE panel to be 4836 m/s and also reasonably uniform in each propagation direction, despite the presence of GFRE composite in the structure, which may be due to unusual plate wave propagation occurring in the FML.

Acknowledgements

The authors would like to thank Airbus for supplying the GLARE specimen.

References


