STRUCTURAL HEALTH MONITORING OF COMPOSITE STRUCTURES USING EMBEDDED SENSORS

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Abstract
This paper presents the results of a series of experiments in which Macro-Fibre Composite (MFC) transducers were embedded within a glass fibre epoxy composite panel to create a self monitoring "smart structure". The transducers were used to detect and locate acoustic emission signals within the panel from both artificial sources and real impact events. A novel mapping technique was utilised to calculate source position and was shown to provide significant improvements of location accuracy in composite materials when compared with the traditional time of arrival method.

1 Introduction
The use of composite materials in the manufacture of large-scale structures is well established in industries such as wind power generation and this adoption of composites is set to continue, with such applications as the next generation of all composite aircraft. These structures can require very time consuming and costly inspection and maintenance to ensure their continued safe operation; however, such costs can be reduced through the effective use of a structural health monitoring (SHM) system. This would ideally be done using an autonomous system embedded within a structure that is capable of detecting, locating and characterising damage in complex structures and often in the presence of high noise levels. This paper presents the results of a series of experiments in which Macro-Fibre Composite (MFC) transducers were embedded within a glass fibre epoxy composite panel to create a self monitoring "smart structure". The transducers were used to detect and locate acoustic emission signals within the panel from both artificial sources and real impact events. Acoustic emission (AE) is a physical phenomenon whereby transient elastic waves are released from the development and growth of damage. Detection of such transient waves using an array of transducers allows an estimation of the source position to be made, based on the wave arrival times. The acoustic emission (AE) technique is very sensitive with no dependency on minimum defect size and therefore has great potential as an SHM tool for early detection of damage onset. It allows continuous and global monitoring of large structures and is capable of detecting and locating damage with a sparse sensor array. Traditional algorithms for location calculation often result in larger errors in complex materials and structures such as composites. A novel source location technique is adopted in this study and is shown to provide significant improvements in location accuracy. Although focussed on embedded sensors in this application the presented location techniques are applicable to all AE monitoring scenarios.

2 Background

Traditionally the calculation of source position is dealt with using the time of arrival (TOA) approach detailed in the NDT Handbook [1]. User-defined inputs of sensor positions and a propagation velocity are required and source location is then resolved using the difference in arrival times (delta t, Δt) of a given signal at different sensor pairs. The accuracy of this calculation is dependent on two key areas: those relating to signal arrival time determination and those relating to processing.

Commonly signal arrival time is determined at a given sensor when the sensor output reaches a certain user defined value, or crosses a threshold and is known as the “first threshold crossing” method. It is often the case that the true arrival time of the signal will not be detected; with a number of signal peaks occurring before the signal amplitude crosses the threshold (Figure 1). In recent years a number of authors have utilised statistical methods to reliably and automatically determine accurate and threshold independent signal arrival times. Lokajicek and Klima [2] utilised a 6^{th} order statistical moment to determine signal onset time, detecting signal arrivals to within ±2 samples for 95% of analysed signals. Kurz et al [3] and Hensman et al [4] have utilised an approach based on the Akaike Information Criterion (AIC) to determine signal arrival times. The approach looks for a change in variance between the uncorrelated noise prior to signal onset and highly correlated signal after signal arrival. This approach has been utilised during this work for signal arrival time determination and is discussed in more detail below (Section 3.1).

Numerous authors have attempted to address the variation in signal propagation velocity experienced in composite materials. Paget et al [5] developed a closed form solution for source position calculation based on the assumption of an elliptical wave front. However, the propagation wave front is only elliptical in composites with specific layups and closed form solutions are rarely stable in the presence of the uncertainties experienced in the measurement system. Others have utilised special sensor configurations to in an effort to achieve better source location. Aljets et al [6] used a closely arranged triangular sensor array to determine the angle of wave incidence upon the array and the propagation distance along this direction, to give a source position. Whereas Ciampa and Meo [7] used a triangular array of three closely spaced sensor pairs (six sensors in total), allowing the source position to be described by six non-linear equations. Solving the equations with an iterative Newton method provides a source position without the need for prior knowledge of the wave velocity behaviour in the material. However, processing times are high, at around 2 seconds per event, and accuracy is likely to reduce in complex geometries.

An alternative approach to AE source location in complex materials and geometries is that of mapping. In this type of process a relationship is formed between known physical positions upon a structure and the Δts that would result from a signal originating at those positions. In this way variations in geometry and propagation velocity are readily accounted for, facilitating accurate source location even in applications where complex materials and geometries are present. Scholey et al [8] approached this problem analytically by calculating the expected Δts from an array of source positions on an anisotropic composite panel. They describe the best-matched point search method which compares measured Δts with the analytical map to find the array point at which the difference is minimised and hence give the location. The accuracy is affected by the resolution of the mapping array, so small spacings of 1-2mm are used, and it is also important that accurate wave velocities are known for a given material. The approach is also not well suited to dealing with complex geometries, in which the calculation of arrival times becomes far more problematic. Other authors [4, 9, 10] have instead used artificial AE sources to determine Δts from known grid positions and therefore generate a map of Δts to aid source location in complex metallic structures. The “Delta T Mapping” methodology [9, 10] generates contour maps of constant Δt for each sensor pair, linearly interpolating between grid points to improve resolution. Map contours corresponding to measured Δts from test data can then be selected for each sensor pair and overlaid to find a crossing point and hence a prediction of source location. Hensman et al [4] followed a similar methodology, but chose to represent the relationship between the Δts and the spatial grid using Gaussian processes. These mapping approaches have been shown to improve source location accuracy in metallic structures with complex geometries and composite materials. In this paper the “Delta T Mapping” methodology is utilised to improve AE source location accuracy of artificial AE sources and impact events in composite materials.

3 Delta T Mapping

3.1 Arrival time estimation

The accurate arrival time estimation of an AE signal is paramount to ensuring accurate location calculation. In this work the AIC based approach, discussed above, is used and involves the minimisation of equation (1) below.

$$AIC(t) = t\log_{10}(\mathrm{var}(x[1;t])) + (T - t - 1)\log_{10}(\mathrm{var}(x[t;T])) \qquad (1)$$

The signal is split into two parts, that from time 0 to time “t” and that from time “t” until the end of the signal. Equation (1) describes the similarity in entropy between two parts of the signal, for every time “t” throughout the signal duration. When “t” becomes aligned with the onset of the signal, the minimum similarity is observed between the high-entropy uncorrelated noise prior to signal onset and the low-entropy waveform showing marked correlation after signal onset. Hence the minimum of the AIC function corresponds to the signal onset time, as can be seen in Figure 1.

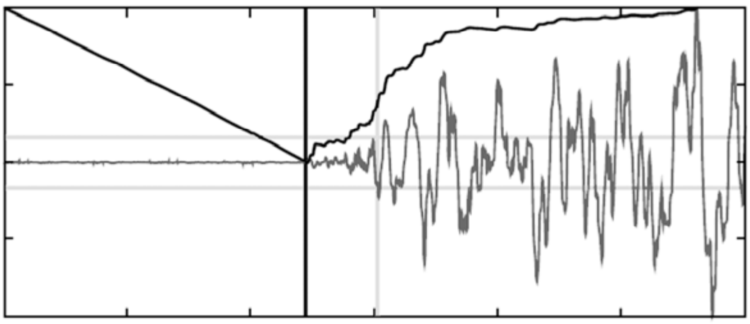


Figure 1. . Arrival time estimation using AIC based approach. The vertical grey line indicates the threshold based arrival time. The black trend is the AIC function and the vertical black line indicates the estimated arrival time at its minimum.

3.2 Location calculation

The "Delta T Mapping" methodology discussed above has 5 associated steps, which are outlined briefly below:

Determine area of interest - Delta-T source location can provide complete coverage of a part or structure, or it can be employed as a tool to improve source location around specific areas of expected fracture, which could potentially be identified via finite element modelling.

Construct a Map System - A grid is placed over the area of interest within which AE events will be located. It should be noted that sources are located with reference to the grid and not the sensors and it is not required that sensors be placed within the grid.

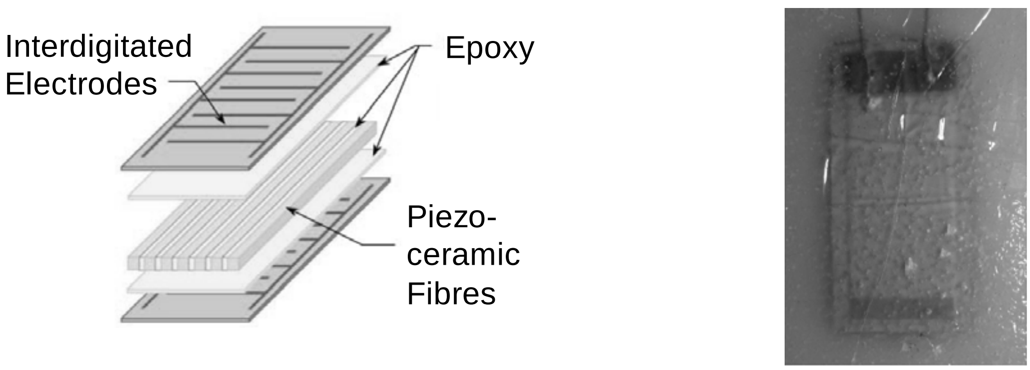
Obtain time of arrival data from an artificial source – An artificial source (nominally a H-N source [11, 12] is generated at the nodes of the grid to provide AE data for each sensor. An average result of several sources is used for each node. Missing data points can be interpolated from surrounding nodes.

Calculate DeltaT map – Each artificial source results in a difference in arrival time or Delta T for each sensor pair (an array of four sensors has six sensor pairs). The average Delta T at each node is stored in a map for each sensor pair. The resulting maps can be visualised as contours of constant DeltaT.

Locating real AE data – The DeltaT values from a real AE event are calculated for each sensor pair. A line of constant DeltaT equivalent to that of the real AE event can then be identified on the map of each sensor pair. By overlaying the resulting contours, a convergence point can be found that indicates the source location. As with time of arrival, a minimum of three sensors is required to provide a point location and more sensors will improve the location. In theory all the lines should intersect at one location, however in practice this is not the case. Thus a cluster analysis is used to estimate the most likely location.

4 Macro-Fibre Composite Transducers

Macro-fibre composite (MFC) transducers are a piezoelectric transducer manufactured by Smart Materials Corp. Unlike monolithic piezoceramic devices they are constructed from piezoceramic fibres with a square cross-section. The fibres are aligned and held in a structural epoxy that is sandwiched between polymide film with printed interdigitated electrodes. Originally designed as actuators the transducers are more recently finding applications as sensors and energy harvesters. To reduce electrical noise in sensing applications the MFCs are supplied with a very thin film of a copper/tin alloy to provide shielding. Due to their thin profile (~0.3 mm) the MFCs are readily embeddable within the layers of a laminate composite.



a) b)

Figure 2. MFC transducers a) schematic of construction and b) embedded in glass fibre composite laminate.

5 Experimental Procedure

A 500 x 550 mm composite panel was manufactured from Amber Composites E644 satin weave material with a (0,90) lay up (Figure 3). Four MFC transducers were embedded between the two central plies in 300 x 300 mm square array (highlighted by white dashed lines) at the centre of the panel and then cured in an autoclave at ***^{o}C. Following manufacture a 300 x 300 mm grid with 50 mm resolution was applied to the panel to assist the collection of Delta T Mapping data and 5 H-N sources were recorded at each grid point. Following calculation of the Δt contour maps, five arbitrary locations were selected to assess the performance of the Delta T Mapping methodology and they are represented in Figure 3 by + symbols. The points were deliberately chosen such that they did not align with any of the grid points used in the mapping phase and five H-N sources were recorded at each and there location calculated using both the TOA and Delta T Mapping methodologies.

Finally a series of 15 impact events were conducted at a single location upon the panel, indicated by the X symbol in Figure 3. During impact the panel was supported between two square supporting frames (Figure 3) leaving a *** x *** mm unsupported area indicative of a realistic composite structure. The panel was impacted using a fully instrumented Instron Dynatup 9250HV impact test machine. The impactor mass was 5.91kg with a 16mm diameter hemispherical impact tup. The impact energies used and the corresponding drop heights are detailed in Table 1.

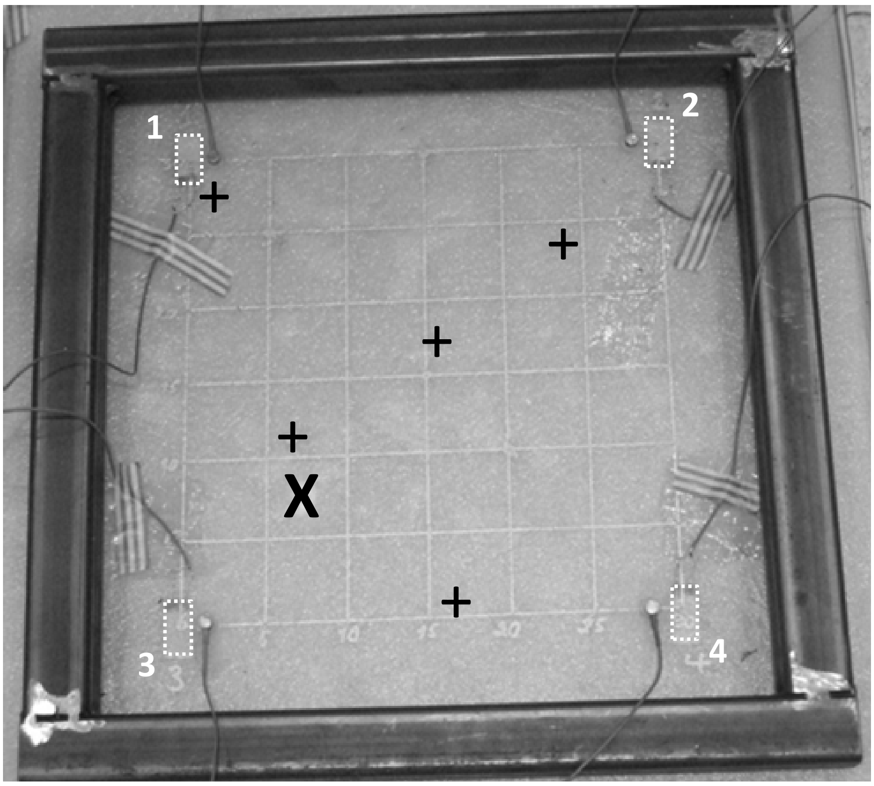


Figure 3. Embedded sensor panel and supporting frame with sensor positions highlighted by dashed white lines and positions of artificial sources (+) and impact location (X) identified.

Impact n°	Impact Energy [J]	Drop Height [m]	Impact n°	Impact Energy [J]	Drop Height [m]
1	4	0.069	9	12	0.207
2	4	0.069	10	14	0.241
3	4	0.069	11	18	0.310
4	5	0.086	12	22	0.379
5	6	0.103	13	26	0.448
6	8	0.138	14	30	0.517
7	10	0.172	15	34	0.586
8	10	0.172			

Table 1. Details of impact events.

6 Location Results

The location results from artificial H-N sources conducted at arbitrary positions on the panel are presented in Figure 4 for both location methodologies, clearly demonstrating the use of embedded MFC transducers for detecting AE signals. It can be seen in the case of position 2, 3 and 4 that location accuracy is high for both location techniques, however the Delta T Mapping technique is seen to be slightly more accurate and have less scatter. In the case of position 5 a clear improvement in location accuracy can be observed and at position 1 the Delta T Mapping locations are still accurate whereas the TOA locations are several hundreds of mm away and outside of the area presented. Table 2 details the RMS location error for each of the 5 positions; demonstrating that for positions 2, 3 and 4 the TOA errors are generally low, however, the Delta T Mapping still offers an improvement in all three cases. For position 5 a more significant reduction in RMS error from 34.3 to 5.4 mm is seen when using Delta T Mapping and most significant of all a reduction in RMS error from 451 down to 10.8 mm for position 1. This demonstrates that although the TOA location technique can achieve a high level of accuracy in certain areas of the sensor array it does not perform consistently throughout. A problem that is likely to increase with the introduction of more complex layups or geometry. Whereas the Delta T Mapping approach provides consistently accurate location throughout the sensor array.

Position n°	TOA RMS Error [mm]	Delta T Mapping RMS Error [mm]
1	451.630	10.844
2	4.551	3.050
3	8.561	3.277
4	15.898	6.717
5	34.306	5.363

Table 2. RMS location errors for H-N sources

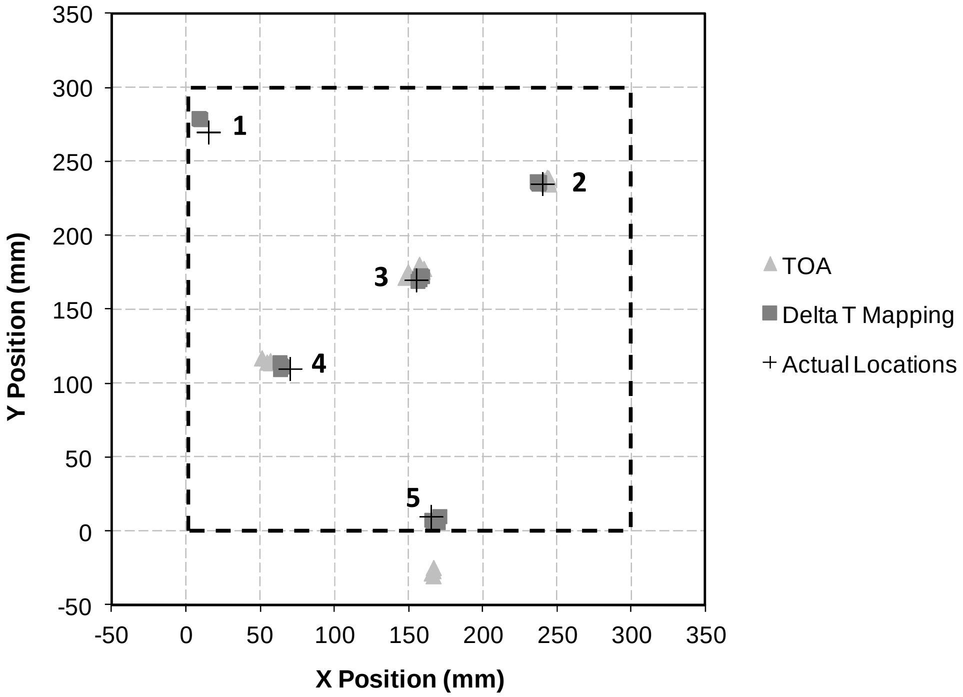


Figure 4. Location results for artificial H-N sources. The area of interest is indicated by the dashed black line.

The location results from the impact testing of the panel are presented in Figure 5. Both methodologies demonstrate good accuracy but as was the case for the artificial sources the Delta T Methodology appears to be slightly more accurate with less scatter. The RMS errors for the TOA and Delta T Mapping techniques are 11.02 and 4.37 mm, respectively, confirming the observations in Figure 5.

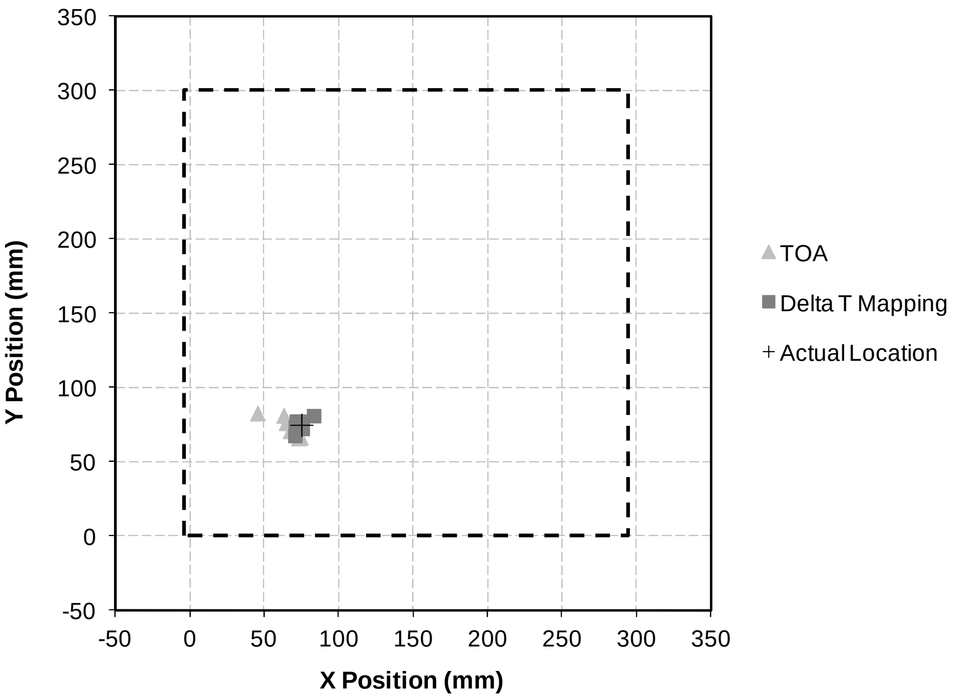


Figure 5. Location results for impact events. The area of interest is indicated by the dashed black line.

7 Conclusions

Four MFC transducers were successfully embedded within a glass fibre composite laminate creating a self sensing panel that was used to detect and locate acoustic emission signals from artificial and impact sources.

The Delta T Mapping location algorithm was demonstrated to reduce the RMS location error in all cases when compared with TOA results. The high level of accuracy achieved using the Delta T Mapping approach was also seen to be consistent throughout the sensor array, unlike the TOA approach which exhibited very large errors in some positions.

The potential for the AE technique to be used in SHM applications for large-scale composite structures such as composite aircraft and wind turbines has been demonstrated. Additionally the potential to embed low profile transducers in composite laminates for AE monitoring has been demonstrated, creating "self sensing" structures.

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