On the Development of a Damage Detection System using Macro-fibre Composite Sensors

R Pullin1, M J Eaton, M R Pearson, C Featherston, J Lees, J Naylon, A Kural, D J Simpson and K Holford
Cardiff School of Engineering, Cardiff University, The Parade, Newport Road, Cardiff, Wales, UK, CF24 3AA

Abstract. Macro-fibre composite (MFC) sensors, originally developed as actuators by NASA, have been investigated for three components of a damage detection system for composite structures; actuation, sensing and energy harvesting. MFC sensors are constructed from piezoelectric fibres embedded in an epoxy matrix and offer greater flexibility than traditional sensors for embedding due to their low profile and low weight. It is proposed that embedded MFCs could be used to act as damage detectors, whilst energy either transmitted ultrasonically or harvested ambiently could be used to power the system. To assess the applicability of the MFCs a scale A320 composite wing was manufactured. Ten MFC sensors were embedded within the wing structure. Through a series of investigations on the wing the use of MFCs as part of an acousto-ultrasonic (AU) and Acoustic Emission (AE) damage detection system were investigated. Utilising AE source location and an AU cross-correlation techniques damage induced by impact was identified. In a further experiment the capability of transmitting and harvesting energy with the same embedded MFC actuators was completed. By impedance matching it was possible to improve the transmitted power. Furthermore an analysis of the MFCs ability to capture ambient vibrations, associated with aircraft structures, was completed. The completed experimental work demonstrated that it would be possible to embed sensors, energise them through active or passive vibration, and detect damage.

1. Introduction
Structural Health Monitoring (SHM) systems offer asset managers a distinct advantage over routine maintenance programmes. The ability to complete prognosis and diagnosis during service allows increased asset use, reducing maintenance costs and furthermore structures can be designed closer to the critical limit which in the example of aircraft can reduce weight and hence emissions.

The application of SHM is critical to composite structures where Barely Visible Impact Damage (BVID) can lead to catastrophic failures. The use of composites is increasing in aerospace applications and in the manufacture of wind turbine structures where the ability to remotely monitor damage is a necessity.

Acoustic Emission (AE) and Acousto-Ultrasonics (AU) offer a real possibility for an SHM system. AE is the most sensitive form of Non-Destructive Testing (NDT) and utilises an array of sensors to detect and locate the stress wave emitted due to damage propagation. AE can be regarded as a passive NDT technique. The AE technique has been applied previously to identify impact damage [1], matrix cracking [2] and delamination and damage growth in composites. AU utilises a pulse and receive

1 pullinr@cardiff.ac.uk

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approach for damage detection. The approach uses the same AE sensor array and is used to validate any detected and located AE sources. AU is often referred to as an active technique.

Any SHM system should ideally be embedded. The structure itself then acts as protection to environmental damage and limits the possibility of being damaged during routine service. Traditional piezoelectric sensors are not suitable for this application due to their geometry. In addition to prevent extra weight being added to a structure through cabling energy harvesting (EH) can be incorporated. EH can be active or passive depending if ambient vibrations are captured and converted to energy or whether energy is transferred through the structure using ultrasonic vibrations.

Macro-fibre composite (MFC) transducers are a piezoelectric transducer manufactured by Smart Materials Corp [3]. Unlike traditional piezoceramic sensors 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 a polyimide film with printed interdigitated electrodes (Figure 1). To reduce electrical noise in sensing applications the MFCs are supplied with a very thin film of a copper/tin alloy to provide shielding.

![Figure 1: Schematic of MFC sensor and MFC embedded in glass fibre and carbon composite laminate.](image)

2. Embedded MFC Carbon Wing Manufacture

A two part wing mould was designed and manufactured at Cardiff School of Engineering. The two parts of the wing were fabricated using four layers of woven carbon fibre (CFRP) and glass fibre (GFRP) composite with a 0-90º layup. Ten shielded MFC sensors (28x14 mm) were embedded between two GFRP plys to give a stacking sequence of CFRP, GFRP, sensors, GFRP and CFRP. Embedding the MFC between the GFRP avoids grounding loop issues. The wing parts were then cured in the University autoclave. Post manufacture, the embedded wing was c-scanned to ensure no damage was present. Finally stiffeners made from CFRP/Nomex honeycomb were added.

![Figure 2: Schematic of wing showing embedded sensors (rectangles) and impact location (circle)](image)
3. Experimental Procedure

Prior to impact testing background AU baseline data was captured. A series of signals were pulsed from each MFC and captured at the remaining sensors [4]. In addition a novel AE source location technique, AIC-delta-T [5,6], was used to identify damage. The technique utilises a ‘touch and learn’ mapping approach to identify the damage position. To assess the performance of the novel approach against the traditional approach artificial sources [7] were created at various points. The wing was then subjected to increasing impact events (2.3-6J) using an instrumented impact test machine. Impact testing was stopped once damage was observed on the inner face of the wing. AE was recorded throughout all impacts and post damage a further set of AU results were captured and the wing C-scanned again. A disbonds of 100m² was identified. To assess the ability of the embedded MFCs to harvest both active and passive energy two further experiments post impact were completed. Initially a 20 V peak to peak signal over a frequency range of 10-200 kHz was used to drive one transducer whilst energy was captured at the remaining sensors. The use of inductors to impedance match the devices at 65kHz was also used. Finally, based on real flight data, the wing was subjected to vibrations of 10-400 Hz and the energy harvested.

4. Results and Discussion

The results of the AE source location investigation using the embedded sensors is shown in Figures 3 and 4. It is evident from the results that in the majority of cases the novel approach outperforms the traditional method. The traditional approach assumes a single propagating velocity which is not the case in composite materials.

![Figure 3: Comparison of AIC delta-T and time of arrival AE source location of artificial sources](image)

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Figure 5 presents waveform traces captured by the closest MFC from non-damage and damage inducing impact events. Superimposed over the waveforms is the load trace from the impact event. The load trace on the right hand image shows distinct drops, beyond the noise, indicating damage which coincides with an increase in the waveform amplitude. It is therefore clear from the plots that it is possible to identify when damage has occurred.
Figure 4: Comparison of AIC delta-T and time of arrival AE source location of impact

Figure 5: Comparison of waveforms recorded during non-damage (a) and damage impact events (b)

Figure 6 presents the AU results using the sensor closest to the impact position pulsing and the nearest four embedded sensors receiving. Channel 6 is a commercial sensor surface mounted for comparison. Three sets of data are presented, the cross correlation coefficient of the pre damage data set (black), the post damage data set (grey) and the post damage compared with the pre damage data set (white). A value of unity for the cross correlation coefficient indicates that two data sets are identical, whilst a value less than unity indicates a difference in the two sets [4]. By comparing the initial waveform recorded before impact with the waveform post impact an indication of damage can be found. It is evident from Figure 5 that damage has occurred in the structure.

Figure 7 shows the results of the active energy harvesting experiment. The power transmitted through the MFC is presented alongside the received power. It can be seen that the experimental results closely matches a simulation model developed at Cardiff, that forms part of a larger research programme [8].
The results demonstrate that 118 µW can be transmitted for a drive of 20V peak to peak. Although this initially appears low it should be remembered that each MFC is receiving power of this magnitude and that the embedded devices have not yet been optimised. Furthermore the drive voltage could be significantly increased.

Figure 7 presents the results of the passive harvesting experiment. As stated the wing was excited at 10-400Hz (aircraft data). It can be seen from the figures that 12µW peak and 5µW rms power was harvested from the MFC closest to the impact due to the vibration source. Again the MFC position has not been optimised for this geometry; however a numerical method to achieve this is currently being investigated. Currently 170 mW of power is required to use the MISTRAS Group wireless AE system. There is clearly a power gap between what has been investigated within this experimental program and what is currently required. However the MISTRAS system has been designed for bridge structures and could be further optimised electronically to increase efficiency. Furthermore the powers found here are worst cases. The position and size of the harvesters have not been optimised and the drive voltage could be increased. To ensure that a system could be installed within a wing structure a number of other aspects need investigating. Wireless technologies will be integrated to ensure data can be transmitted. In addition to vibrational sources, thermal gradients exist during flight cycles and these
could be used to generate further power to reduce any gap. However to complete this an effective power management systems would be required. This is currently being investigated at Cardiff.

![Figure 7: Passive energy harvesting](image)

**5. Conclusions**
The completed research program on a composite wing with embedded MFCs has demonstrated true potential. Impact locations can be accurately located with a novel AE method whilst damage can be identified using both AE and AU. Furthermore the powering of an SHM system has been explored through active and passive harvesting. Further work needs to completed on power management and wireless technologies to ensure a full embedded system can be created.

**6. Acknowledgements**
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