Impact Damage Detection and Assessment in Composite Panels using Macro Fibre Composites Transducers

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Abstract. Structural health monitoring of composite components is vital to the use of these materials in aerospace applications. Being highly susceptible to impact damage, composite materials can sustain internal damage that is very difficult to detect externally. This paper explores the use of macro fibre composite (MFC) transducers not only to detect acoustic emission (AE) released during the impact event but also as pulse/receivers to further quantify damage. To assess the dual functionality of these transducers, two were adhered to a composite panel and subjected to a number of impacts. A commercial AE system recorded signals during the impact event. After each impact, signals were pulsed and received between the two transducers and a C-scan inspection of the panel was conducted to assess the extent of the damage. Post test analysis demonstrated a clear correlation between the AE signal energy and the increase in delamination size. Furthermore, a cross correlation technique was utilised to compare signals in the undamaged plate with those at varying damage levels. The results demonstrated a decreasing correlation of signals with increasing damage severity. The results have shown that MFC transducers offer a real possibility for identifying and sizing impact damage in composite structures.

1. Introduction
Structural health monitoring (SHM) techniques allow a structure to be continuously monitored by the use of permanently mounted/embedded transducers on the structure. Such a system can detect the deterioration of the structure and alert the user that action is required. The advantages of a SHM system for aerospace applications is that it enables early identification of damage and consequent reduction in the structural performance, leading to lighter components and a reduction in the amount of exhaust emissions. A further advantage is that it could vastly reduce the amount of scheduled and un-scheduled maintenance which is currently undertaken on an aircraft, as a SHM system could advise on the damage status and remaining life of certain components. SHM of composite materials is essential for the use of these materials for aerospace applications. Composite materials can often suffer internal damage which vastly reduces the life of the structure; they are also susceptible to flaws within the material being introduced during the manufacturing stage; both these aspects could substantially reduce the life of a component. Moreover composite materials are highly susceptible to impact damage which leads to delamination of the plys, which is often very difficult to detect externally and can lead to a dramatic reduction of design strength and service life. In summary a SHM could remove the uncertainties that are present in the design and implementation of composites in an aerospace application leading to optimised structures.
Two fundamental techniques that could be used for a SHM system are Acoustic Emission (AE) and Guided Lamb waves (GLW). AEs are stress waves generated by mechanical deformation of materials. In terms of damage assessment AE is related to different damage mechanisms within a material releasing small amounts of energy that travel within the material in the form of ultrasonic stress waves. AE is seen as a passive approach where ultrasonic stress waves propagate through the material causing small displacements on the surface; these small displacements are detected by transducers using the piezoelectric effect.

Acousto-ultrasonics (AU) is another damage assessment technique that uses the fundamentals of guided lamb waves (GLW). Lamb waves are essentially elastic waves that propagate in a solid media where the motion is determined by the plate normal and the propagation direction, the term guided refers to a Lamb wave restricted in a real object. The GLW technique is seen as an active approach, exciting the structure and detecting changes in the received waveforms due to reflections and wave scattering from flaws within the material.

Macro Fibre Composites (MFC) transducers are types of composite piezoceramic transducer more commonly known as active fibre composites (AFC). There are many different types of AFC transducer and many use piezoelectric elements as their active element. Their main advantages over piezoelectric crystals are that piezoelectric fibres have much higher strengths when compared with monolithic wafers of the same materials and that the fibres are also less brittle and have an increased damage tolerance due to their inclusion within a polymer matrix. MFC transducers use rectangular piezoceramic materials that are sliced from a larger monolithic wafer. The piezoceramic fibres are held in a structural epoxy which inhibits crack growth in the fibre and bonds the transducer together. Interdigitated electrodes are placed on the top and bottom surfaces of the fibre epoxy matrix, which in a sensing application enables the voltage to be transferred from the piezoceramic fibres. There are two types of MFC transducer the P1 and the P2, the difference between the two types is in the direction that they are poled. The P1 types have alternating polarities of interdigitated electrodes on the top and bottom surfaces of the fibre epoxy matrix, this permits poling of the fibres along their length between the positive and negative terminals on both surfaces, while the P2 types have a positive electrode on the top surface and a negative electrode on the bottom surface and this permits poling through the thickness of the fibres.

The use of AFC transducers for SHM applications is well established, Schulz et al [1] developed an AFC transducer in the form of a tape, the advantages of using interdigitated electrodes meaning that the AFC tape can be divided into several sections effectively allowing multiple sensors on just one acquisition channel. The segments in the transducer could also be spaced in order to act as a frequency filter which is advantageous in damage detection.

Park et al[2] demonstrated the use of a instantaneous baseline detection for a SHM system which collected baseline waveforms each time the structure was interrogated. By monitoring all the transmission paths in an array, any changes in received signals due to damage could be detected. This eliminated any environmental changes which could affect the baseline data. This technique was successfully used in a pitch-catch scheme to detect damage within the array and a pulse-echo scheme which detected damage outside of the array.

A cross correlation technique was developed by Zhao et al[3] for monitoring complex geometries. A circular array of PZT discs were implemented on a wing panel and a cross correlation analysis was used to detect changes in the received waveforms from a normal to a damaged state. Tracking the magnitude of the change in a signal enabled the monitoring of damage growth. To determine the location of the damage the system assumed the probability of a defect occurring at a particular position based on the severity of signal changes between different transmission paths in the array.

Wagner et al [4] compared several conventional AE sensors and non-conventional piezoelectric transducers with regard to their performance in impact damage detection. The conventional AE sensor manufactured by Vallen and PAC and a SMART Layer manufactured by Acellent all performed well, a polyvinylidene fluoride (PVDF) foil sensor performed the worst.
Markmiller and Change [5] developed a sensor location optimisation method to maximise the performance of an impact detection SHM system with the fewest sensing elements. The system was analysed on the probability of detection (POD), this was optimised to give the maximum POD for optimal sensor location. A genetic algorithm was integrated into a SHM system to enable the optimisation process.

Wang and Chang [6] developed an active diagnostic technique for detecting and locating impact damage in a composite plate. The proposed system utilised a network of piezoelectrics as both actuators and sensors. Detecting a scattered wave from damage by using a baseline subtraction method and performing a joint time frequency analysis (spectrogram) it was possible to determine the arrival time of the scattered wave. The location can be determined from the measured time differences. The damage size can also be estimated by minimising differences between measured arrival and calculated arrival times of scattered waves.

Tracy and Chang [7] developed a computer program to identify impact force and its location in a composite plate. The method utilised a system model identifying the dynamic response of the plate and a response comparator to estimate impact location and force history. Two iterative steps are used to determine the impact load and force history, firstly estimating the impact force-time history by selecting a random impact location. The response comparator performs an optimisation based on least square fitting which generates the impact history, minimising the error between calculated and measured outputs, this enables a figure of merit to be determined. The process continues until the figure of merit is reduced to a minimum.

Guyomar et al [8] demonstrated a passive method of locating impact damage using piezoelectric elements. The proposed method was based on power flow of the wave generated by an impact. Propagation and energy balance models were utilised to create an analysis that would enable the impact location to be determined. Using piezoelectric patches each coupled with a resistor, converted electric energy could be monitored, as the wave propagates past further patches more energy is converted to electrical energy. Assuming that each patch converts the same ratio of energy it is then possible to determine impact location by comparing the energy dissipated at each resistor.

Schubert et al [9] studied the interaction of Lamb Waves in carbon fibre panels with impact damage for the application of AU techniques. Piezoceramic fibres were used to generate fundamental S₀ and A₀ Lamb waves and a scanning vibrometer was used to compare damaged and undamaged panels to determine changes in their fundamental modes. The out of plane parts of the S₀ and A₀ have the greatest interaction with the impact damage, also the interaction of the A₀ mode with the impact damage creates a time delay in that part of the wave when compared to an undamaged panel. Therefore amplitude ratios and the time delay of the A₀ mode could be used to detect impact damage.

This paper builds on the previous reported work and presents the findings of an initial investigation into the use of a cross correlation technique to detect damage within a carbon fibre re-inforced plastic panel (CFRP). Further investigation was undertaken to detect impact damage in a CFRP panel using both an active (AU) and passive (AE) health monitoring techniques.

1.1. Cross Correlation Technique

Cross correlation can be used as a signal processing technique to determine how similar two particular waveforms are to one another. In this work the “xcorr” function in MATLAB was used to firstly conduct an auto correlation which gave the maximum integral of the product of the waveforms at zero delay and this was then used as a normalisation for the remaining cross correlations. For example two exact waveforms with no delay between them would give a normalised cross correlation coefficient of 1. The cross correlation function alters the phase of one of the signals with respect to the other, the phase shift is altered for each sample and the integral of the cross product of the two waveforms is calculated for each phase shift. The phase of the waveforms is changed until the maximum integral of the product is realised, this results in a correlation value when the signals are the most similar, which is normalised against the auto-correlation of the original signal.
2. Experimental Set-up

2.1. Preliminary Investigations
An initial investigation was conducted to establish the sensitivity of the cross correlation technique in detected changes in the received waveforms due to the presence of damage. A carbon fibre panel was manufactured from 8 plies of 0-90 woven CFRP manufactured by Cycom with the following material code 950-1a-t650-39%-316-1270. The panel dimensions were 500mm x 500mm and 2mm thick.

Two Physical Acoustics Corporation (PAC) Nano-30 sensors were adhered to the panel using a Silicon RTV (Loctite 595) and left to cure for 24 hours; the configuration on the panel can be seen in Figure 1. Table 1 shows the location of the transducers and the damage site with reference to the bottom left hand corner of the panel. A PAC Microdisp with an incorporated wave generation board was used to pulse a 150V square wave through one of the Nano 30s, the other recorded the resulting waveform in the plate. This was conducted at three different frequencies of 100, 300 and 500kHz. 100 waveforms were recorded when there was no visible damage in the plate and these formed the baseline waveforms which formed the basis of the cross correlation analysis. Damage was then introduced along the centre line between the sensors using a drill, and the drill bit size was increased from 1mm to 13mm. After each damage state was introduced into the panel another series of 100 waveforms were recorded, using the same pulse/receive configuration, and this procedure was repeated for each drill bit size. The cross correlation technique was then used to correlate waveforms that were collected at each damage state and to correlate the waveforms at each damage state to that of the baseline waveforms.

Table 1. Location of the transducers on the panel from the reference corner of (0,0)

|            | x location, mm | y location, mm |
|------------|----------------|----------------|
| Nano30 1   | 135            | 240            |
| Nano30 2   | 412            | 240            |
| Damage Site| 250            | 240            |

Figure 1. Experimental set-up for the preliminary investigations

2.2. Impact Testing
A further investigation into damage detection using both AE and AU techniques for known impact forces was completed. Another carbon fibre panel was manufactured with same dimensions and from the same material. Two M2807-P2 MFC transducers, which are P2 MFCs with an active area of 28x7mm and a PAC Pico were adhered to the panel using cyanoacrylate; this configuration can be seen in Figure 2. Table 2 shows the location of the transducers and damage site measured from the bottom left hand corner as a reference of (0,0).The panel was scanned using a C-scanner to see if there were any defects in the material. A test bed was fabricated to place the panel underneath the impact machine and the panel was clamped around the unsupported area in the middle of the test bed, this is shown in Figure 3. An Instron Dynatup 9250HV was used to subject the panel to a number of 4J impacts based on an impactor weight of 5.75kg and a velocity of 1.14m/s. An energy of 4J was used to slowly progress the damage in the plate. During the impact event all three transducers were used to record AE using a PAC PCI-2 system. After each impact the two MFC transducers were used to collect waveforms for the cross correlation technique a 60V square at 100kHz was pulsed to one of the
transducers and the other recorded the resulting waveform using the same PCI-2 system after each subsequent impact the plate was C-scanned for damage. As previously described a series of baseline waveforms were recorded when there was no damage in the plate. Firstly the cross correlation technique was used to compare the waveforms recorded after each impact with its own data set and the waveforms at each damage set were then compared with the baseline waveforms.

Figure 2. Experimental set-up for the impact investigations

Figure 3. Clamping arrangements for the impact investigations

Table 2. Location of the transducer and damage site for the impact investigation measured from the reference point of (0,0)

| Channel 1 (MFC 1) | 135 | 250 |
| Channel 2 (MFC 2) | 365 | 250 |
| Pico            | 250 | 210 |
| Damage Site     | 250 | 250 |

3. Experimental Results and Discussion

3.1. Preliminary Investigation

Figure 4 shows the average cross correlation coefficients calculated from a series of 100 waveforms cross correlated within each data set at each damage level at three different frequencies of 100, 300 and 500 kHz. This figure shows that the waveforms recorded within each data set are almost identical demonstrating that the source is very repeatable. This provides confidence that any changes in the cross correlation coefficient when the waveforms are compared with the baseline waveforms is due to the presence of damage and not because of changes in the pulse/receive configuration.

Figure 5 shows the cross correlation coefficients calculated from a series of 100 waveforms. This time the waveforms were cross correlated to the first baseline waveform therefore allowing any damage in the plate to be detected due to a change in signal propagation as a result of the change in structure. Examining the results of the 100kHz signal in Figure 5 demonstrates that this frequency pulse detects the damage introduced using the 1mm drill bit the best as it has the largest change in cross correlation coefficient. This is due to the size of the defect and the wavelength of the pulsed wave. However the 100kHz pulse does not detect the changes in signal at larger defect sizes as well as the other two frequencies. The 300kHz signals detected the greatest change in the received waveforms, overall this is most likely because the frequency pulse of the wave was close to the resonant frequency of the Nano 30 itself resulting in more energy being input into the plate. All the cross correlation coefficients for the three different frequencies show an approximate linear relationship with a decreasing trend from 0 to 10mm drill bit size, however there is a relatively large decrease in cross correlation coefficient using a 13mm drill bit size, this may have arisen due to delamination or fibre...
breakage occurring using the larger drill bit size in the area surrounding the hole. Unfortunately an empirical relationship cannot be drawn between the change in cross correlation coefficient and overall damage due to the drilling process.

Figure 4. Average Cross correlation coefficients of the waveforms collected after each drill bit size and compared within each data set.

Figure 5. Average Cross correlation coefficients of the waveforms collected after each drill bit size and compared with the baseline waveforms.
3.2. Impact Tests

3.2.1. C-Scan Results. Figure 6 shows the C-scan results after the first impact of 4J based on the drop height and weight of the impactor, the initial impact caused a delamination area of 66mm². The C-scan images from the second impact of 4J is shown in Figure 7, the figure shows the second impact further increases the delamination area to 320mm². The third impact of 4J again further increases the delamination area to an approximate area of 520mm², this is shown in the C-scan image in Figure 8. The C-scan results shows the progression of damage in the form of delamination from the repeated impacts in the centre of the carbon fibre panel, the C-scan results were used as a method of quantifying the damage in the plate as a function of the delamination area.

3.2.2. AE Results. Figure 9 shows the acoustic energy of the detected signal attributed to the impact damage in the plate, the acoustic energy is the energy contained within that particular AE waveform. The figure shows the acoustic energy for each of the three channels. Channel 1 and 2 were the MFC transducers and channel 3 was the PAC Pico transducer. The acoustic energy is correlated against the change in delamination area between the impacts and shows an approximate linear trend for all three channels, showing the energy of the impact AE waveform is closely related to the increase in delamination area. Channel 1 (MFC 1) shows the most linear trend between acoustic energy and the change in delamination area demonstrating a relationship between energy released by the impact and the extent of the resulting damage. The energy of the first impact is much lower than the other two channels and for the subsequent impacts this channel indicates the highest energy. This could have arisen from uneven clamping force on the unsupported area and the clamping arrangement causing superimposed reflections in the AE waveform. Channel 2 (MFC 2) shows the same trend but it is not as pronounced as channel 1. The acoustic energy of the first impact is one of the highest but is considerably lower for the other impacts this is more likely than not due to attenuation of the signal in that direction and again due to uneven clamping force on the plate. Channel 3 (Pico) was placed in the unsupported area in the centre of the panel and would expect to see the highest energy for all three impacts, however this is not the case, this is due to the reflection for this example having to travel the furthest and therefore not having the same level of superposition on the AE waveforms. Again for channel 3 the relationship is approximate linear and could enable a certain estimate of the delamination area present. It is difficult to further determine the confidence in this relationship as only 3 impacts occurred before significant damage was introduced in the plate. A further study would be necessary to progress the damage more slowly. However if the sensor configuration changed the acoustic energy trends would also change due to attenuation and the location of the sensors to the damage.
3.2.3. AU Impact Results. Figure 10 shows the average cross correlation coefficients of the waveforms recorded as the baseline and after each impact. These particular waveforms are cross correlated to the first waveforms within their data set. For example the first baseline waveform was used to correlate the baseline waveforms. The cross correlation coefficient is now correlated against the delamination area as this was quantified after each impact using a C-scanner. This figure shows that the repeatability of the pulse/receive configuration for each data set is very high, the maximum error from the figure is 0.00065. This gives a large confidence level that the waveforms that are recorded as a new data set are very similar and there is no significant change in these waveforms, therefore suggesting the pulse/receive configuration has not altered.

Figure 11 shows the average cross correlation coefficients for a 100 waveforms when correlated to the baseline waveforms and shows that as delamination area increases there are changes in the waveforms when compared with the baseline waveforms. The changes in the waveforms after each impact must be due to the presence of damage because the waveforms collected within each data set are almost identical showing the source is repeatable. The cross correlation coefficient becomes less as the impact damage increases, at the largest delamination area of 520mm² the average cross correlation falls to 0.8, showing that this technique can detect damage in this configuration. This technique also demonstrates the ability to detect small delamination areas, however after the first impact which caused a delamination area of 66mm² the cross correlation coefficient falls from 0.999625 to 0.997448. Although this fall in correlation lies outside the maximum error of 0.00065 found in each data set, careful consideration would be necessary in order to deduce that damage is present. It also depends on the application, in some cases a delamination area of 66mm² maybe seen as not crucial however in the cases where any level of damage needs to be detected the cross correlation technique may not be best suited.
Figure 10. Average Cross Correlation the baseline and impact damage waveforms correlated within each data set.

Figure 11. Average Cross Correlation the baseline and impact damage waveforms correlated to the baseline waveforms.

4. Conclusions

4.1. Preliminary Investigation
The AU technique utilising a cross correlation technique for damage detection investigations demonstrated a very simple technique for the detection of damage within a composite plate. The
findings show that the cross correlation technique could detect a change in the signal even when a 1mm drill bit was used. Overall the 300kHz signal was the best for detecting damage and this is probably due to the frequency of the pulsed wave being close to the resonant frequency of the sensor. Also the frequency which the energy travels in the plate due to the thickness of the specimen will also have an effect. However no quantification of damage size and fall in cross correlation could be drawn because the amount of damage was not known.

4.2. Impact Tests
The passive and active health monitoring of carbon fibre panels subjected to impact damage has been demonstrated. Both the AE and AU techniques were able to detect damage in the form of delamination area, quantification of the damage was enabled by utilising a C-scanner. The cross correlation technique was able to detect changes in the received waveforms due to the presence of a delamination, however further work is required to improve the sensitivity of this method, as significant changes in the cross correlation coefficient were only found at the more significant delamination areas. An approximately linear relationship was found between the absolute energy of the impact AE waveforms and the change in the delamination area. This could allow a prediction of the approximate size of the defect area due to the energy realised. However more data would have to be collected in order to further establish this relationship.

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