Assessment of Damage Detection in Composite Structures Using 3D Vibrometry

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Abstract. Carbon fibre reinforced polymers (CFRP) have been used significantly more in recent years due to their increased specific strength over aluminium structures. One major area in which their use has grown is the aerospace industry where many now use CFRP in their construction. One major problem with CFRP's is their low resistance to impacts. Structural health monitoring (SHM) aims to continually monitor a structure throughout its entire life and can allow aircraft owners to identify impact damage as it occurs. This means that it can be repaired prior to growth, saving weight with the repair and the time that aircraft is grounded. Two areas of SHM being researched are Acoustic Emission (AE) monitoring and Acousto-Ultrasonics (AU) both based on an understanding of the propagation of ultrasonic waves. 3D Scanning laser vibrometry was used to monitor the propagation of AU waves with the aim of gaining a better understanding their interaction with delamination in carbon fibre reinforced polymers. Three frequencies were exited with a PZT transducer and the received signal analysed by a cross correlation method. The results from this and the vibrometer scans revealed 100 kHz as the most effective propagating frequency of the three. A high resolution scan was then conducted at this frequency where it could be seen that only the out of plane component of the wave interacted with the damage, in particular the A_0 mode. A 3D Fast Fourier Transform was then plotted, which identified the most effective frequency as 160 kHz.

1. Introduction

Carbon Fibre reinforced polymers (CFRP) components have many additional issues over aluminium ones, a major one being their ability to withstand impact damage and the difficulties associated with spotting said damage, due to delamination between the ply's of the material. This is becoming a serious issue in many safety critical industries, in particular the aerospace sector where they are becoming more widely used. Structural Health Monitoring (SHM) aims to continually monitor a structure throughout its entire life, both during manufacture and throughout its service life. The benefits of this over the traditional method of inspections at regular intervals is the early detection and repair of damage, leading to lighter and more efficient structures. Integration of SHM onto an aircraft structure would also lead to less down time of the aircraft, as inspection and maintenance could be conducted as and when damage was detected.

Acousto-Ultrasonics (AU) is an active form of SHM which consists of exiting ultrasonic lamb waves using a transducer bonded to a surface of the structure. This wave is then received by a sensor and by comparing the change in received signal over time using a method such as cross correlation, an indication of whether damage is present can be gained. In this work, the "xcorr" function from

MATLAB had been utilised to determine a cross correlation coefficient. This function compares two waveforms on their similarity, for example if two waveforms are exactly the same, they will have a cross correlation of 1 [1].

Zhao et al [2] utilised the cross correlation technique across a circular array of sensors bonded with a complex geometry. The sensors took turns pulsing and receiving waves and by comparing to baseline values damage could be detected and localised using a reconstruction algorithm. This test setup however required a closely spaced array with lots of sensors. Better understanding of wave propagation and interaction with damage would allow for greater optimisation of operating frequency, sensor location and a reduction in the number of sensors needed for arrays of sensors to detect damage.

The ultrasonic waves utilised for AU applications in plate like structures are known as lamb waves, which are complex elastic stress waves which propagate parallel to the surface of a solid medium throughout its thickness. These high frequency waves are able to travel long distances and are heavily influenced by damage or boundary’s, making them perfect for use in damage detection [3]. Lamb waves exist in a number of modes, symmetrical and asymmetrical, existing both in and out of plane. Symmetrical modes move throughout the structure symmetrically with respect to the mid-plane whilst extending and compressing into an elliptical shape [4]. The main symmetrical mode, S_0, tends to be dominated by longitudinal vibration, i.e. in plane. S_0 also tends to be quicker and less susceptible to attenuation (the reduction in signal amplitude as the wave propagates) than its corresponding asymmetric mode, A_0 [5]. Asymmetrical modes produce more out of plane displacement due to the waves moving in the same directions on the top and bottom surfaces [6]. In theory an infinite number of S and A modes can be present within an elastic medium, as when the frequency of the wave increases more occur [4]. Dispersion curves show the modes present within a plate and their velocities at various frequencies, Figure 1 shows the dispersion curve for a 2.15mm composite panel, similar to the ones used for the testing presented in this paper. This dispersion curve shows that the S_0 and A_0 should be the only modes present and that velocity should not change significantly up to 500 kHz.

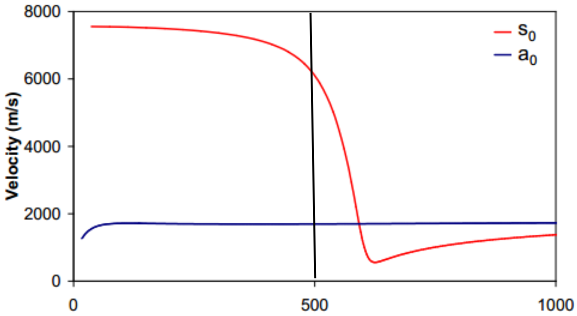

Figure 1 - Dispersion curve for a 2.15mm thick composite plate [5]

The Polytec PSV-500-3D Scanning Vibrometer is able to measure the velocity of vibration not only out of plane (Z axis), as can be measured on a standard 1D vibrometer, but also in plane (X and Y axis). Using this technology to monitor an AU system is equivalent to bonding thousands of sensors to the surface of the structure and enables a non-contact visualisation of wave propagation. The system consists of three laser heads which are alighted on the surface of the specimen and operates by analysing the change in frequency and phase caused by Doppler shift within the backscattered light from a surface. This shift is caused by changes in vibrational velocity and displacement on the surface of the structure.

Schubert et al [7] preformed a similar study using 3D laser vibrometry to analyse the interaction on lamb waves with impact damage in CFRP specimens, whilst comparing results with AU data. The results showed that only the out of plane parts of the A_0 and S_0 mode interacted with the damage and that a time delay was created when the A_0 wave front passed over the damage location.

2. Experimental Procedure

The tested specimen was manufactured from CFRP 2/2 twill with fibres running 0^0 and 90^0, eight ply's were laid in a 0/0 format. The specimen was 300mm x 300mm and 1.75 mm thick with cut edges to ensure constant reflections of the AU waves. Prior to any testing, an ultrasonic inspection was conducted with a C-Scanner, which revealed no delamination present within the specimen.

AU baseline scans were then taken using two Pancom Pico-Z piezoelectric sensors bonded to the structure, in the positions shown in Figure 2 (a), which have a high frequency response from 100-500 kHz. A five cycle square wave was used to excite the transducer at 100 kHz, 300 kHz and 500 kHz so to test the impact of the damage on a range of frequencies. A sine envelope was then applied to the generated signal as was a 5MHz filter to reduce noise. The tests were conducted 50 times and the cross correlation technique applied to these to ensure good repeatability of the received signal. Laser vibrometer scans were then conducted at each frequency to observe wave propagation in an undamaged structure. 3000 points were scanned over a 280mm x 120mm area in the centre of the plate.

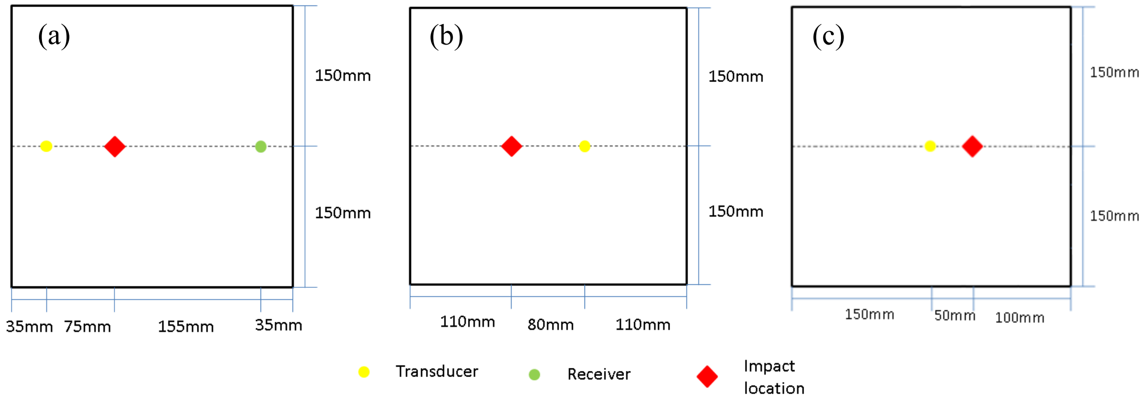

Figure 2- Layout of sensors and impact location for initial setup (a), high resolution scan (b) and second panel high resolution scan (c)

Once initial testing had been conducted, the specimen was impacted at rising energies, 4, 4, 4, 4, 5, 5, 6 and 7 joules, using an INSTRON dynatup 9250HV impact tester. The aim of these impacts was to ensure sufficient delamination was present in the structure without causing a hole to be created. The location of the impact was close to the transducing sensor, so to get a greater change in the received wave. In-between each impact AU tests were conducted, which were correlated to a baseline taken once the specimen had been clamped into the impact test rig. Though damage was visible with the naked eye a C-Scan was conducted which revealed sufficient.

After reviewing the first set of testing, it was decided that a higher resolution scan covering a smaller area would give clearer results. To reduce the reflections from the boundaries of the panel present when the wave fronts interact with the damage, the transducer was moved to the setup shown in Figure 2 (b). The same signal was used as in the first test setup, however only 100 kHz was tested due to the long period required for the scan to take place. Over 10,000 points were scanned over a 94mm × 80mm area with the damage in the center.

In order to create a 3D Matrix Fast Fourier Transform (FFT), a chirp signal was pulsed though the structure and a high resolution scan of the area around the damage was recorded. A chirp signal has a range of frequencies in this case 10-500 kHz within it; the purpose of this was to excite each frequency to see how it interacts with the damage. By taking Fourier Transforms for each frequency it was possible to see which frequencies have the most interaction with the damage. A cross section was plotted showing the magnitude of each frequency across the entire range.

The results from the 3D matrix FFT identified a frequency where wave interaction with the damage should be at its greatest. This frequency was used to produce another high resolution scan on a non-damaged panel of equal layup and size to the one used in the first set of tests. The transducer was located in the middle of the specimen, so to reduce the effect of edge reflections on the leading edge of the propagation wave as it passes over the area of interest. The impact tester applied a 9 J impact to the panel in the location shown in Figure 2 (c), which produced a delamination of similar size to the one from the initial specimen. A final high resolution scan was then conducted on the post impacted specimen.

3. Results and discussion

The initial vibrometry pre impact scans show the wave propagating through the structure with the S_0 propagation elliptically at 0° and 90°. The A_0 mode can also be seen to be propagating cylindrically at a much slower rate than the S_0 mode [5]. It was also apparent that the in plane (X and Y) plots were only observing the propagation of the S_0 mode whereas the out of plane Z axis was detecting both, but predominantly A_0. Examples of these various modes can be seen in Figure 3 where some of the 100 kHz scan plots can be seen.

By comparing the plots at each frequency it could be seen that there was little difference in wave velocity as the frequency changed, this is in line with the dispersion curve for a 2.15mm composite panel, shown in Figure 1. It was noticed however that there was far greater attenuation as the frequency increases, i.e. the rate at which amplitude drops. This is shown Table 1 which gives the amplitude of the out of plane (Y Axis) S_0 signal and the in plane (Z axis) A_0 signal for each frequency, taken from the vibrometry data in the middle of the panel.

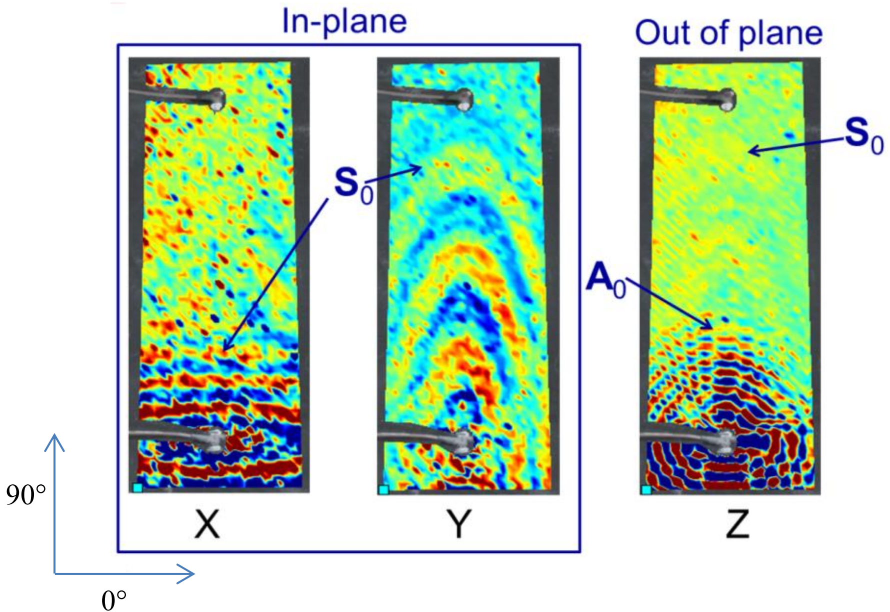

Figure 3 – 100 kHz wave in each individual axis

Table 1 – Amplitude of vibrational velocity at the centre of the specimen

Frequency (kHz)	In plane S_0 (μm/s)	Out of plane A_0 (μm/s)
100	850	540
300	800	250
500	700	200

The results of the AU tests throughout the impact testing are shown in Figure 4. It is clear from these results that 500 kHz gives the greatest change in wave correlation, however also the most un-repeatable results, due to its high standard deviation. The results show clear indication that damage is present in the structure after the 6th impact, where the correlation began to lower. The C-Scan conducted on the specimen after the impacts revealed a delamination 22mm in diameter, this compares was a visual inspection where only 13mm of damage was observed.

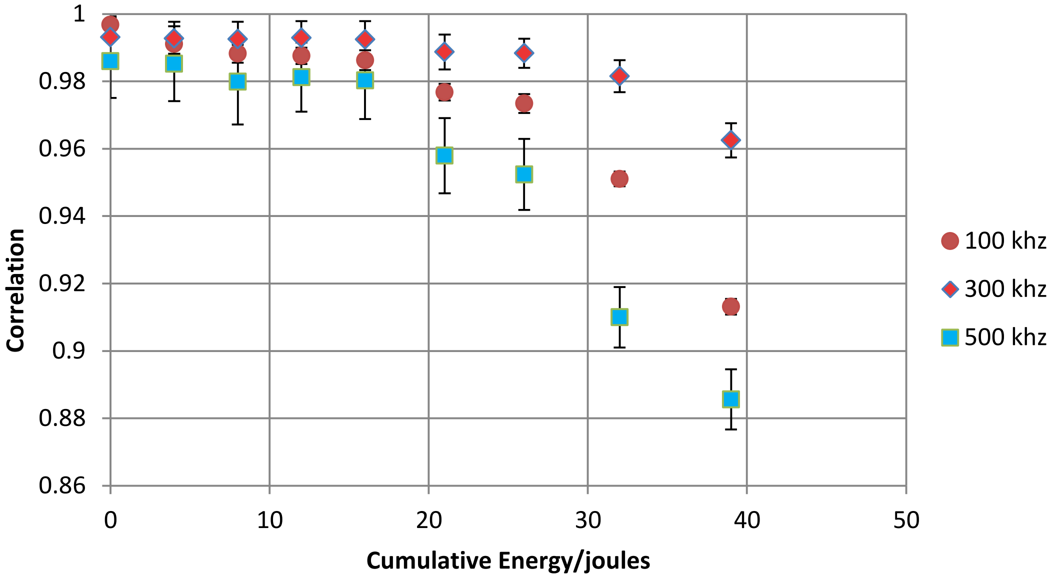

Figure 4 - AU correlation throughout impact testing with error bars showing standard deviation

The vibrometer scans conducted on the specimens after the impacts revealed that the A_0 mode could be seen to interact with the damage. Reflections were seen from the point of impact once the wave had passed over, and a changed wave front of the AU wave as it continues through the specimen was observed. This was far clearer at 100 kHz, due to the lower attenuation of the wave; however it was also seen for the other frequencies.

The higher resolution scans of the same specimen showed very clearly the A_0 interaction with the delamination shown in Figure 5. Closer inspection was conducted with the out of plane S_0 mode using a FFT of only the time period where the S_0 was passing over the area of damage. This is shown in Figure 6, and worth noting the semicircle of higher energy from the left is the approaching A_0 mode. This revealed some minor effect of the wave due to the damage; however this did not affect the continuing wave. The reason for the greater effect on the A_0 than the S_0 was probably due to its greater wavelength, meaning that it was passing over the delamination, rather than interacting with it in any significant way. It was also clear that there was no observable interaction of any in plane waves with the damage; this is likely to be because delamination occurs through the Z plane, as opposed to cracks which are predominantly in the X/Y. These results are in line with the work conducted by Zhao et al [2] where only the out of plane part of the modes were observed to interact with the delamination.

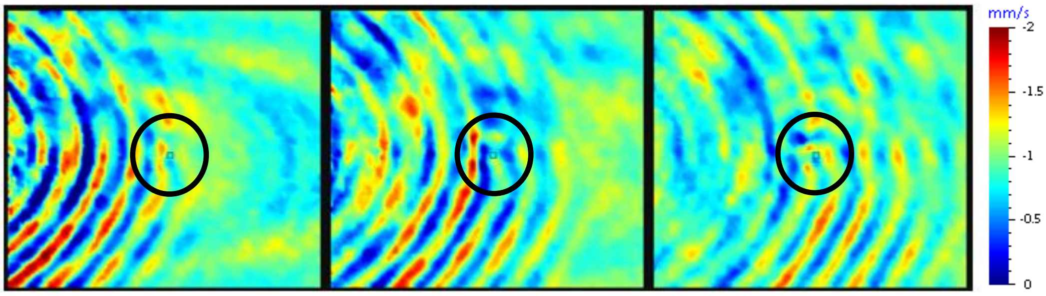

Figure 5 – Interaction of the A_0 mode with the damage from the high resolution scan at 100 kHz (205 µs, 220 µs and 235 µs) with area of damage circled

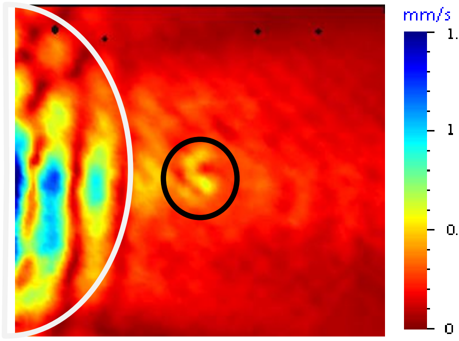

Figure 6 – FFT for the time period where the S_0 mode passes over the damage (approaching A_0 mode (white) and area of damage (black) circled)

The 3D matrix FFT plot can be seen in Figure 7. This plot shows a range of FFT results at different frequencies for a cross section of x at the point of impact. It identifies a peak at 160 kHz, meaning that this frequency has the most interaction with the delamination. This should also mean that this frequency should yield the greatest change in cross correlation.

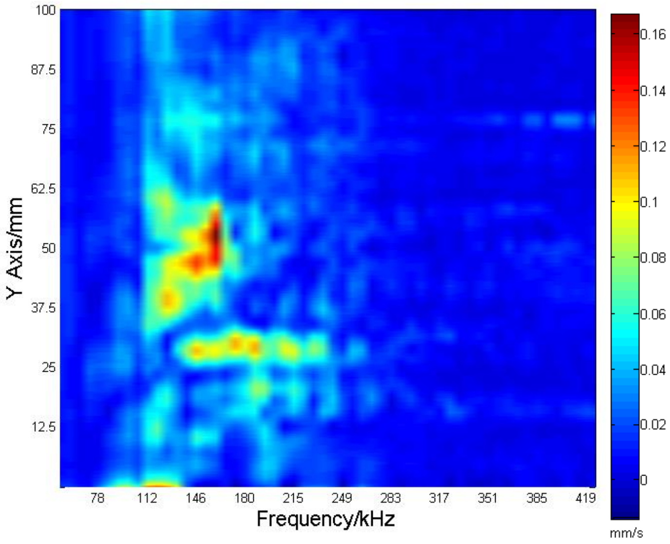

Figure 7 – 3D matrix FFT

The results from the 160 kHz scan showed that the wave at this frequency had a very strong interaction of the out of plane part of the A_0 mode with the delamination, as shown in Figure 8. Investigation into the S_0 mode did not reveal any interaction, as was present in the previous test setup at 100 kHz. The most probable reason for this is its greater wavelength causing it to fully pass over the damage, with no observable interaction. At this time it is hard to say if the 3D matrix FFT results are correctly showing the optimum frequency for transmitting in AU tests, however it gives a promising indication.

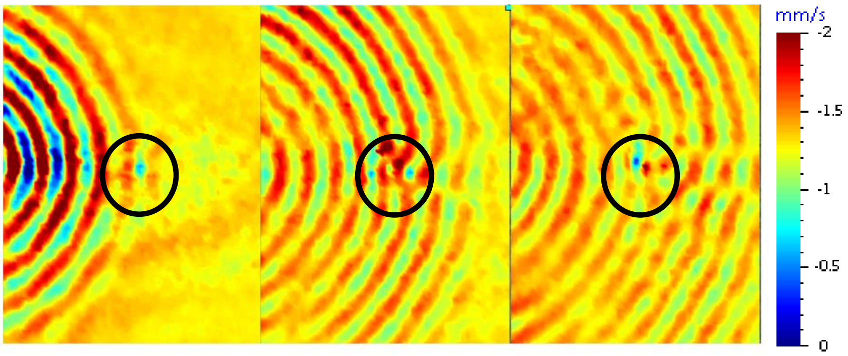

Figure 8 - Interaction of the A_0 mode with the damage from the high resolution scan at 160 kHz (205 µs, 220 µs and 235 µs) with area of damage circled

4. Conclusion

Acousto-ultrasonic wave propagation and damage interaction through a CFRP panel was recorded and analysed. Having greater knowledge of this interaction can be applied to future AU testing to better optimise the systems and tailor the sensors used to each structure. The wave propagation was monitored both in and out of plane; the latter clearly being the component of the wave interacting with the delamination. No in plane interaction was observed. Of the two modes produced by the transducer, the A_0 had far more interaction with the delamination than the S_0 and it would appear that with an increased frequency, the S_0 mode has no interaction.

The 3D matrix FFT shows that for an AU system to effectively detect delamination in a panel similar to which tested upon, transducers with a frequency response of around 160 kHz should be selected which are able to exited and receive the fundamental A_0 mode effectively. This is not by any means conclusive and testing should be conducted to further investigate this as well as the system's ability to detect smaller and different types of damage.

5. References

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