Acoustic Emission in Wide Composite Specimens

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Abstract. Acoustic emission (AE) is an attractive technique for the structural health monitoring (SHM) of aerospace systems. To reach its full potential in this role a quantitative approach must be adopted to study damage mechanisms in composite materials.

In this paper, some of the practical issues regarding acoustic emission testing in composites are addressed. A model describing Lamb wave propagation through plates is described and used to make phase velocity and attenuation measurements in both aluminium and carbon fibre reinforced plastic plates. Results are then implemented in the frequency domain to conduct an experimental study of normal incidence Lamb wave reflections. Comparisons are made with finite element analysis (FEA) models with good results.

Introduction

Acoustic emission (AE) is a sensitive technique, capable of detecting various types of damage mechanisms in composite materials (Johnson and Gudmundson, 2000). This, coupled with the small number of sensors required makes AE an attractive technique for structural health monitoring (SHM). By providing in-service monitoring, SHM aims to reduce maintenance cost and downtime. Such savings are of particular interest to aerospace systems, where strict maintenance regimes greatly influence system operations (Boller, 2001). As the use of composite materials in such systems increases, so does the complexity of the damage modes present. Therefore to maximise the potential of AE in an aerospace SHM role it is necessary to quantify AE in composite materials.

AE testing on composites is generally conducted on narrow specimens and this has two major drawbacks. Firstly, the close proximity of the specimen edges can influence measurements (Hamstad et al., 2001) giving waveform observations that differ depending on the test specimen size. Secondly, the narrow specimens limit measurements to one direction relative to the damage mechanism (Groot et al., 1995; Lim and Lee, 1997; Nam et al., 2003). It is the belief of the authors that in a practical AE system the location of the damage mechanism is unknown, therefore both distance and angular dependency are important.

In this paper, practical issues of AE testing in wide composite materials are addressed. Adopting the modular approach of QAE-Forward (Wilcox et al., 2006), all aspects of the AE system are considered. For isotropic materials, dispersion curves are independent of angular direction, however this is not the case for anisotropic materials. In these materials angular dependence is seen in all aspects of wave propagation including attenuation (Neau, 2003). Usually, the phase velocity characteristics can be predicted with reasonable accuracy from known material properties. However there is generally more uncertainty in the material properties that determine guided wave attenuation and this is therefore better measured directly by experiment. Phase velocity and attenuation are examined in a composite cross-ply plate using existing measurement techniques. Using these results, further experimental work is conducted on the characterisation of edge reflections.
Elastic Wave Propagation

It has been recognised that AE signal amplitude provides limited information about the damage source as propagation affects waveform amplitude (Prosser et al., 1995). The propagation of elastic waves through plate materials differs from those in bulk materials. Initially waves propagate away from a damage source as longitudinal and transverse waves, as in bulk materials, but are however quickly guided by the plate faces to form Lamb waves (Neau et al., 2004). Dispersive in nature, that is phase velocity is frequency dependent, Lamb waves have two types of propagating modes; symmetric (denoted by the letter S) and anti-asymmetric (denoted by the letter A). In the low frequency-thickness regime only fundamental Lamb wave modes exist and these are identified by zero subscripts: S₀ and A₀.

Whilst elastic waves propagate in all directions from an acoustic source, by considering only elastic waves which interact with the receiving transducer, the amount of propagation information required is drastically reduced (Fig. 1).

This approach, used in QAE-Forward, is known as ray-theory and allows wave propagation to be described using a series of transfer functions (Eq. 1).

\[ H(\omega) = \sum_{1}^{n} [E(\omega)P(\omega)A(\omega)B] \] (1)

where \( H(\omega) \) is the frequency domain propagation transfer function, \( B \) is the beam spreading function and \( E(\omega), P(\omega) \) and \( A(\omega) \) are the frequency domain transfer functions for excitability, time-delay and attenuation respectively.

The excitability function describes how much a particular acoustic source stimulates the two Lamb modes. The time delay component implicitly includes dispersion effects with result in a “spreading out” of the wave over time. Whilst no energy is lost through dispersion, a decrease in signal amplitude (due to the spreading signal) is seen as the wave propagates. The expansion of the wave front as it radiates outwards, is described by beam spreading and results in a further reduction in amplitude. Finally energy loss through absorption and backscatter is described by the attenuation function.

Experimental Work

Measurement Techniques. Measurements have been made on both aluminium and carbon-fibre reinforced plastic (CFRP) plates. Using estimated phase velocity curves, experiments have been developed to minimise the effects of reflections and mixed-mode interaction.
The acoustic source was an in-house constructed circular single-element PZT, diameter 3 mm and height 3 mm. The transducer was broadband and gave high fidelity measurements in the range 50-450 kHz. For the aluminium the tone-burst used was a 200 kHz (2 Cycle) Hanning modulated sine wave. This gave a large bandwidth, minimising the number of measurements to be made. For the composite, the tone-burst was varied over a range of frequencies and number of cycles was selected to suit experimental needs (i.e. the balance between bandwidth and duration) (Wilcox 2003).

Propagating waves were measured using a laser vibrometer (Polytec OFV-505) with 2 MHz bandwidth. This non-contact device allows consistent surface measurements of the plate, from point to point. It is this consistency which allows many of the measurements to be made. The poor sensitivity of the pulsing transducer meant that the signal to noise ratio of the laser measurements was low, thus many averages had to be taken to provide a good signal.

A₀ measurements were made by mounting the pulsing transducer on the surface of the plate (near the centre to avoid reflections). This out-of-plane displacement excites the A₀ mode, leading to a better signal to noise ratio when measuring with the laser. S₀ measurements were taken by placing the transducer on the specimen edge. This improved the signal to noise ratio of the S₀ mode.

Phase Velocity Measurements. Although the phase velocity of a propagating Lamb wave can be calculated from a 6x6 stiffness matrix, the exact values of all the elements in the stiffness matrix may not be known, thus a method of measuring phase velocity is required. Phase velocity was measured using a phase-delay technique. Using a permanently coupled pulsing transducer, two measurements were taken at different points along a chosen ray-path using the laser vibrometer. The phase delay due to propagation is given by (Eq. 2).

\[ P(\omega) = \exp \left( -\frac{i \omega d}{v_{ph}(\omega)} \right) \]  

where \( \omega \) is the angular frequency, \( d \) is the propagation distance from the source and \( v_{ph}(\omega) \) is the frequency domain representation of phase velocity. By comparing the frequency/phase relationships at two points along a ray-path, the phase velocity can be calculated. Since the propagation distance between measurements is large relative to wavelength, the number of cycles the wave has undertaken is unknown. As a result, an estimated value of \( 2\pi n \) is required to complete the phase velocity measurement (Eq. 3).

\[ v_{ph}(\omega) = \frac{\omega (d_2 - d_1)}{2n\pi - i \ln \left( \frac{P_2(\omega)}{P_1(\omega)} \right)} \]  

Phase velocity was measured in both the aluminium and CFRP plates, in the 90° direction for the latter. These were compared with estimated phase velocities, obtaining using DISPERSE 2.0.16 (Imperial College, London). This program uses a global matrix method to estimate dispersion curves given the stiffness and density values (Lowe, 1995; Pavlakovic and Lowe, 2000). Aluminium properties and the stiffness values used for the composite, measured at the University of Bordeaux I, are provided in the Appendix.

The agreement between the measured and predicted phase velocity in the aluminium plate is good as shown in Fig. 2(a). This is expected, since the propagation of Lamb waves in isotropic materials is well understood. Good agreement is also seen with the predicted measurements in the CFRP as shown in Fig. 2(b). There are however noticeable discrepancies, the most obvious being the reduced dispersion in the 300-400 kHz range. It is thought that this deviation may be attributed to frequency dependence of the material stiffness values, the values quoted in the appendix being measured using an ultrasonic technique at a frequency of 1 MHz.
Reported work on Lamb wave signal decrement in plates is rare. Accurate attenuation measurements require that other signal decrement mechanisms be accounted for, allowing their effects to be removed. By studying entire wave packets along a single ray-path the effects of dispersion can be removed (Eq. 4).

\[ A_i(\omega) = \frac{1}{\sqrt{d_i}} \cdot e^{-\alpha(\omega)d_i} \]  

(4)

where \( A(\omega) \) is the excitability normalized frequency domain amplitude, \( d \) is the propagation distance from the source, \( \alpha(\omega) \) is frequency dependent attenuation and the subscript \( i \) denotes different measuring stations. By examining amplitudes at two stations on a ray-path, attenuation measurements can be made by studying the frequency content of wave packets at two points along a ray-path (Neau, 2003).

\[ \alpha(\omega) = \frac{1}{(d_1 - d_2)} \cdot \ln \left[ \frac{A_2(\omega) \sqrt{d_2}}{A_1(\omega) \sqrt{d_1}} \right] \]  

(5)

Attenuation measurements were made on both the aluminium and CFRP plates. The need to ensure adequate energy propagating at a particular frequency, combined with the need to separate modes, meant two overlapping frequency measurements were made in the composite. The results of these measurements are shown in Fig. 3.

The attenuation in aluminium was expected to be approximately zero, which is in agreement with the measurement. This is due to the high difference between the acoustic impedance of the aluminium and air resulting in little energy loss. The aluminium is also a continuous medium minimizing loss through scattering and has no associated viscosity. Large deviations from the value of 0 Np/m occur at the extremes of the measurement bandwidth where the amount of energy in the input signal is small. For the CFRP an increasing value of attenuation with frequency is seen. Again the difference between the acoustic impedance of the composite and surrounding air is small, however, it has visco-elastic properties and may lose some energy through scattering at fibre/matrix interfaces.
Propagation Prediction. Using the measured values of phase velocity and attenuation, the propagation of an experimental waveform was predicted and compared with a measured result. Good predictions of Lamb wave propagation are achieved as shown in Fig. 4. To be able to view the predicted and measured lines a vertical offset has been applied.

Reflection Study. Using the technique described in the earlier section it is possible to examine the effects of an edge reflection. Edge reflections can lead to mode conversion and also loss of energy due to transmission into surrounding media. In this experiment, the reflection is normal to the edge and below the cut-off values for higher order modes. This combined with large acoustic impedance of the material relative to the surrounding air results in little energy loss in the wave-packet. Measurements made on the CFRP cross-ply plate indicate little energy loss for both $S_0$ and $A_0$ modes and show that the reflection induces phase shifts of 180º and 90º respectively as shown in Fig. 5. The small discrepancies in amplitude between the predicted and measured waveforms are due to errors in the attenuation measurements, which are made over relatively short distances compared to the reflection measurements.

To confirm the phase shift results, 2D cross-section models of an aluminium plate were constructed using Abaqus CAE. It was found that square elements, with an edge length of 0.25 mm generated an adequate representation of Lamb wave propagation. Comparison of the phase shift required two models with output nodes both placed at the same propagation distance from the source. One model included a reflection in the propagation, the other did not. Results are in agreement with the experimental technique described earlier, indicating a phase shift of 180º for the $S_0$ mode and 90º for the $A_0$ mode as shown in Fig. 6.
Conclusions

The work discussed has demonstrated the ability to characterise the propagation of Lamb waves in isotropic and anisotropic structures with relatively few measurements. This is of great importance for practical structures on which AE based SHM is likely to be performed, where the exact material properties may not be known.

Phase velocity measurements have shown good agreement with predicted values from known stiffness values over a large bandwidth. Attenuation measurements in the CFRP cross-ply plate indicated increasing attenuation with frequency.

The quality of the results greatly depends on the ability to identify and separate propagating modes. This requires that the entire wave-packet of each mode is separated in the time-domain and captured. The unsmooth results of phase velocity and attenuation measurements are thought to be caused by incomplete mode separation.

Propagation prediction measurements have been made using the measured values of phase velocity and attenuation. For both aluminium and the CFRP cross-ply the predictions were found to be in close agreement with measured results. This confirms that the phase velocity and attenuation measurements previously taken were correct.

Normal incidence reflection measurements have shown that there is a phase shift of 180° for S₀ and 90° for A₀ wave packets. Agreement between experimental techniques and FE analysis is achieved. This is an example of the type of study which will be conducted on simple geometrical features for inclusion within the QAE-Forward model (Wilcox et al., 2006).
Inversion of the prediction code is relatively simple, allowing received waveforms to be back-propagated. This holds promise for the possibility of studying the AE source, through back propagation of received waveforms.

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Appendix

Aluminium

\[ E = 70 \text{ GPa} \]
\[ \nu = 0.33 \]
\[ \rho = 2700 \text{ kg/m}^3 \]
\[ t = 3 \text{ mm} \]
Dimensions = 1500 x 1000 mm

Cross-Ply

\[ C_{11} = 12.15 \text{ GPa} \quad C_{44} = 4.70 \text{ GPa} \quad C_{12} = 8.39 \text{ GPa} \]
\[ C_{22} = 70.87 \text{ GPa} \quad C_{55} = 3.00 \text{ GPa} \quad C_{13} = 7.73 \text{ GPa} \]
\[ C_{33} = 64.24 \text{ GPa} \quad C_{66} = 2.97 \text{ GPa} \quad C_{23} = 5.60 \text{ GPa} \]
\[ \rho = 1615 \text{ kg/m}^3 \]
\[ t = 3.5 \text{ mm} \]
Dimensions = 1166 x 942 mm

where \( E \) is Young’s modulus, \( \nu \) is Poisson’s ratio, \( \rho \) is density, \( t \) is thickness and \( C_{ij} \) are components of the material stiffness matrix.

References


