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Influence of attenuation on acoustic emission signals in carbon fiber reinforced polymer panels

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ABSTRACT

Influence of attenuation on acoustic emission (AE) signals in Carbon Fiber Reinforced Polymer (CFRP) crossply and quasi-isotropic panels is examined in this paper. Attenuation coefficients of the fundamental antisymmetric (A_0) and symmetric (S_0) wave modes were determined experimentally along different directions for the two types of CFRP panels. In the frequency range from 100 kHz to 500 kHz, the A_0 mode undergoes significantly greater changes due to material related attenuation compared to the S_0 mode. Moderate to strong changes in the attenuation levels were noted with propagation directions. Such mode and frequency dependent attenuation introduces major changes in the characteristics of AE signals depending on the position of the AE sensor relative to the source. Results from finite element simulations of a microscopic damage event in the composite laminates are used to illustrate attenuation related changes in modal and frequency components of AE signals.

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1. Introduction

Acoustic emissions (AE) are stress waves generated due to localized release of strain energy by processes such as crack growth in structural materials. These stress waves which propagate in the structures can serve as indicators of damage growth. AE signals in composite laminates originate from multiple failure modes such as transverse matrix cracks, delaminations, and fiber breaks. The different failure modes are expected to act as distinctly different acoustic sources within the laminate.

In plate type structures, stress waves generated by damage events propagate as combinations of different Lamb wave modes [1–4]. The presence of each type of Lamb wave mode and its frequency content is determined by the location and type of the damage event. In composite test specimens, results from previous studies [5–7] indicated occurrence of AE signals in the frequency range between 100 kHz and 500 kHz. In this frequency range, the stress wave propagation is dominated primarily by the fundamental symmetric and antisymmetric modes, commonly referred to as S_0 and A_0 modes and the shear type SH_0 modes [8–12]. Near the higher end of the specified frequency range, higher order modes occur in some cases. These higher order modes are either too small or undetectable by commercially available AE sensors. Hence, experimental AE signals in composite materials, in the specified frequency range, are likely to be combinations of the fundamental modes.

There were numerous attempts in the literature [7,13–15] to classify AE signals according to the likely failure modes that generate these signals. However, definitive relationships between the different failure modes and the features of resulting AE signals have not been established. Such correlations would be feasible only if the distinguishing features such as ratio of different modes, and different frequency components are preserved in the signals as they propagate along the composite laminates. If these features are not preserved during the propagation of AE related waves, it would be futile to repeat the attempts to relate features of AE signals to composite failure modes.

The characteristics of AE signal waveforms in terms of the amplitudes of individual wave modes and frequency components are important for identifying types of failure modes. Both the amplitude and frequency content of the AE signals are altered by different attenuation mechanisms as the waves propagate in the laminates. Geometric spreading as well as frequency dependent dispersion reduces the amplitude of AE signals. The viscoelastic nature of the matrix in carbon/polymer composites introduces significantly higher levels of attenuation.

There have been several studies in the past on the measurement of attenuation in aluminum and composite structures. Mason [16] describes a general procedure for the measurement of attenuation

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in materials. Ramadas et al. [17] modeled attenuation of Lamb waves using Rayleigh damping model. Pandya et al. [18] experimentally studied the reduction in amplitudes of stress waves with distance in a ballistic impact test in composites. Wandowski et al. [19] conducted attenuation measurements by means of PZT sensors placed on a composite laminate. Kerber et al. [20] used Chirplet transform to calculate attenuation of Lamb wave modes. Sun et al. [21] studied the effects of material viscoelasticity by using numerical model of laser generated Lamb waves. Drinkwater et al. [22] examined the effect of compressively loaded elastomer on propagation of A_0 and S_0 wave modes experimentally. Aggelis and Matikas [23] used numerical model of a homogeneous material to present how features of AE signals such as duration, rise time and frequency change with distance. Maillet et al. [24] used energy attenuation as an indicator for damage monitoring and lifetime prediction.

The major objective of the present work is to examine how the AE signals generated by damage mechanisms are modified as they propagate across composite laminates. In addition to understanding the changes introduced to AE signals during propagation, the information generated in this paper will also be useful for developing appropriate experimental procedures including the selection of sensors, number of sensors, and their locations for monitoring composite structural members. The AE signals, as discussed earlier, are composed of different frequency and modal components of Lamb waves. Attenuation coefficients of the fundamental Lamb wave modes which constitute AE signals, over a range of frequencies were measured experimentally in selected directions for a crossply and a quasi-isotropic plate. The AE transducers used in this study are sensitive to out of plane displacements and because of this the SH_0 component is not included in the study. These attenuation coefficients were later incorporated into numerically generated AE waveforms to illustrate the effect of attenuation on AE signals detected at various distances from the source. The details of the experimental as well as numerical procedures and results are presented in the following sections.

2. Experiments to determine material related attenuation as function of mode and frequency

Attenuation coefficients of the A_0 and S_0 wave modes in crossply and quasi-isotropic laminates were determined. The stacking sequences for the crossply and the quasi-isotropic laminates were $[0/90]_{6s}$ and $[+45/90/-45/0]_{3s}$ respectively. Both of the laminates had a total of 24 plies. The dimensions of the crossply and quasi-isotropic laminates were 600 mm × 600 mm × 3 mm and 425 mm × 425 mm × 3 mm, respectively. The laminates were inspected using thermography to ensure that they were free from major defects. The fiber volume ratio for the laminates was determined to be 0.65.

The panels were excited by single frequency five cycles Hanning window tone burst signal at frequencies ranging from 100 kHz to 500 kHz, in 50 kHz increments. The pulses were applied at locations selected to minimize the effect of reflections from the edges. The peak amplitudes of the A_0 and S_0 components of the received pulses were measured along the directions of 0°, 30°, 45°, 60° and 90° as shown in Fig. 1. Along each of these directions, the amplitudes were measured at equally spaced points up to a maximum distance of 250 mm. At each of these locations the signals were measured on both surfaces of the laminates, so that the S_0 and A_0 components of the signals could be separated by the addition and subtraction of the signal waveforms.

The stress wave signal was introduced into the laminate in most cases using a 5 MHz, 6 mm diameter, damped ultrasonic transducer. In order to generate stronger S_0 modes below 300 kHz, a piezoelectric wafer bonded to the surface of the laminate was used. The response signal waveforms were received using another 5 MHz, 6 mm diameter, damped ultrasonic transducer. The received waveforms were amplified by a preamplifier with 50 kHz high pass filter and recorded in a commercial AE monitoring system at a sampling rate of 5×10^6 samples/s.

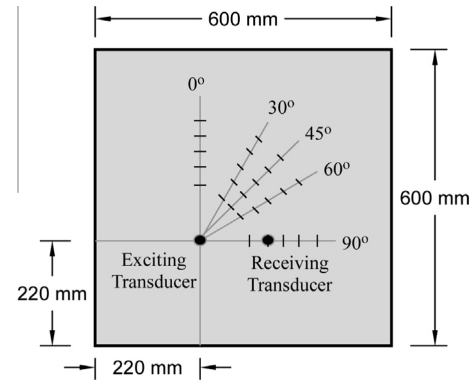

Fig. 1. Angles of measurement.

3. Experimental results

3.1. Identification of A_0 and S_0 modes

Surface excitation of the panels by the sine wave pulses resulted in excitation of multiple Lamb wave modes. For the relatively low frequencies considered here, the Lamb waves predominantly propagated in the form of S_0 and A_0 modes that are separated in time because of the differences in their velocities. The SH_0 component was not detectable as it produced no out of plane displacements. Fig. 2 shows two waveforms obtained at the same location but on opposite faces of the crossply laminate. These waveforms were obtained along the 0° direction, for 200 kHz input excitation at distance of 100 mm. The A_0 and S_0 wave mode components can be clearly distinguished from the figure.

3.2. Dispersion curves of the laminates

The experimentally determined Lamb wave dispersion of the fundamental A_0 and S_0 modes along 0° direction in the laminates is shown in Fig. 3. Time-of-flight analysis was used to generate the dispersion curves. As mentioned earlier, multiple measurements were available at each frequency. The best estimate of the velocity at a given frequency was obtained through averaging. The experimentally determined dispersion curves were assessed for validity through review of similar curves which were generated

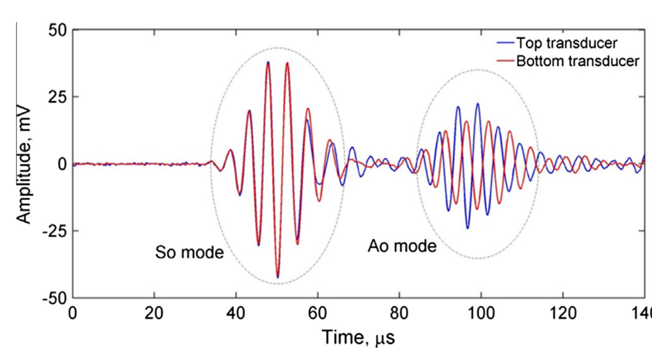

Fig. 2. Representative waveforms used for measuring received signal amplitudes; waveforms in crossply laminate.