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Identifying the arrival of extensional and flexural wave modes using wavelet decomposition of ultrasonic signals

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ABSTRACT

In health monitoring applications of composite materials, the health state of specimens is often evaluated using naturally occurring and simulated Acoustic Emission stress waves. For such applications, identifying the arrival times of the extensional and flexural wave modes from acquired signals is a crucial step, and must be performed reliably and potentially on large sets of signals. This article proposes using the wavelet decomposition of a signal to develop a fast, algorithmic and automated approach to estimate the arrival times of the extensional and flexural wave modes. Algorithms are developed that estimate the two arrival times using wavelet decomposition data, and which can be employed to consistently and reliably identify the arrival times from large sets of signals iteratively. MATLAB scripts to automatically execute the algorithms are also developed, and are made available online.

1. Introduction

1.1. Acoustic Emission and Lamb waves

One of the major methods of studying the health state of composite materials is to use Acoustic Emission (AE) signals [1–3]. The acoustic stress waves that are generated any time a localized load redistribution or energy release event occurs in a material are referred to as Acoustic Emission. In metallic materials, AE is generated any time a crack is created or propagated; in composite specimens, AE is generated due to a variety of events, such as fiber breaks, matrix cracks and delaminations [4–6]. In contrast with such natural AE, acoustic stress waves can also be generated by the sudden removal of a small concentrated load on the specimen. Such a sudden load removal can be used to generate simulated AE (since this simulates load-redistributions that generate natural AE).

In specimens taking the shape of 'plates', i.e. where one dimension is much smaller than the other two dimensions, Lamb wave modes dominate [7–9] AE wave propagation. Specifically, two infinite sets of Lamb wave modes propagate: (a) symmetric modes, or longitudinal modes, with vibrations symmetrical about the midplane of the plate, and (b) anti-symmetric modes, or transverse modes, with vibrations anti-symmetric about the midplane. When the propagating waves have wavelengths greater than the thickness of the plate, the plate can be termed a 'thin plate'. In such plates, only two Lamb wave modes propagate: the Extensional and Flexural mode [10,3]. The extensional mode is dominated by in-plane displacements and are not dispersive in nature. The flexural mode is dispersive, i.e. their wave velocities vary according to frequency, and is dominated by out-of-plane displacements [11].

In Acoustic Emission testing, these extensional and flexural modes are of most interest, since many specimens under consideration satisfy the 'thin plate' criterion. Further, since in most cases the sensors that acquire the signals are attached to the 'face' of the plate, these sensors only detect the out-of-plane components of any propagating waves. For the extensional mode, the out-of-plane component is much smaller than its in-plane component; for the flexural mode this is exactly reversed. Therefore, for most cases, the acquired signals have a small extensional mode component arriving first, followed by a larger flexural mode component.

A sample AE signal, as acquired by two sensors along the same path traveled by the stress wave, is shown in Fig. 1. The flexural mode in Fig. 1a arrives soon after the extensional mode, indicating that the source is quite near to the sensor. On the other hand, in Fig. 1b the time separation between the arrival of the two wave modes is larger, showing that the sensor is farther from the signal source. Considering the same AE wave being detected by two sensors, this difference in arrival between the extensional and flexural modes, as well as the difference between the signal amplitudes, provide clues as to the location of the signal source.

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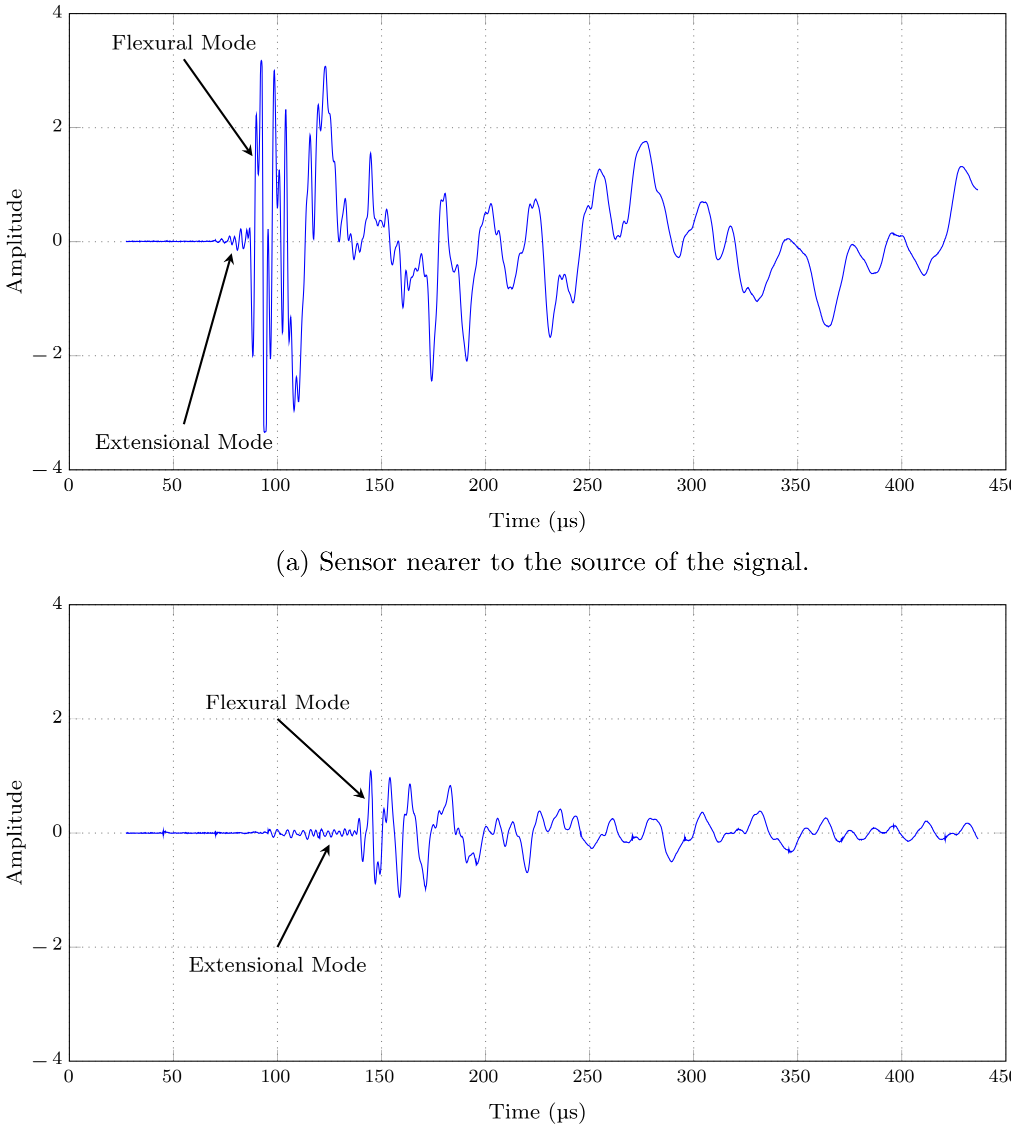

(a) Sensor nearer to the source of the signal.

(b) Sensor farther to the source of the signal.

Fig. 1. Sample Acoustic Emission signal. Extensional and Flexural modes are indicated.

1.2. Wavelet analysis

Wavelet analysis [12] is an important tool [13,14] in the time-frequency analysis of transient signals such as ultrasonic stress waves. The Fourier transform shows the frequency content of the entire signal, but the temporal aspects of the frequency components are lost. The windowed Fourier Transform attempts to improve on this, but has the disadvantage of using a time window of constant time width, thereby losing any information about wave components whose wavelengths are longer than the window width. The wavelet transform provides a versatile method to discriminate signal components along both the time and frequency axes.

Similar to the Fourier transform, the basic idea of the wavelet transform is to use a basis function (called the 'mother wavelet') to compare and characterize different portions of the signal. Unlike the Fourier transform, which only uses sine and cosine waves as basis functions and their higher harmonics to match higher frequency components, the wavelet transform may use many different kinds of mother wavelets. The mother wavelet has the property of being transient, i.e. having non-zero amplitude only for a small duration in time. In addition, the wavelet transform performs two operations [14] to identify different frequency components appearing in different time positions in the signal: (a) translation of the mother wavelet along the time axis, and (b) dilatation and contraction of the mother wavelet to match different frequencies. The mathematical differences between Wavelet spectra and Fourier spectra are described by Perrier et al. [15].

The Gabor Wavelet Transform, or the Continuous Wavelet Transform (CWT), performs well [16] with transient signals, and is given by:

$$X_w(a,b) = \frac{1}{|a|^{1/2}} \int_{-\infty}^{\infty} x(t)\overline{\psi}\left(\frac{t-b}{a}\right) dt \quad (1)$$

where

- $x(t)$ is the input signal as a function of time
- $\psi(t)$ is the particular mother wavelet used, and must be continuous both in the time and frequency domains. $\overline{\psi}(t)$ denotes the complex conjugate of $\psi(t)$.