Sound of a Composite Failure: An Acoustic Emission Investigation

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Abstract. The failure progression characteristics of adhesively bonded Carbon Fiber Reinforced Polymer (CFRP) composites are investigated using Acoustic Emission (AE) technique. Different failure progression modes such as matrix cracking, fiber breakage, delamination and through-thickness crack growth releases AE waveforms in different frequency domains. The characteristic features of these different AE waveforms are studied in Mel Scale, which is a perpetual frequency scale of average human hearing frequency. The recurring noise in the recorded waveforms has been identified more efficiently when the waveforms are analysed in Mel Scale. The recorded AE signals from the adhesively bonded CFRP under static tensile loading are stretched to match the Mel filter banks. The sampling rate of the recorded signal is adjusted from 1 MHz to 20 kHz. Following that, the Mel spectrogram and its cepstral coefficients are used for identifying the different failure modes from which the AE signals are generated. A comprehensive comparison of the AE analysis in Mel scale with conventional waveform processing techniques such as Fast Fourier Transform (FFT), Continuous Wavelet Transform (CWT), Wavelet Packet Transform (WPT) and Hilbert-Huang Transform (HHT) has been made. The advantages and further applications of Mel Scale over traditional waveform processing techniques in defining the failure modes in the composites are also discussed.

1. Introduction

Any irreversible deformation in a material or a structure due to the external loads generates elastic waves [1]. The characteristic features of these elastic waves in the time-frequency domain carries the signature of their source. For instance, in a Fiber Reinforced Plastic (FRP) composite material, the sources of these elastic waves are matrix cracking, delamination, fiber breakage and so on. Each of the source generates elastic waves at a certain frequency, propagating for a certain wavelength and duration [2]. The propagation of these elastic waves within a solid, in this case, a composite material is known as Acoustic Emission (AE). Most of the energy of these elastic waves (or acoustic waves) lies within 1 kHz and 1 MHz frequency range while, most of the significant energy of the elastic waves can be said to be in the ultrasonic frequency range. Nonetheless, these acoustic waves are essentially sound waves.

Sounds waves are recognized by human auditory system not in a linear scale, but rather in a logarithmic scale. Mel scale, the word which is taken from ‘melody’ is the perpetual scale in which the human can recognize sounds [3]. If the frequency characteristics of the acoustic waves generated from the failure of a composite material, or general in a structure can be converted to into their Mel scales, perhaps, one may then have the sound of a failure. However, a question may arise on why the Mel scales must be used for analysing the AE waves from a composite failure. The objective of this research work
is to characterize the time-frequency features of the AE signals generated from a CFRP composite failure using different waveform processing techniques and compare them with the Mel spectrogram. The advantages of using Mel scale and its applications are also discussed in this research work.

2. Experimental Procedure
The acoustic waves taken for this study are generated from a CFRP specimen in Single Lap Shear (SLS) configuration; subjected to a static tensile load. The dimensional configurations of the specimen are presented in Figure 1.

![Figure 1. Schematic of SLS Specimens.](image)

Two piezoelectric sensors with an operating frequency of 150 kHz to 400 kHz are used for recording the acoustic signals generated during the failure progression of the specimen [4]. The acoustic waveforms are sampled at a frequency on 1 MHz, which means the acoustic waves with frequency of 500 kHz are recorded according to the Nyquist criterium. The length of the waveforms recorded is of 3072 samples. Since this research work focuses on perceiving the failure progression in the CFRP as a sound, more importance is given to the subsequent sections, that are dedicated to the defined purpose.

3. Acoustic Emission Signal Processing

3.1. Selection of Acoustic Emission Signals
During the entire loading history of the SLS specimen, a total of 510 AE signals are recorded by both the piezoelectric sensors. The peak frequency of the AE signals as a function of the duration of the test is plotted in Figure 2.
Analysing all the waveforms in the time-frequency domain is quite difficult owing to the large storage space and time required. Therefore, the characteristic acoustic waves representing different damage progression has been taken for this study. It has been extensively discussed in the literature that different failure modes generate acoustic signals with different peak frequency [2, 5]. It is illustrated in Table 1. Based on that, two AE waveforms representing each damage mode is taken from different loading stages and analysed further.

**Table 1.** Frequency characteristics of acoustic waves generated from different failure modes.

| Mode of Failure Progression | Frequency of the Acoustic Waves |
|-----------------------------|---------------------------------|
| Matrix Cracking             | 150 kHz – 200 kHz              |
| Debonding/Delamination      | 200 kHz – 300 kHz              |
| Fiber Breakage              | Above 300 kHz                  |
| Interlaminar Crack Growth   |                                  |

3.2. **Waveform Processing Techniques**

The selected waveforms from the entire dataset are processed initially using different waveform processing techniques. The details and the parameters involving the waveform processing techniques used in this study are presented in this section.

First, Fast Fourier Transform (FFT) is used for processing the waveform and also for obtaining the frequency characteristics of the waveform. Next, the time-frequency characteristics of the waveform are studied using Continuous Wavelet Transform (CWT). One of the analytical wavelets named, Morse wavelet is used for CWT. The Fourier transform of this wavelet vanishes for negative frequencies, which makes it suitable for time-frequency studies. Morse wavelet with the symmetry parameter 3 and the time-bandwidth product of 60 is used with the number of octaves being 3 and number of voices per octave 32.

For Wavelet Packet Transform (WPT), the same Morlet wavelet is used, while the decomposition level is set at 3. The waveforms are decomposed to level 3 giving 8 frequency components.

Finally, for HHT, the signals are decomposed into 5 Intrinsic Mode Functions (IMF) before removing the noise, reconstructing them and analysing the time-frequency characteristics in the Hilbert spectrum.

3.3. **Mel Spectrogram**

Since the human auditory system can hear sounds only up to 20 kHz, the frequency rate of the acoustic waveforms is first rescaled from 1 MHz to 20 kHz. Then the waveforms are buffered into frames with...
a window length of 64. The frames are overlapped by 16 number of samples, followed by converting the frames into their time-frequency representation. Then each of these frames carrying the time-frequency representation is passed through 32 Mel filter banks. The Mel frequency \( f_m \) representation equivalent to the original frequency \( f \) can be given by Eqn. (1).

\[
f_m = 2595 \log \left( 1 + \frac{f}{700} \right)
\]  

(1)

4. Results and Discussions

For discussing the different waveform processing techniques, excluding the Mel scale frequency representation, the acoustic waveform generated from a matrix cracking event is taken. The waveform to be processed is presented in Figure 3.

The frequency representation in FFT and the time-frequency representation in CWT, WPT and HHT are presented in Figures 4(a), 4(b), 4(c) and 4(d), respectively.

In Figure 4(a), the waveform seems to be a peak frequency around 150 kHz and also have some significant amount of spectral density around 275 kHz and 300 kHz. Nonetheless, it does not show any information about the time domain. On the other hand, CWT, WPT and HHT shows the information about the localization of different frequency band in time domain.

Now, for the same waveform, the Mel spectrogram is calculated by passing the frames of time-frequency values through Mel filters and is presented in Figure 5. In Mel spectrogram, the features of the waveform in the time-frequency domain are clearer and it shows the perpetual representation of how human ears would perceive the matrix cracking. This also gives a visual for how many frames the sound resonates and where its maximum power is centered.

Following this, a total of 8 waveforms are selected, each representing the different failure modes (indicated in Table 1) and are analysed. The results are discussed in this section.
Figure 4. a) FFT, b) CWT, c) WPT and d) HHT of the Acoustic Emission waveform generated from a matrix cracking event.

Figure 5. Mel Spectrogram of the acoustic wave generated from Matrix Cracking event.
Figure 6. Mel Spectrogram of the acoustic wave n.2 generated from a Matrix Cracking.

Since Figure 5 already shows the Mel spectrogram of one of the matrix cracking events, the second one is presented in Figure 6. Similarly, the results of acoustic waves generated from delamination events are presented in Figure 7 and Figure 8.
Unlike the matrix cracking event, which resonates for a longer duration and its frequency in Mel scale is maximum between 1.93 kHz and 4.39 kHz, acoustic waves from delamination event have the maximum amplitude centered around 5 kHz in Mel scale. Particularly, the event presented in Figure 7 repeats its pattern after a certain period of time and is very much comparable to the acoustic wave presented in Figure 8, showing significant similarity between the two events.

The Mel spectrograms of the acoustic waves generated from interlaminar crack growth events are presented in Figure 9 and Figure 10. The Mel scale where these events centered are higher than the delamination event, while they show a repetitive pattern, with the acoustic signal in Figure 10 shows more repetition. Nonetheless, the resonance of the repetition seems to get smaller as the number of repetitions progresses.

Finally, the Mel spectrograms of the acoustic events from fiber breakage events are presented in Figure 11 and Figure 12. Although the frequency in Mel scale with maximum power is almost the same as the events from interlaminar crack growth events, the signals from Fiber breakage are much shorter and they barely resonate. This is commensurable to the time-frequency analysis of fiber breakage and interlaminar crack growth events found in the literature. The peak frequencies of the acoustic signals from these two events mostly look similar, however, the fiber breakage event produces more transient signals between the two.
Figures 5-12 are essentially the apparent sounds of failure in the CFRP specimen tested for this study. What analysing the acoustic signals from different failure modes as ‘sounds’ accomplice? First, the repetitiveness of the frequency bands is more apparent in Mel scale. Even though CWT and WPT shows the time-frequency representations of the signal, it could not clearly magnify the repetitiveness in the time domain. Secondly, when these waveform features are processed for some other applications such as machine learning, CWT, WPT or HHT does not provide more features for classifications. On the other hand, Mel spectrogram has visually more features, which can be extracted and analysed for machine learning purposes. In fact, for most of the machine learning operations such as speech/words recognition, the Mel spectrogram is preferred over CWT or any other waveform processing techniques.

5. Conclusions
The acoustic emission signals generated from different failure modes in a SLS configuration of a CFRP specimen tested under static load is analysed. First, the waveforms are processed using conventional waveform processing tools such as FFT, CWT, WPT and HHT. The limitations in these conventional tools are explored. Then the acoustic waveforms from different failure modes are converted to their Mel scale equivalent in the time-frequency domain. The apparent sounds of failure in the Mel scale are analysed for find the characteristic differences between the signals generated from different failure modes. The results show that analysing the acoustic signal as ‘sound’ show clearer differences in defining the signals from different sources.

References
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