MODAL ANALYSIS OF HIGH FREQUENCY ACOUSTIC SIGNAL APPROACH FOR PROGRESSIVE FAILURE MONITORING IN THIN COMPOSITE PLATES

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ABSTRACT

During the past few decades, many successful research works have evidently shown remarkable capability of Acoustic Emission (AE) for early damage detection of composite materials. Modal Analysis of AE signals or Modal Acoustic Emission (MAE) offers a better theoretical background for acoustic emission analysis which is necessary to get more qualitative and quantitative result. In this paper, the application of MAE concept in a single channel AE source location detection method for failure characterization and monitoring in thin composite plates was presented. Single channel AE source location is one of the recent studies for composite early damage localization, owing to the growing interest and knowledge of modal analysis of AE wave. A tensile test was conducted for glass fiber epoxy resin specimen with small notch. A single channel of AE system was used to determine the AE source location on specimen under testing. The results revealed that AE single channel source location provides reasonable accuracy for glass fiber laminate which was tested.

Keywords: Modal acoustic emission, time frequency analysis, composite plates.

1.0 INTRODUCTION

Acoustic emission (AE), one of the non-destructive testing techniques, is increasingly popular in the last few decades, especially in the health monitoring of structures such as buildings, bridges, wind turbines and transport vehicles. This technique is established today owing to its ability to reveal in advance of any impending failure of a building structure, but more than that, this non destructive method can be done online or offline. AE can be defined as a high frequency acoustic signals that are released when material is under stress or strained [1]. In general, AE technique performs well and is able to give accurate and consistent result for metallic structures. However, in composites, the challenge for a reliable AE results is huge due to the anisotropic behavior of the materials. Several studies have been done to investigate the potential of AE technique for health monitoring of composite structures and are becoming more quantitative leading to more general result instead of case specific [2].

Accurate source location determination in composite plates is still a major issue due to its complex structure and wave propagation behavior. Location detection is very important especially when monitoring the progressive failure inside the composite laminates. Accurate location observing can give the precise information on the crack velocity, size of delamination and its orientation and many more. For this purpose, the calculation of effective wave propagation velocity is critical since it will affect the accuracy of arrival time determination at each AE sensors. In commercial application, effective wave velocity is calculated manually using standard Hsu-Nielsen source location test with a known distance. This step though suitable for isotropic materials, can be eliminated with the calculation of effective group velocity in modal analysis of acoustic emission signals [3 & 6].

Nowadays, owing to the recent advances in signal processing algorithms and assimilation of AE theory for plate-like structures [7 & 8] modal analysis of AE signals or Modal Acoustic Emission (MAE) offers a better theoretical background for acoustic emission analysis. The MAE treats the AE signals as the mechanical waves which propagate through a structure in a variety of modes and have the characteristics of dispersion and attenuation. Analyzing these different modes of AE signals will give more accurate result of source location detection [3 & 4]. Accurate wave group velocity value can be easily calculated through dispersion curve and can be used in AE source location detection algorithm [5 & 6]. Also, with the appropriate time frequency analysis such as wavelet transform or short time Fourier transform the source location can be done will lesser number of sensors [5]. The dispersion curves are derived from Lamb's characteristic equation [9],

$$\frac{\tan(\beta d/2)}{\tan(\alpha d/2)} = -\frac{4\alpha\beta k^2}{(k^2-\beta^2)^2} \quad \text{for symmetric modes} \qquad \text{(Eq. 1)}$$

and

$$\frac{\tan(\beta d/2)}{\tan(\alpha d/2)} = -\frac{(k^2-\beta^2)^2}{4\alpha\beta k^2} \quad \text{for asymmetric modes} \qquad \text{(Eq. 2)}$$

where $\alpha = \sqrt{\frac{\omega^2}{c_L{}^2} - k^2}$, $\beta = \sqrt{\frac{\omega^2}{c_T{}^2} - k^2}$ and $k = \omega/c_p$. The parameters d, ω, k, c_p, c_l and c_t are the plate thickness, angular frequency, wave number, phase velocity, longitudinal wave velocity and transverse wave velocity respectively. The relation between the group velocity (c_g) and phase velocity (c_p) is [8],

$$c_g = \frac{dk c_p}{dk} = c_p + k\frac{dc_p}{dk} \qquad \text{(Eq. 3)}$$

Figure 1(a) and figure 1(b) show the dispersion curves generated for 28.7 cm × 2.5 cm fiberglass epoxy resin plate with density value 1559 kg/m^3 and thickness 2.64 mm. It is observed that, when frequency excited is smaller than 400 kHz, only fundamental modes; S_o (Symmetric) and A_o (Asymmetric) are exist.

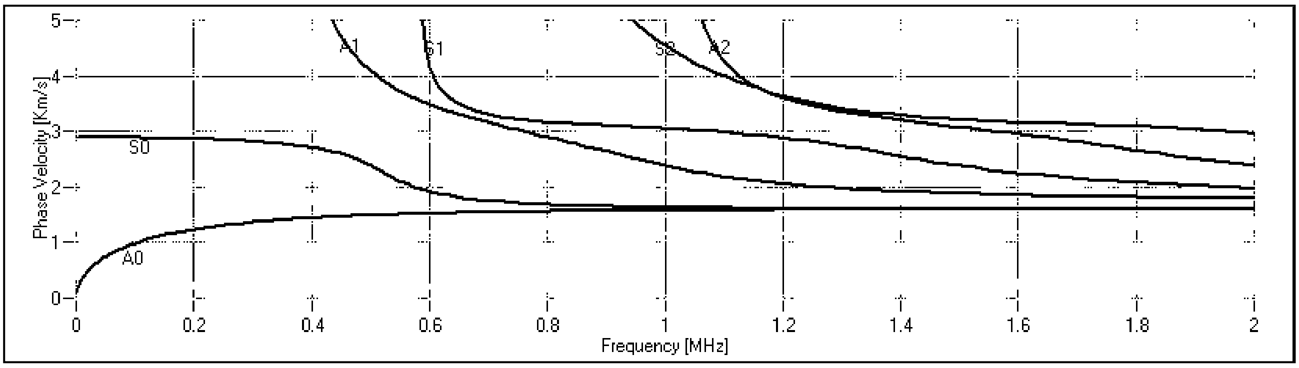

Figure 1(a): Phase velocity dispersion curves

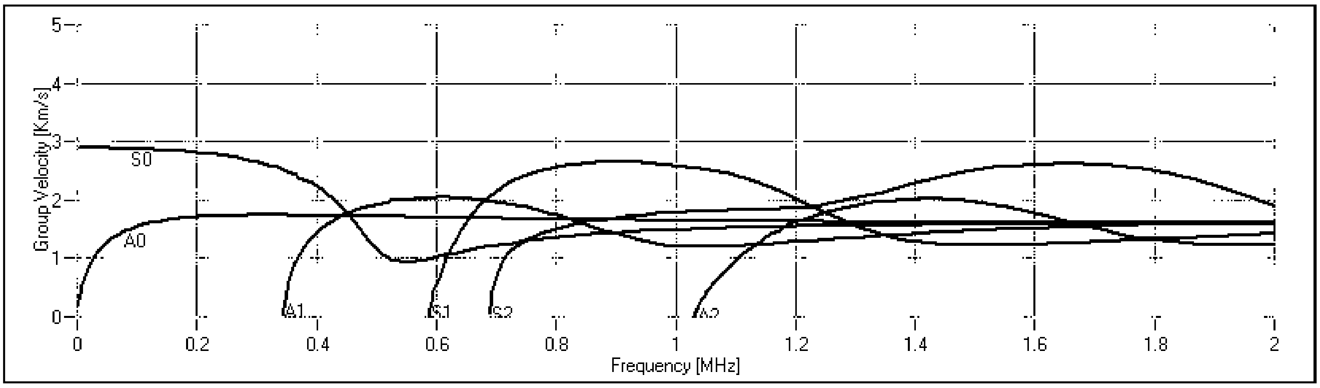

Figure 1(b): Group velocity dispersion curves

This article reports the use of modal analysis of AE theory for thin composite plates, in particular for location detection purpose. Instead of pencil break test, a tensile test was used in this study to produce similar AE signal as in real application.

2.0 EXPERIMENTATION

A standard tensile test (ASTM, D3039/D3039M) was carried out on a 28.7 cm × 2.5 cm fiberglass epoxy resin plate and thickness 2.64 mm. The unidirectional laminate with stacking sequence $[0^o]_4$ was fabricated using the hand lay-up method. An artificial notch with approximately 3 mm length was created and located 7.5 cm from sensor to initiate crack and AE activity. The experimental set-up was as shown in Figure 2. Two piezoelectric sensors were coupled to the surface of the plate which were placed 15 cm apart from each other. The sensors were individually connected to two PAC AE Node Systems (data acquisition from Physical Acoustic Corporation) for waveform acquisition and were synchronized with the help of *AE Win* software. All the acquired signals were analogue filtered to the range of 20 kHz – 200 kHz. The sampling rate for acquisition was set to 5 Mega sample per second and threshold was set to 45 dB. In the *AE Win* software, the first time threshold crossing (FTC) was chosen for the source location detection. All acquired waveforms were stored in computer for further analysis.

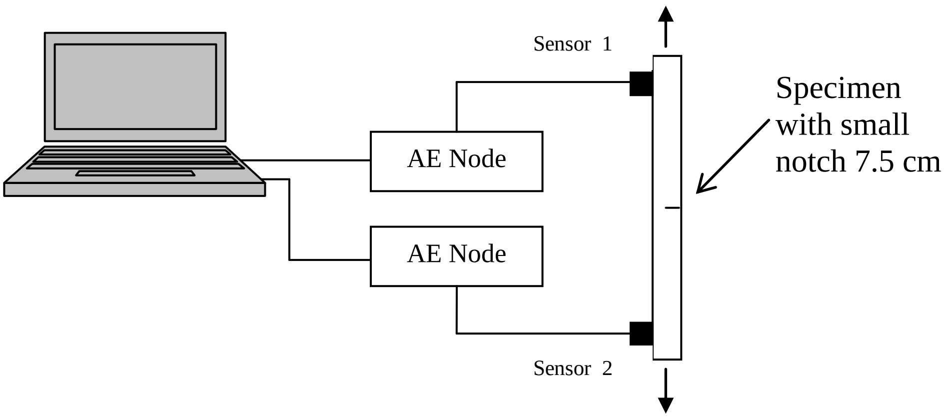

Figure 2: Set-up of the test

3.0 RESULTS AND DISCUSSION

AE system successfully captured a few very powerful AE signals at the beginning of cracking process at notch area, during 30 percent of strain (approximate). A lot of AE signals appeared later of more than 70 dB and located scatter around the notch area as shown in Figure 3. Figure 4 shows the typical AE waveform and Figure 5 shows its amplitude spectrums at the source point. Two peak frequencies appeared indicating the existent of two modes of wave, extensional and flexural wave modes. The different arrival time of both wave modes can be used for single channel location detection.

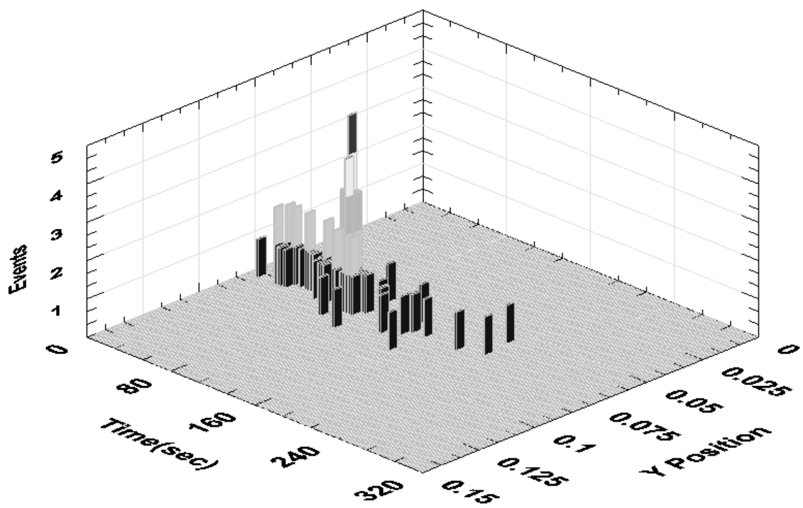

Figure 3: AE events at crack location; near notch.

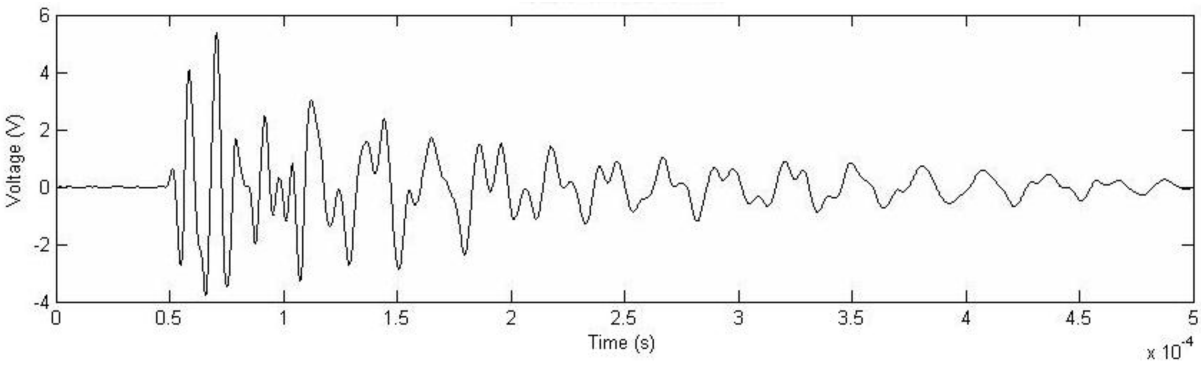

Figure 4: Waveform from sensor 2

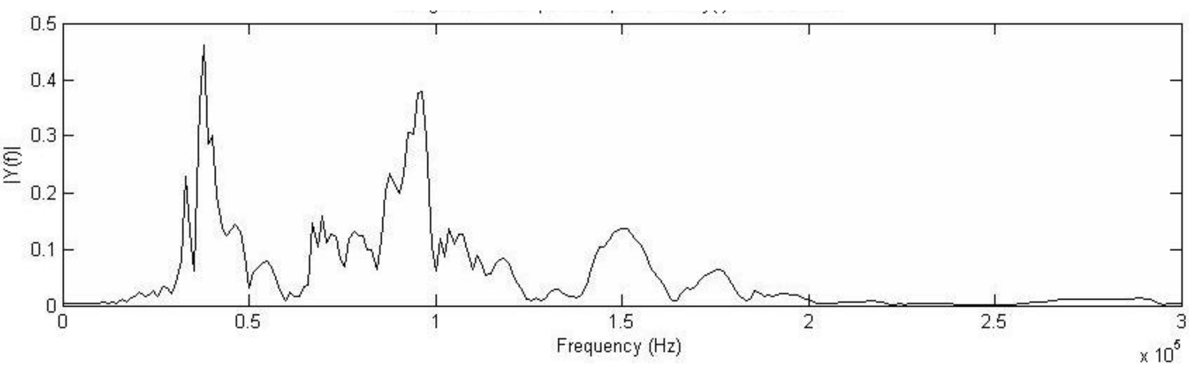

Figure 5: Amplitude spectrum of AE signal in Figure 4 (above)

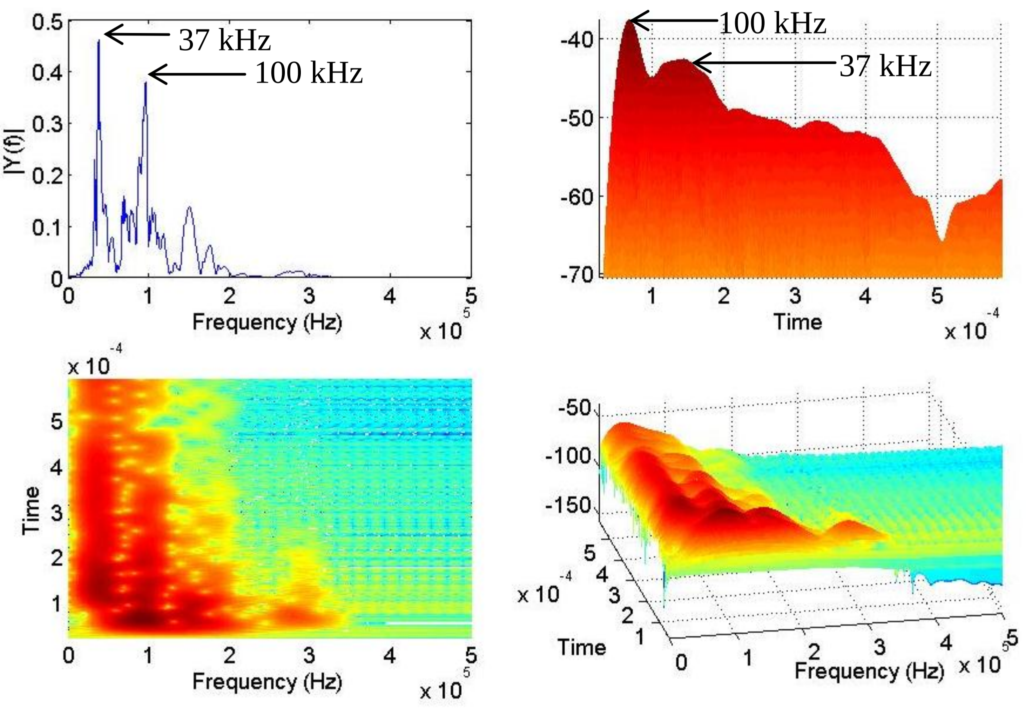

Figure 6: STFT analysis

Further analysis using Short Time Fourier Transform (STFT) was done for the waveform acquired from Sensor 2 (Figure 4). STFT successfully displayed the arrival time of each frequency band in the waveform spectrum as shown in Figure 6. By calculating the time arrival of two peak frequency from dispersion curve (Figure 1b); 37 kHz (flexural wave, A_o) and 100 kHz (extensional wave, S_o) and each corresponding group velocities, the location of AE source can be predicted. According to [5] the distance from AE source to Sensor 2, l_2 can be calculated as,

$$l_2 = \frac{t(f_A) - t(f_S)}{[c_g(f_A)]^{-1} - [c_g(f_S)]^{-1}} \qquad \text{(Eq. 4)}$$

where $c_g(f_A)$ and $c_g(f_S)$ are the group velocities of frequency at A_o and S_o modes and $t(f_A)$ and $t(f_S)$ are the arrival time of frequency at A_o and S_o modes to Sensor 2.

From STFT analysis, the arrival time for A_o and S_o wave modes were 0.1136 ms and 0.0688 ms, respectively. Meanwhile, based on the group velocity dispersion curve, the wave velocity for A_o and S_o wave modes were 1160 ms^{-1} and 2870 ms^{-1}, respectively. Therefore the distance between source location and Sensor 2 can be determined using Eq. 4. The result is 8.7 cm; 12 % or 1.2 cm error compared to actual location (7.5 cm). Note that the error can be decreased if Continuous Wavelet Transform (CWT) analysis was used instead of STFT. CWT performs better time and frequency resolution compared to STFT thus can lead to more accurate result [10].

4.0 CONCLUSION

The experimental evaluation of modal analysis of acoustic emission has been presented. Instead of performing standard pencil break test of the composite plate as artificial source for AE signals, this study used the tensile test for specimen with small notch which closer to replicate the real application. The application of single channel source location detection was presented. A random sample of waveform was chosen for time-frequency analysis and has performed promising result. Although the error was more than 10%, it is believed that if using the Wavelet analysis, the result will be more accurate.

It can be concluded that the MAE is an effective tool for source location prediction. As mentioned earlier, an accurate source location method can be a very good tool for progressive failure monitoring in composite structure. Further investigation will lead for better quality of structure health monitoring of composites.

5.0 ACKNOWLEDGEMENT

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