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Non-velocity Based Analysis of Passive Ultrasonic Signal for Source Location Detection in Composite Plates: A Pilot Study

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Abstract. Acoustic Emission (AE) evaluation is one of the fast growing non-destructive techniques, owing to its ability to reveal in advance of any impending failure of a building structure. This capability makes the so called passive ultrasonic technique a very good tool in structural health monitoring; especially for composite structures. In metallic structures, AE technique is currently well established and able to provide accurate and consistent result. However, in composites, the challenge for a reliable AE results is huge due to the orthotropic behaviour of the materials. The present study investigates the energy attenuation of AE signals in thin composite plate and utilized the attenuation pattern into non-velocity based source location detection. Standard Hsu-Nielsen source location testing was applied on a glass fibre epoxy resin laminate and a single channel AE system was used to acquire AE signals with the support from *AEWin* software for signal analysis. A linear source location algorithm utilizing AE signals energy attenuation patterns was developed and tested for the composite specimen. The results revealed that the source location algorithm provides reasonably accurate results of source location for glass fibre epoxy resin laminate.

1. Introduction

Ultrasonic technique is one of the most popular non-destructive testing in current decades. The fast growing of the ultrasonic technology is owing to the recent achievement and development of computer technology which support the complex and tedious signal processing and analysis. The application of ultrasonic evaluation is numerous in Structural Health Monitoring (SHM). With more complicated design of current structures, the evaluation method for health monitoring also needs to be advance. Acoustic emission (AE); a technique that utilize the ultrasonic range of acoustic sound is also increasingly popular the last few decades, especially in the health monitoring of structures such as buildings, bridges, wind turbines and transport vehicles. It also can be called passive ultrasonic method, where the ultrasonic wave; can be continuous or burst signals, released from any source (e.g. flaws, cracks) travelled in medium of solid materials (e.g. concrete, metals) and can be easily captured by AE sensory systems.

AE technique differs from commercial ultrasonics method in one major aspect; it doesn't require the ultrasonic wave as input [1]. The energy released is totally from the test object, but this lead to the main drawback in AE method where the sources can contain a lot of information and a complex signal analysis need to be done to interpret the data. However, modern computer technology helps solving this problem. The active sources of acoustic emission can be investigated in two main areas. Some researchers focused in statistical analysis of AE data [2-7] while the rest more interested in doing the wave analysis or modal analysis of AE signals [8-13].

One of the main advantages of AE technique is it able to reveal in advance of any impending failure of a building structure. In metallic structures, AE technique consistently performs well and able to give accurate result. But in composites, the challenge for a reliable AE results is huge due to the orthotropic behaviour of the materials. A lot of recent studies are done to make AE technique for health monitoring of composite structures become more quantitative, leading to more general result and not case specific [14, 15].

Location detection is very important especially when monitoring the progressive failure. Accurate location observing can give the precise information on the crack velocity [16], size of delamination and its orientation and many more. Location detection or damage localization in composite materials pulls a lot of study since commercials AE tools always give relatively bigger errors and inconsistent result. This is due to the anisotropic characteristic of composites.

There are a lot of source location methods for acoustic emission technique. One of the easiest ways of source location finding is by using zonal method where it utilizes the attenuation characteristic of acoustic waves. The theory is simple; AE sensor (in an AE sensor array) that nearest to the active sources will capture the highest AE signal amplitude. However, it needs to have a lot of sensor to get good accuracy [17, 19]. The other source location technique is the Time of Arrival (TOA) of AE wave at different sensors [18, 19]. Through this method, two AE sensors is required for linear location detection, while at least three AE sensors is needed for two dimensional detection or source point on a plate. AE sources must be inside or near the sensors array to get good result. Another source location method is by using modal analysis of AE waves [9-12] where it is one of the most recent developments. The technique applies the knowledge of two major wave modes in AE signals; asymmetric and symmetric wave mode. Both wave modes have different wave velocity and arrive at sensor at different arrival time. This makes single sensor linear source location detection possible [11, 12].

In both TOA and modal analysis methods, the information of wave velocity is compulsory for accurate result. However, AE waves didn't travel with a constant velocity in composite materials [20]. This present study describes an alternative concept for identification of damage sources in composite materials using non-velocity approach; signal energy attenuation. Also includes is the modal study of energy signal attenuation.

1.1. Signal Energy Attenuation

In ultrasonic wave study, it is necessary to include the effect of wave signal attenuation. Generally, sound wave attenuates with this relation [21],

$$A = A_0 e^{-\alpha z} \tag{1}$$

where A_0 is the amplitude of the propagating wave at some location or defect source. The amplitude *A* is the decreased amplitude as the wave travelled into distance *Z* from source or initial location. α value refers to attenuation coefficient of the wave travelling in z-direction and its dimension is *nepers/length*. The same model is applied to the signal energy attenuation in AE signals.

The main factors that weaken the AE signals energy is the combined effect of dispersion, diffraction and scattering. When AE wave travels through any medium, its signal energy will drop with the increase of distance and can be expressed with a universal model,

$$E_i = E_o e^{-\beta(|x_i - x_o|)} \tag{2}$$

In equation (2), x_o is referred to the location of source, x_i is the location of sensor *i*, E_o is the energy at source, E_i is energy at sensor *i* and β is the decay constant. By using equation (2), a set of two sensors can be used for linear source location detection. In the case of β value is unknown, three sensors are needed. Its relation can be expressed as,

$$\left(\ln\frac{E_3}{E_2}\Big/\ln\frac{E_2}{E_1}\right) = \frac{|x_2 - x_0| - |x_3 - x_0|}{|x_1 - x_0| - |x_2 - x_0|} \quad (3)$$

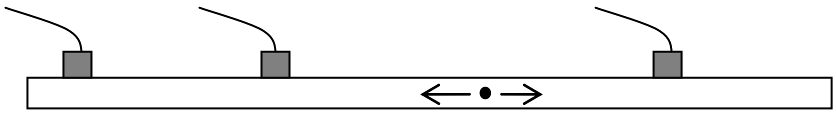

Figure 1. Source location using three sensors for pipe leak detection.

Energy attenuation source defect localization is mainly applied in linear structures such as pipe leak detection (figure 1) and tubes defect. However, for 2D planar source location, the concept of energy attenuation source location also can be applied with appropriate number of sensors.

One of the main benefits of using this method compared with conventional wave velocity dependent method is; no other input is required for source location calculation. Attenuation rate of AE wave will change with the age of the structure and also with different lay-up configuration. In the case of linear source location using three channels, the decay constant or attenuation constant doesn't need to be included into calculation because the number of sensors itself allow the in-situ attenuation rate determination; using equation (3). This is different with velocity dependent approach where AE wave velocity need to be calculated for each measurement.

2. Experimental details

An unidirectional laminate; 28.7 cm × 2.5 cm fibreglass epoxy resin plate and thickness 2.64 mm with stacking sequence $[0^o]_4$ was fabricated using the hand lay-up method. AE data acquisition used for experimentation was a single channel Physical Acoustic Corporation AE Node Systems, with AE sensor NANO-30 (working frequency 100 kHz to 700 kHz) and support by *AE Win* software. All the acquired signals were analogue filtered to the range of 20 kHz – 1000 kHz. The sampling rate for acquisition was set up to 5 Mega sample per second and threshold was set to 45 dB. All acquired waveforms were stored in mini notebook for further analysis.

2.1. Attenuation behaviour

The plate's signal energy attenuation rates were plotted for four different angles; $[0^o]$, $[45^o]$, $[60^o]$ and $[90^o]$. It was done by breaking the pencil lead; a standard Hsu-Nielsen source testing at several points along the given angles in straight line, starting from one edge of the composite specimen towards other edge. Angle $[0^o]$ referred to a line along the glass fibre. An AE sensor was located at point C (figure 2) and captured all the AE signals. The signal's energy was calculated automatically using the AE Win software.

2.2. Source location

Only single channel of AE system were used for the linear source location detection testing, where the sensor was placed at three different positions; A, B and C as shown in figure 2, at different time, while breaking the pencil lead in fixed location. In other words, pencil break test at same location were done three times in order to get AE readings at position A, B and C. Source location computation for [0°], [45°], [60°] and [90°] were done by using an algorithm, developed base on equation (3).

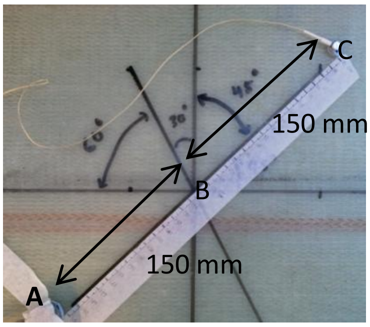

Figure 2. Unidirectional Glass Fibre Reinforced Polymer (GFRP) composite plate with attached AE sensor.

3. Results and discussions

Figure 3 shows the decay rate of AE signals energy in composite specimen for three different configurations. It can be seen that, the AE signals energy attenuation for the specimen, follow the general model of ultrasonic wave attenuation. The R-square show quite high values (near to 1.0) and the average decay constant for all configurations were 0.006.

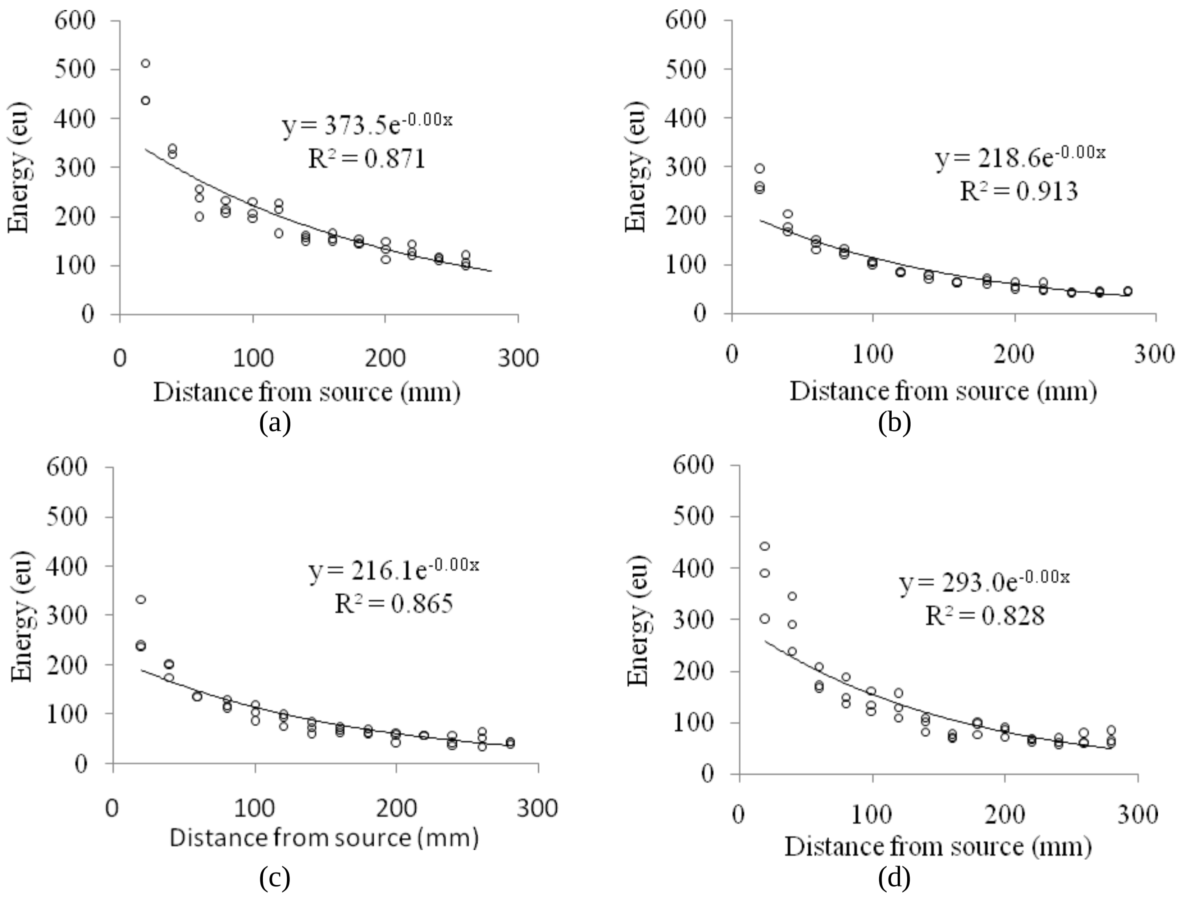

Figure 3. (a) Attenuation rate for [0°], (b) attenuation rate for [45°], (c) attenuation rate for [60°] and (c) attenuation rate for [90°].

Samples of typical AE signals and it frequency spectrums at 100 *mm*, 200 *mm* and 280 *mm* from AE sensor for [45^o] are as shown in figure 4. Two major wave modes exist which are asymmetric (flexural) mode and symmetric (extensional) mode. Extensional wave mode usually has higher frequency and arrived earlier to sensor [13]. It's clear that energy from extensional mode dominates the total signal energy closer to the source but it attenuated very fast and shows a significant reduction with the distance. Meanwhile, the flexural wave energy was remained the same or reduced very little with the distance.

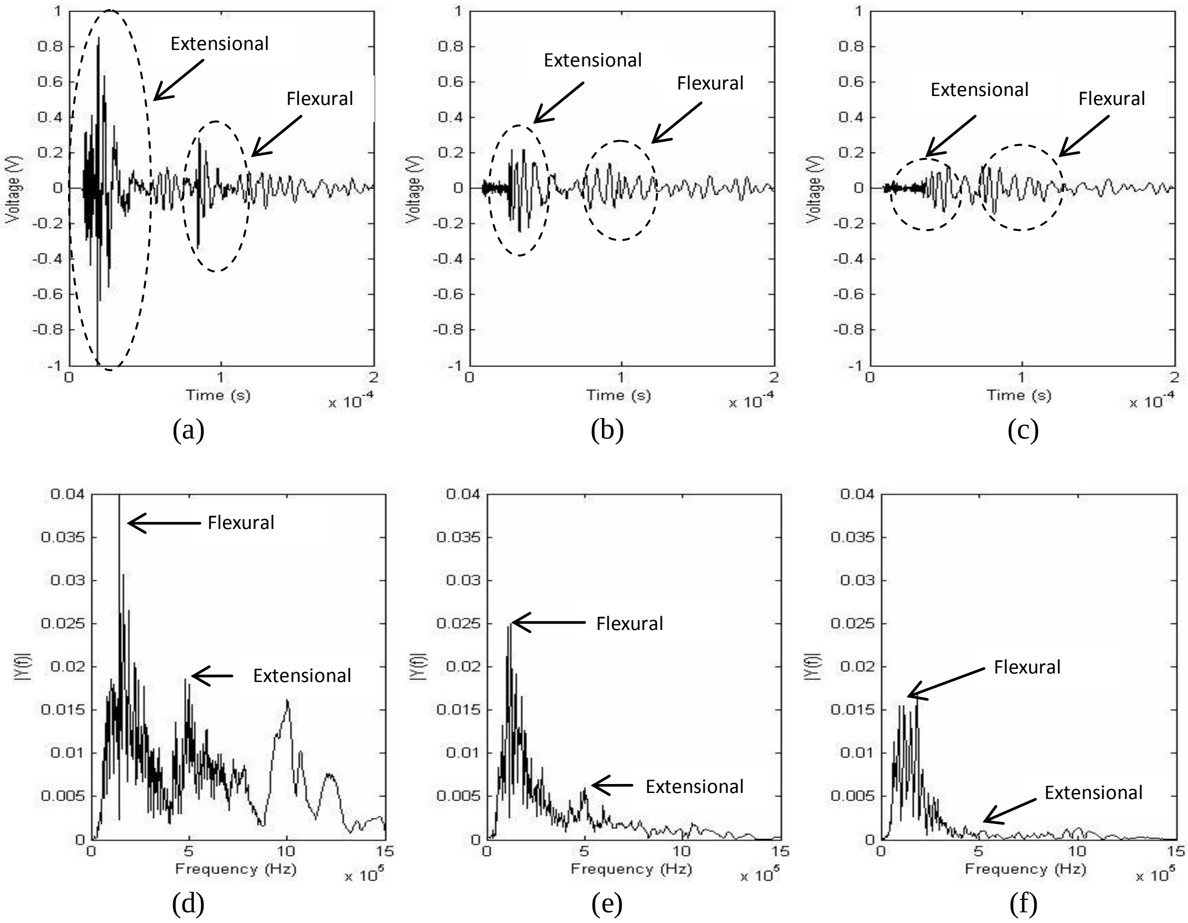

Figure 4. AE signals and its frequency spectrum at 100 *mm* (a), 200 *mm* (b) and 280 *mm* (c) from AE sensor for configuration [45^o].

Test result for unidirectional composite plate with [45^o] configuration source location determination using energy attenuation algorithm can be shown as in figure 5. Meanwhile, figure 6 shows test result for [0^o] and [90^o]. All plots randomly scattered very close to the actual source (triangle). The average errors can be concluded by table 1.

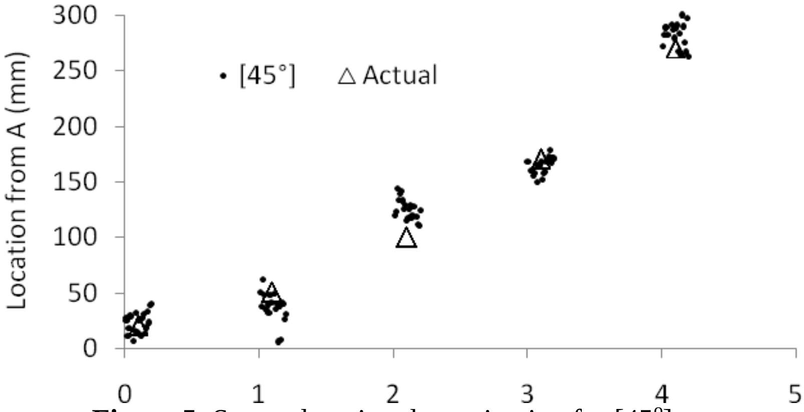

Figure 5. Source location determination for [45°].

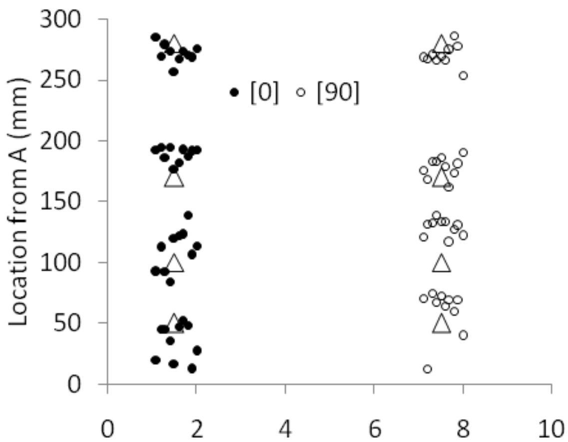

Figure 6. Source location determination for [0°] and [90°].

Table 1. Comparison between averages test results and it actual value.

	Calculated location (mm)	Actual location (mm)	Error (mm)
0°	34.97	50.00	15.03
	110.37	100.00	10.37
	188.91	170.00	18.91
	271.72	280.00	8.28
45°	36.96	50.00	13.04
	125.27	100.00	25.27
	163.78	170.00	6.22
	283.58	280.00	3.58
90°	59.98	50.00	9.98
	128.66	100.00	28.66
	178.28	170.00	8.28
	269.90	280.00	10.10

4. Conclusions

The experimental evaluation of linear source location detection using energy attenuation of acoustic emission signal has been presented. It can be concluded that the non-velocity dependent source location algorithm utilizing exponential model of AE signals energy attenuation shows a prospective approach for damage localization for composite materials.

Further investigation will be done using a more practical testing such as a standard tensile test for GFRP to further study the applicability and practicality the proposed algorithm. In addition, instead of only linear source location, 2D damage mapping of GFRP composite plate using the algorithm also will be investigated.

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