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WAVE PROPAGATION SCATTERING DUE TO DEFECT ON THIN COMPOSITE PLATES

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ABSTRACT

The engineering structures which based on laminated composites, have a high probability of unexpected damage development during services. The damage formations must be monitored from the beginning before it headed towards structural failure which could result in substantial damage. This lead to the necessity of Structural Health Monitoring (SHM) system to be installed during the construction of laminated composite structures. However, an understanding of damage area detection and damage characteristics is essential, before a SHM system can be integrated into the structures. This article presents the effects of propagating wave propagation through an existing damage on composite plates. Theoretically, a propagating wave that started from any source will vary when crossing an area with damage. This study shows a high frequency wave propagation (kHz range) show different reactions when passing through the damaged area, compared with the low frequency wave propagation. Results of the study will lead to good damage detection method, which utilizing the available vibration source; especially for the condition monitoring of thin laminated composite structures.

***Keywords*:** SHM; wave propagation; wavelet analysis; Gl/epoxy composites.

INTRODUCTION

Composite material is known as one of the catalyst for the growth of modern structures; especially the development of smart structures. For instant, a high ratio of material strength compared to its weight, causing it to become one of the main choices in aircraft construction. However, the structure of the composite material is exposed to the danger of the formation and propagation of internal damage, which barely predictable. Failure of the structure can be started from various causes, either during manufacturing process (e.g. voids) or when the structure is being used (e.g., impact or fatigue). It leads to the strong reason why an effective SHM system needs to be installed in every composite structure. One of the concepts in SHM; so called wave-propagation-based SHM is becoming popular recently. The idea is based on the propagation of acoustic waves. In general, this method is usually referred as guided waves, or ultrasonic guided waves, or Lamb waves. Croxford et al. (2007) has claimed that, the guided acoustic waves perhaps the only detection method that combines an acceptable level of damage detection sensitivity, with significant propagation range. Moreover, waveform analysis of the guided waves can provide more detailed information on the location and nature of smaller defect (Mal et al., 2005). A thorough literature study has been done by Diamanti and Soutis (2010) for the use of Lamb waves in aircraft composite structure and they concluded that this technique can lead to an active SHM for laminated composite structures; which utilizing embedded piezoelectric wafer into layered composite structures. Composite materials display a wide variety of failure mechanisms as a result of their complex structure and manufacturing processes, which include fiber failure, matrix cracking, buckling and delamination (Orifici et al. 2008). Damages can develop and propagate very slowly from inside the composite layers (e.g. matrix cracks, delamination and matrix-fiber debonding). As a result, it will affect material properties of the composites, such as, the material strength and the stiffness.

Formation of damage such as matrix cracking sometimes can be seen with the naked eye, however, the damage such as delamination, is a silent killer, in which case, it is almost impossible to detect from the surface of the structure. There are various methods, highlighted by the researchers to identify the damage in the composite structure; particularly for thin laminated composite plates such as the Fiber Bragg gratings, ultrasonic, acousto-ultrasonic, x-ray imaging, and acoustic emission (AE) methods (Kahandawa et al., 2012; Popovics, 2009; Muravin et al., 2010; Lam et al., 2009). However, the passive fault detection system was focused in this study, as it that can be used online, more practical, less equipment and relatively cheaper system. One of the main challenges for a passive system is to create the classifying technique which can evaluate the condition of the examined structures. In other words, passive monitoring must combine with a good signal analysis in order to produce a robust and reliable system. AE technique may suit the need. Despite of the fact that AE usage is highly established for metallic materials, however, there is a huge challenge in detecting the good AE signals that can be correlated to any damage formation and propagation; especially involving composite materials.

This present study highlights a different approach/concept which may be an alternative and more practical in the real application. The idea is, to manipulate the available vibration source in order to identify the existence of damage in thin composite plates. This concept can also be considered as a passive monitoring. Consider a composite structure that is constantly exposed to constant vibration; in any frequency range will produce wave propagation in the structure. For thin plates, this wave propagation is called as the Lamb waves. When the wave propagates through areas with damage, such as matrix cracking or delamination, this wave will change its form and some characteristics, as it is affected by the existence of the damaged area. This article will reveal the results of several experiments that have been carried out on a thin composite sample; in which a small hole has been made to indicate the presence of the damaged area.

EXPERIMENTATION

265 mm × 97 mm × 4.4 mm of Gl/epoxy resin laminates with a stacking sequence of $[0^{\circ}]_8$ were fabricated by hand lay-up method. A hole was drilled in the middle of the sample as indicated in the Figure 1. Two sets of case study were done, which were aimed to understand the effect of high frequency and low frequency wave propagation passing through damage area.

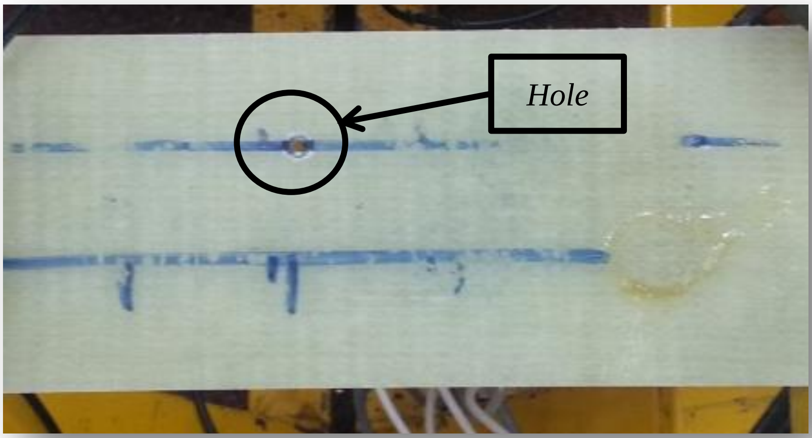

Figure 1. Gl/epoxy resin laminates for the experiments.

High Frequency Case

Figure 2 shows the experimental setup. Two piezoelectric sensors (labeled as number '1' and '2', as shown in Figure 2) were coupled to the surface of the plate. 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. The sampling rate for acquisition was set to 1 Mega sample per second and threshold was set to 45 dB.

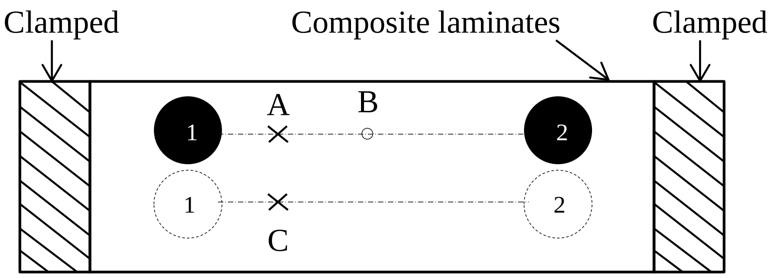

Figure 2. Set-up for 'high frequency source' test.

Point B states the hole's location. Pencil lead break (PLB) test was done at point A. PLB test was chosen as it can excite high frequency wave propagation, approximately 30 kHz. The signal propagation due to lead breaking will be acquired by both piezoelectric sensors. For this case, sensor '2' captured the signal which propagating across the artificial damage area (hole). Finally, for comparison, the lead breaking was also done at point C; as this area has no damage in between the sensors.

Low Frequency Case

The test arrangement was shown as in Figure 3. Both piezoelectric sensors were connected directly to a digital storage oscilloscope and the sampling rate was set to 100 kHz. An impact with hammer was done at point F in order to excite the low frequency wave propagation on the thin plates. The wave propagated and travelled crossing the point B, and then captured by sensor ‘1’. At the same time, sensor ‘2’ also detected the same signal; but it was not propagating through any damage area before reaching the sensor. Impacts were repeated at point E and F; where no wave propagation was expected to cross the damage area.

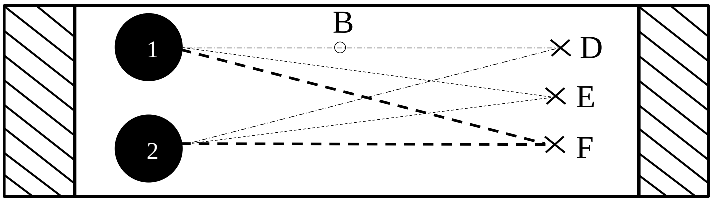

Figure 3. Arrangement for ‘low frequency source’ test.

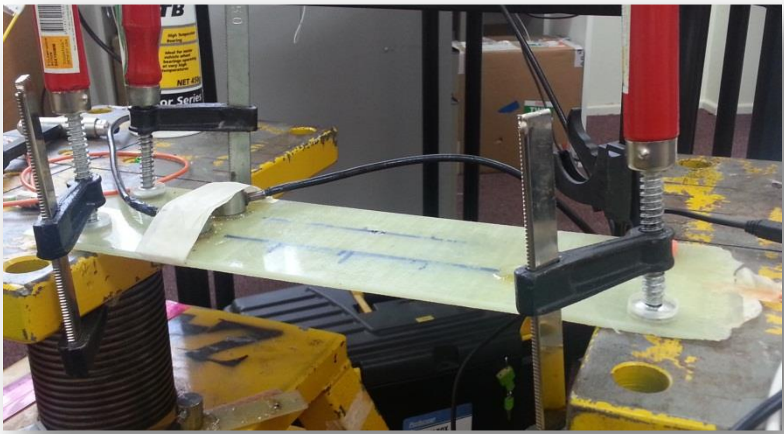

Figure 4. Specimen prepared before the low frequency impact by hammer.

RESULTS AND DISCUSSION

When a Lamb waves propagate past the damaged area, it will experience a wave scattering. The wave scattering effect due to defect on composite materials, has been discussed theoretically by some researchers. Wave scattering is varied depends on the propagating wave frequency range. Based on several experiments that have been done, the propagation of a high frequency wave experienced a very clear wave scattering, compared with the wave propagation of low frequency range.

High Frequency Case

Figure 5 and 6 show the waveform and its respective fast Fourier transform (FFT) of Lamb wave signals due to PLB at point A and C. It is difficult to evaluate the difference between the signals obtained from the two sensors; except an obvious reduction in the signal amplitude and signal energy, which is caused by the effects of attenuation. So too when looking at the results of comparisons of their FFT analysis. Therefore, further analysis is needed to see more clearly the effects of this wave scattering. However, the two major modes of wave propagation still can be observed, which they are always associated with lamb wave propagation; the flexural and extensional modes.

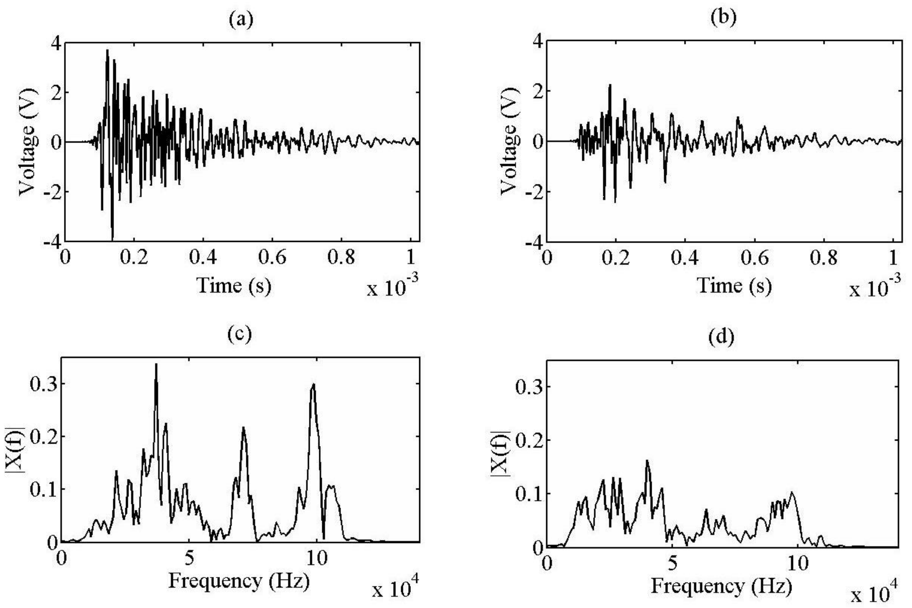

Figure 5. Response due to PLB at point A; (a) and (c) are from sensor ‘1’, while (b) and (d) are from sensor ‘2’.

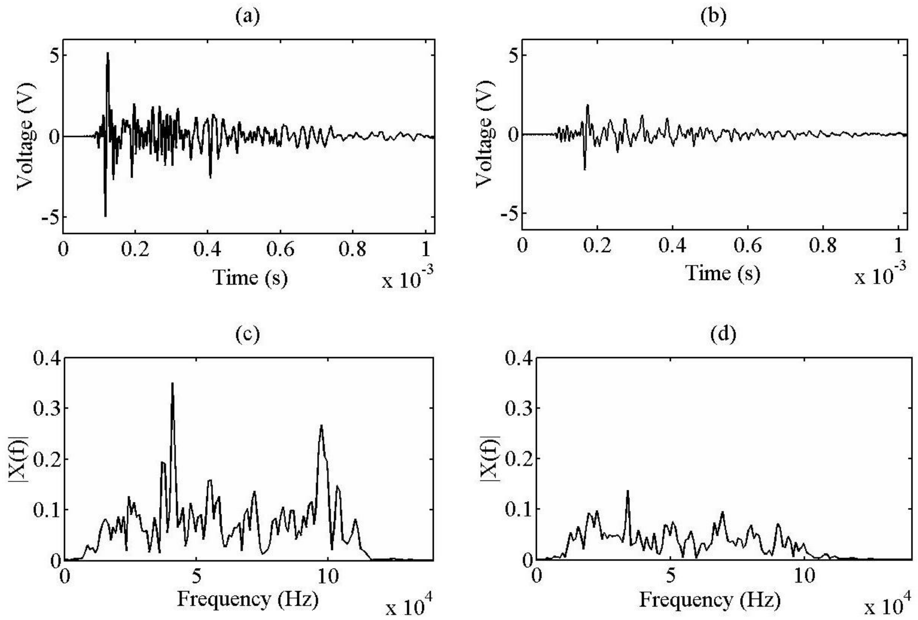

Figure 6. Response due to PLB at point D; (a) and (c) are from sensor ‘1’, while (b) and (d) are from sensor ‘2’.

Meanwhile Figure 7 shows the result after the Continuous Wavelet Transform (CWT) is performed on the signals. The CWT, one of the time-frequency analyses, can provide extra information from any given time domain signal (Jingpin et al., 2008; Hamstad et al., 2002; Zohari et al. 2012). The CWT of a function, as defined by Chui (1992), can be expressed as,

$$WT_f(s,\tau) = \frac{1}{\sqrt{s}}\int_{-\infty}^{\infty} f(t)\psi^*\left(\frac{t-\tau}{s}\right)dt \quad (1)$$

where $s > 0$ and the superscript * indicates the complex conjugate. The term $\psi(t)$ is the basic wavelet. The parameter s in Equation 1 stands for the scale of basic wavelet and is related to signal frequency. Meanwhile, the parameter τ stands for shift or position of basic wavelet and it can be related to the time of the signal. Plotting wavelet transform magnitude on $s - \tau$ axis gives the time-frequency view of a signal.

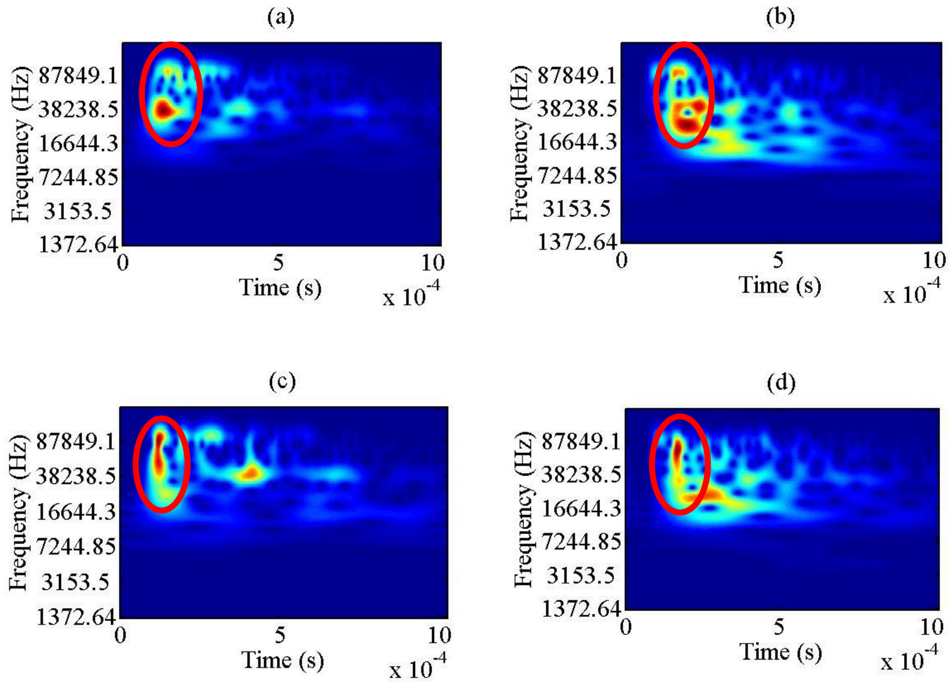

Figure 7. Wavelet analysis of the (a) signal from sensor '1' due to PLB at A; (b) signal from sensor '2' due to PLB at A; (c) signal from sensor '1' due to PLB at C; and (d) Signal from sensor '2' due to PLB at C.

There are many basic wavelets available and appropriate choice of it will give better result. In this study, Morlet wavelet which is identical to Gabor wavelet (Simonovski and Boltezar, 2003) and has similar shape as an impulse (Lin, 2001) was used. It can be defined as (Simonovski and Boltezar, 2003; Lin, 2001),

$$\psi(t) = \left(e^{-i\omega_0 t} - e^{-\omega^2/2}\right)e^{-t^2/2} \quad (2)$$

The scale, s can be related with the frequency by this relation,

$$\omega = \eta/s \quad (3)$$

where the coefficient η or can be written as wavelet centre frequency, ω_o is depends on the sampling frequency and the selected minimum scale; as explained by Simonovski & Boltezar (2003).

Now then can be clearly observed, the effect of changes in wave propagation which caused by the presence of the damaged area. The circles in Figure 7 (a, b) indicate the changes of the signal waveform in term of time-frequency analysis due to the existence of the artificial damage. Meanwhile, result in Figure 7 (c, d) show no significant variation.

For high-frequency wave propagation (kHz), the overall wave will traverse the existing artificial damage area (hole). This is because the wavelength is very small compared to the size of the hole. As the consequences, this lead to the overall impression of the waves undergoes scattering effect as shown in Figure 7. However, this outcome should not be confused by the wave dispersion and attenuation effect that it always occur when Lamb wave propagate in a thin plate.

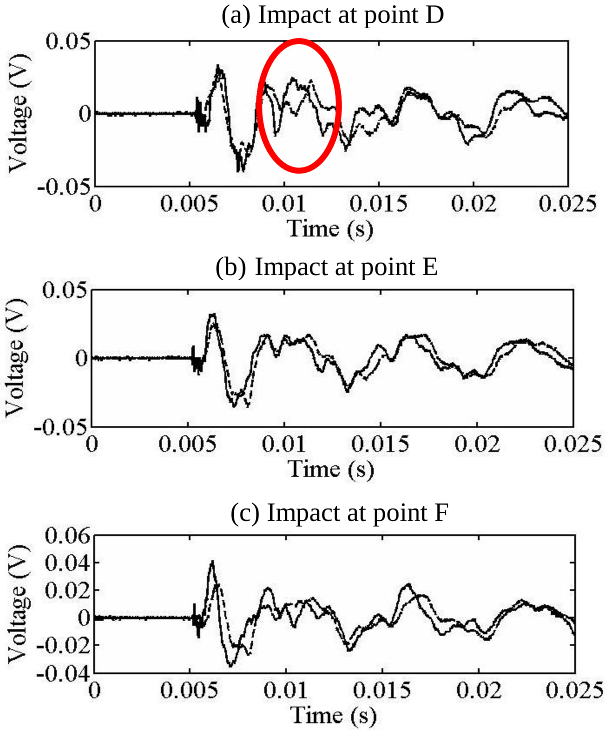

Figure 8. The effect of low frequency wave travelling across the perforated region (indicated by red circle). Two lines in each figures indicated the two waveforms which captured by two different sensors (sensor ‘1’ and sensor ‘2’).

Low Frequency Case

At the meantime, for low-frequency wave propagation, not the entire wave packet traversed the hole at point B. A part of the propagated wave seems to change a little compared with the wave which propagated without passing the perforated region. After a few test, it can be observed that almost 80 to 90 percent of low frequency wave which travel passing the artificial damage area, will have the changes as stated in the result in Figure 8. Figure 8 (a) shows that, if the impact by hammer was done at point D (refer Figure 3), there is a significant variation of the waveform which captured by sensor ‘1’ and sensor ‘2’; although the waveform actually came from the same source. This situation did not happen if the impact was done at other location (E and F). This is due to none of the source will propagate across the point B (the hole).

CONCLUSION

This study has been successfully reported on the effects of wave propagation traverse the defect area. In the case of a real composite structure, propagation may originate from various sources, such as engine vibration and rotation of the ball bearing. This investigation is still in the early stages and is very useful in order to develop an effective monitoring system for composite structures.

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