DEVELOPMENT OF A METHOD FOR CLASSIFYING CFRP FRACTURE MODES BY AE TESTING

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Abstract

Wavelet transform (WT) is one of the best analytical tools for AE and many researchers use WT to extract AE features such as group velocity of Lamb wave AE. T. Oshima et al. proposed improved WT named AP-WT using seismologic knowledge [1]. In the method, original AE waveforms are separated into amplitude dependent part called minimum phase shift function (MPS) and not amplitude dependent part called all pass function (AP). In this paper, two kinds of AE from matrix crack and delamination from CFRP were detected and analysed. Though both matrix crack and delamination are fracture of matrix, these fracture mechanisms are different and need to be separated to assure the integrity of CFRP structures. In this study, applicability of AP-WT to separate two types of AE was examined. The simulated AEs from different orientation fractures were easily classified by using AP-WT, although, it was difficult to separate AEs from matrix cracking and the delamination as noise was emphasized by AP-WT.

Keywords: Carbon Fibre Reinforced Plastic, Fracture Mode Classification, Lamb Wave, Wavelet Transform, Signal Processing, All Pass Function, Phase Shift Function

1. Introduction

Carbon Fibre Reinforced Plastic (CFRP) has been increasing and expanding the fields where it is used. CFRP is a composite material, which made from carbon fibre impregnated with resin matrix. Mainly, it is used in aerospace applications because of its high strength and light weight. As CFRP is applied to a critical section of structures, a structural health monitoring (SHM) method such as acoustic emission testing for detecting damage during service is highly required [2]. However, it is difficult to evaluate remained strength of the damaged CFRP structure, because CFRP has several fracture modes. For example, delamination highly affects compressive strength of CFRP structure while matrix cracking does not. So far, M. Eaton et al. revealed that fracture modes vary the measured amplitude ratio (MAR) value of the two primary Lamb wave modes [3]. For example, in-plane fractures such as matrix cracking get higher MAR value and out-of-plane fractures such as delamination get lower value. Though this MAR analysis is effective, it is time-consuming because MAR value has to be measured manually.

This paper focuses on extracting primary Lamb wave features corresponding to fracture modes by other method. Thus, to obtain both time and frequency information from AE waveforms, wavelet transform (WT) is applied to detected AEs. WT applied in the paper is an improved WT proposed by T. Oshima et al. [1] to clarify the result of WT in the wider frequency range. For the improved WT, original AE waveforms are separated into amplitude dependent part called minimum phase shift function (MPS) and not amplitude dependent part called all pass function (AP). General WT contour map of AE is useful to obtain peak amplitudes of dominant frequencies of AE, although, is not useful to obtain change in frequency respect to time since small amplitude signals may be buried by dominant large peaks in the contour map. As for AP-WT, amplitude information is eliminated, all frequency range can be obtained in the contour map. In this paper, two primary modes of Lamb wave
AE from different fracture modes were analysed by AP-WT and applicability of AP-WT for classifying AE signals were examined.

2. AP-Wavelet Transform

In order to obtain AP-WT contour map, the original waveforms are factorized into a minimum phase shift function (MPS) and an all pass function (AP) in frequency domain. Followings are procedures to obtain all pass function [1].

When a causal system function in frequency domain is defined as $H(\omega)$, the relationship between the real part and the imaginary part of $H(\omega)$ is expressed as below with Hilbert transform (HT).

$$\text{Re}[H(\omega)] = \text{HT}[	ext{Im}[H(\omega)]]$$

The relationship described in equation (1) is called Kramers-Kronig (K-K) relationship. K-K relationship also can be applied to the amplitude spectrum and the phase spectrum of the transfer function which satisfies causality. This is because the logarithm of the complex transfer function is also expressed as complex representation such as equation (2). Here, $i$ is imaginary unit and take care that the equation assumes that the amplitude spectrum $|H(\omega)|$ has no zero point.

$$H(\omega) = |H(\omega)| \exp\{i\varphi(\omega)\}, \quad \ln[H(\omega)] = |\ln H(\omega)| + i\varphi(\omega) \ldots \ldots (2)$$

AE signals also satisfy causality similar to seismic waves. Then the phase spectrum $\varphi(\omega)$ can be derived from the amplitude spectrum. The function composed of the amplitude spectrum and the phase spectrum derived from the amplitude spectrum is called minimum phase shift (MPS) function $F_{\text{MPS}}(\omega)$. $F_{\text{MPS}}(\omega)$ can be calculated by the amplitude spectrum of an AE waveform as shown in equation (3). Thus $F_{\text{MPS}}(\omega)$ is literally amplitude dependent part of the AE.

$$F_{\text{MPS}}(\omega) = |S(\omega)| \exp\{i\text{HT}[\ln|S(\omega)|]\} \ldots \ldots \ldots (3)$$

On the other hand, non-amplitude dependent part is obtained as below by dividing Fourier spectrum of the AE by MPS function. This function is called all pass (AP) function $F_{\text{AP}}(\omega)$. $F_{\text{AP}}(\omega)$ is eliminated the amplitude dependent part from the original AE. Therefore $F_{\text{AP}}(\omega)$ has no amplitude information as you can see in equation (4).

$$F_{\text{AP}}(\omega) = S(\omega)/F_{\text{MPS}}(\omega) = \exp\{i(\varphi(\omega) - \text{HT}[\ln|S(\omega)|])\} \ldots \ldots (4)$$

Finally, the frequency domain AP function is transformed into time domain. Then general wavelet transform with Gabor mother wavelet is conducted to the AP function and AP-WT contour map can be obtained.

3. AP-WT of simulated AE waveform

To compare the features of AP-WT with normal wavelet transform, these two WTs are applied to a simulated Lamb-wave AE. Lamb wave has two different propagation modes; asymmetric (A) mode and symmetric (S) mode and the amplitudes of these modes are affected by the orientation of AE sources; in-plane or out-of-plane. Schematic images of various fracture modes at CFRP are shown in figure 1. In the context of CFRP, in-plane AE sources are considered as a matrix cracking and out-of-plane AE sources are considered as a delamination. Though a fibre breakage must be in-plane fracture, it doesn’t matter for the classification because the AE from fibre breakage shows relative high amplitude and short
rise time comparing to other fractures. Therefore, by examining modes of Lamb wave AE, fracture modes can be classified.

![Various fracture modes of CFRP](image1)

**Figure 1. Various fracture modes of CFRP**

### 3.1 Simulation conditions

The two AE waveforms induced by in-plane and out-of-plane fracture were simulated by ultrasonic simulator (Wave 2000™: Cyber Logic Corp.). The propagation length of AE is set as 40[mm]. Isotropic plate with a 1.8[mm] thickness was assumed. Mechanical properties of the plate are set as a unidirectional 8ply CFRP laminate.

Generally, original AE waveforms at the source are distorted by several factors during propagation (See Fig. 2). In frequency domain, the recorded signals by the measurement device can be expressed as the product of these factors. The simulated AE waveform didn’t include these influences caused by the factors, so a band-pass filter shown in figure 3 was applied to simply simulate these factors. Note that actual distortion is more complicated than figure 3.

![Typical factors distort an original AE waveform](image2)

**Figure 2. Typical factors distort an original AE waveform**

![Band pass filter imitating the distortion factors of](image3)

**Figure 3. Band pass filter imitating the distortion factors of**
3.2 Results and discussion

The simulated signals before filtered and after filtered are shown in figure 4 and 5 respectively. The waveforms shown in figure 4 (a), (b) and even figure 5 (b) seems easy to apply MAR analysis since two predominant wave packets could be found. On the other hand, as for the waveform in figure 5 (a), it seems difficult to apply MAR analysis since there is only one wave packet.

![Simulated waveforms before filtered](image1)

**Figure 4.** Simulated waveforms at the condition explained in the section 3.1, but not filtered yet. (a) was from in-plane fracture and (b) was from out-of-plane fracture.

![Filtered simulated waveforms](image2)

**Figure 5.** Filtered, simulated waveforms at the condition explained in the section 3.1. (a) was from in-plane fracture and (b) was from out-of-plane fracture.

The results of normal WT and AP-WT applying to the simulated waves are shown in figure 6 and 7 respectively. As shown in the figure 6, only the dominant frequency of Lamb wave AE is observed in the contour map when normal WT is applied. The small amplitude wave is existed after the largest amplitude wave in the original wave (figure 5 (b)), although, the information related to the small amplitude wave doesn’t exist in WT contour map (figure 6 (b)). The smaller amplitude wave seems to be buried by the predominant peak.

On the other hand, the results of AP-WT (figure 7) shows wider frequency range compared to normal WT. The principal Lamb wave modes which are mainly measured experimentally are S\(_0\) and A\(_0\) modes. These modes have different features about frequency respect to time progress. S\(_0\) mode increases its frequency respect to time, while A\(_0\) mode decreases.

Frequency of AE by in-plane fracture increased with time as shown in figure 7 (a). On the other hand, Frequency of AE by out-of-plane fracture decreased with time as shown in figure 7 (b). These results correspond to the fracture orientation difference. Therefore, AP-WT will be able to use fracture modes classification more effectively compared to normal WT since AP-WT could clearly extract the Lamb wave’s feature.
4. AP-WT on measured AE waveforms

Normal WT and AP-WT were applied to the experimentally measured AE waveforms to evaluate effectiveness of AP-WT in actual situation. AEs from two kinds of fracture modes: matrix cracking and delamination were detected by AE sensor and analysed.

4.1 Experimental setup

Two specimens to generate matrix cracking and delamination were prepared respectively for the experiment. The specimens are 8-ply unidirectional CFRP plate with 1.8[mm] thickness. To generate exact fracture modes, notches or pre-crack were installed before the test. Experimental setup for matrix cracking is shown in figure 8 (a). Tensile load is applied to the specimen with two parallel notches. Matrix cracking is initiated at the tip of the notches. Figure 8 (b) shows setup to generate delamination. Pre-crack was installed at the right side of specimen before the test. Three-point bending test is conducted for this specimen.

For acquisition of AE, AE sensors (Physical Acoustics Corp. Type: PICO) were attached to the specimens with silicone grease as acoustic couplant. The acquisition was conducted at the sampling frequency of 5[MHz] with 600 sampling points using Physical Acoustics Corp. PCI-2 AE board & system.
4.2 Results and discussion

Figure 9 shows one of the typical AE waveforms measured during the experiment and figure 10 and 11 are the results of normal WT and AP-WT of detected AEs. The contour map of AP-WT shown in figure 10 was noisy and scattered compared to that of simulated waves as shown in figure 7. This is because noises are involved in experimental AE signals, and the noises are emphasized by eliminating amplitude information to obtain AP function. The noise problem should be solved, although, the results showed possibility of AP-WT to classify Lamb-wave AE. From the results of normal WT as shown in figure 10 does not show any dispersive nature of Lamb-wave AE. On the other hand, there was a trend of frequency varying respect to time in figure 11. In figure 11 (a), lower frequency (0~100kHz) was detected at around 50[µs] and high frequency (250~500kHz) was detected after 60[µs]. This frequency changing may be considered as the frequency increasing caused by S\(_0\) mode. Similarly, in figure 11 (b) higher frequency was detected at around 30 [µs] and lower frequency was detected at around 50[µs]. This frequency changing may be considered as the frequency decreasing caused by A\(_0\) mode. From these results, AP-WT can be used to judge the dispersion modes of Lamb wave and then can be used for fracture modes classification in plates.

5. Conclusion

AP-WT was applied to the simulated and measured AEs and compared to normal WT. With AP-WT, the simulated AEs from different orientation fractures were easily classified by extracting the feature of Lamb wave propagation mode. Applicability of AP-WT was also examined by using experimentally detected AEs. It was found that noises in AE signals were emphasized by applying AP-WT. The noise problem should be solved in future, although, it is also confirmed that AP-WT can be used for fracture modes classification.
Figure 9. Measured AE waveforms at the experiments which was explained in the section 4.1. (a) was from matrix cracking and (b) was from delamination.

Figure 10. Results of normal WT applied to the measured AE waveforms shown in figure 9. (a) was from matrix cracking and (b) was from delamination.

Figure 11. Results of AP-WT applied to the measured AE waveforms shown in figure 9. (a) was from matrix cracking and (b) was from delamination.

References
