Assessment of Impact Damages in Composite Laminates Using Wavelet Transform

Hyung-Joon Bang[1, a], Sang-Wuk Park[1, b], Ji-Yong Song[1,c] and Chun-Gon Kim[1,d]

[1]Dep. of Aerospace Engineering, Korea Advanced Institute of Science and Technology

373-1 Kusong-dong, Yusong-gu,Daejon 305-701, Korea

[a]joony@kaist.ac.kr, [b]zztwo@kaist.ac.kr, [c]jiysongkr@kaist.ac.kr, [d]cgkim@kaist.ac.kr

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Abstract. In this study, to know the attenuation characteristics of impact induced AE signals, low velocity impact tests were performed on composite plate by changing the impact distances from the PZT sensors. And then to quantify the variation of frequency characteristics of AE signals, sharing portion of the wavelet details were compared. In case of an impact damage occurrence, the sharing portion of wavelet detail D_4 shows an increment of 20 ~ 25 % over undamaged case. Therefore, the comparison of sharing portion change in wavelet details D_4 and D_1, largely changing components in damaged case, can be an effective criterion of the damage assessment in composite laminates from low-velocity impacts. Moreover, the wavelet details of AE signal show the consistent tendency in sharing portion regardless of the propagation length in composites medium. Thus this signal processing method can be effectively used as a damage assessment method of the applications that uses AE sensing for a structural health monitoring in composite structures.

1. Introduction

The frequency characteristics of AE from composites fractures change rapidly with time, therefore, recently, in order to know these transient characteristics of AE signals, time-frequency analysis methods, such as short-time Fourier transform (STFT) and wavelet transform (WT), are frequently applied to a structural damage assessment[1-2]. As the approaches to find the fracture characteristics of the composite materials, many successful researches have been conducted using the intensity level of a AE of the composites fractures [3-4]. However, without considering the attenuation property of the AE signal on composite materials, the damage estimation scheme using the intensity level of AE component would make errors in estimating the structural fractures.

In this research, we investigated the frequency characteristics of impact induced AE signals focused on the leading wave in advance and chose the key factors to discriminate the damaged condition quantitatively. And then, we established a damage assessment technique using the sharing percentage of the wavelet detail components, and conducted a low-velocity impact test on composite laminates to confirm the feasibility of the proposed signal processing method.

2. Signal Processing

In order to quantify the variation of frequency characteristics of AE signals, the shared portion of the wavelet details were compared. To decompose impact induced AE signals, we used the Daubechy 4(*db4*) wavelet basis function, which it is suitable to analyze irregular transient signals, such as composite fractures. In the first procedure of the signal processing, a 1 *MHz* sampled input signal was saved in a data logger and then decomposed into 4 level wavelet details, $D_1^{1M} \sim D_4^{1M}$, by using the *db4* wavelet basis function. The upper index refers to the sampling frequency of acquired signal and the lower index refers to the decomposition level of the wavelet components. In the second stage, a 5-points moving average process is applied to eliminate the noise components, such as bit noise. Then, a numerical integration is performed to calculate the energy portion of each wavelet detail. Finally, the integrated shared portion of the wavelet details is calculated and compared to investigate the effect of signal attenuations and fracture characteristics in composite materials.

3. Experimental Setup

The composite plate specimen was made of CU-125NS (Hankook Fiber Glass Co., Korea) carbon/epoxy prepreg with a stacking sequence of $[0_2/45_2/\text{-}45_2/90_2]_s$ and cured in an autoclave. The specimen had a squared shape with 830×830×2 (w×l×t) *mm* dimension, and the 30 *mm* of the four edges were rigidly fixed by the clamp so the test area becomes 770×770 mm^2.

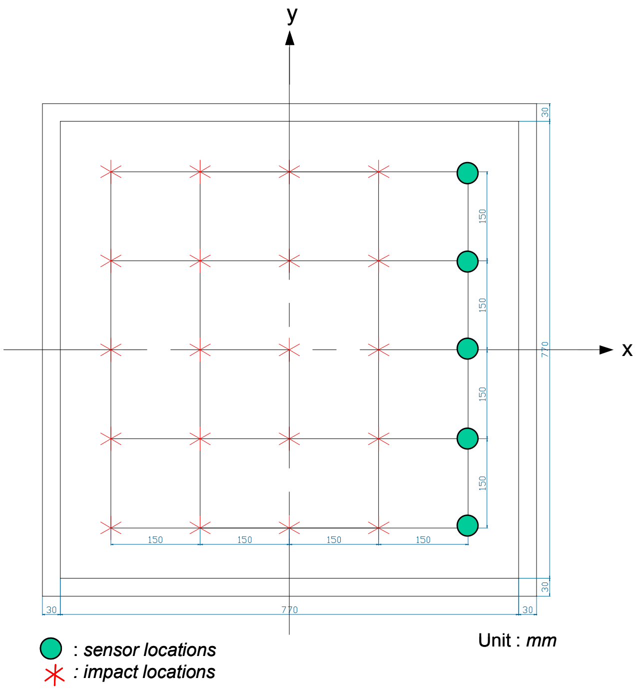


Fig. 1 Locations of acoustic sensors and drop impacts in the composite panel specimen.

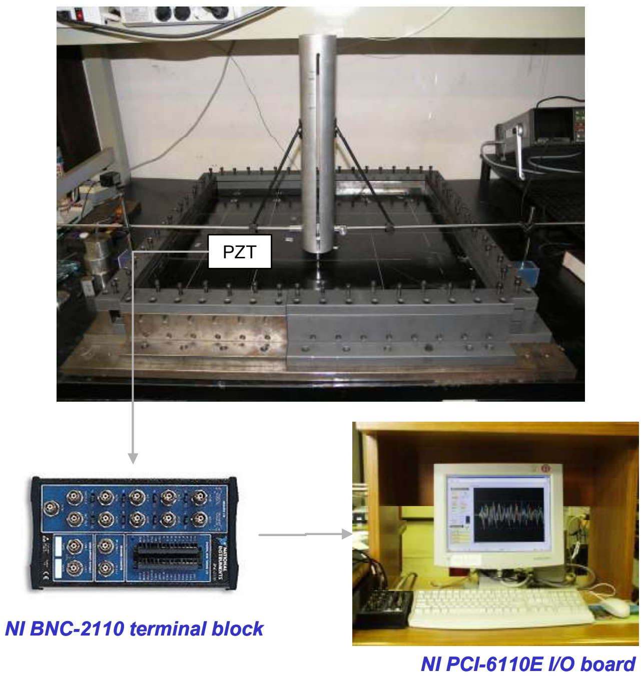


Fig. 2 Experimental setup of low-velocity impact test using PZT sensors.

Fig. 1 shows the locations of the PZT sensor and the applied impact. In the figure, the x-axis is parallel to the 0°fiber direction of the composite laminates. On the surface of the composite panel, 5 PZT sensors (C6, Fuji Ceramics co., Japan), each 5 *mm* in diameter, were bonded using cyanoacrylate (CN, TML co., Japan) adhesive. From 150 *mm* to 600 *mm*, four impact locations were selected to have different path length of AE propagation with 150 *mm* spacing. The experimental apparatus is presented in Fig. 2. Impact loads were applied by dropping the guided weight, of which the impact point was rounded with a 10 *mm* diameter, and impact energy was changed by controlling the mass of the weight and dropping height. To make the impact induced delamination, which is not invisible from external observations and only can be found by the NDE methods as C-SCAN, we applied impact energy of 5.0 *J* and compared the results with the undamaged case of 0.1 *J* impact energy. To acquire the infinitesimal AE signals, such as delamination in composite materials, a data acquisition system must have high input resolution. In this experiment, we used a PCI-6110E (National Instrument™, U.S.A.) data acquisition board which has input resolution and sampling rate of 16 *bit* and 4 *MHz*, respectively.

4. Experimental Results and Discussion

Fig. 3 shows the shape of a dented surface on the composite plate and C-SCAN image of low velocity-impact induced delamination. When 5.0 *J* of impact energy is applied to the composite specimen, a delamination of 15 × 20 mm^2 is observed inside the composite laminates.

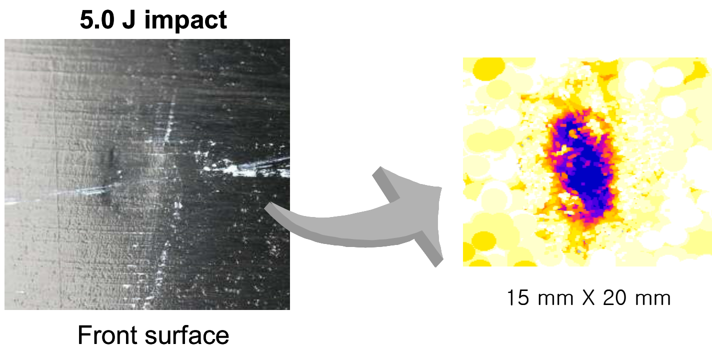
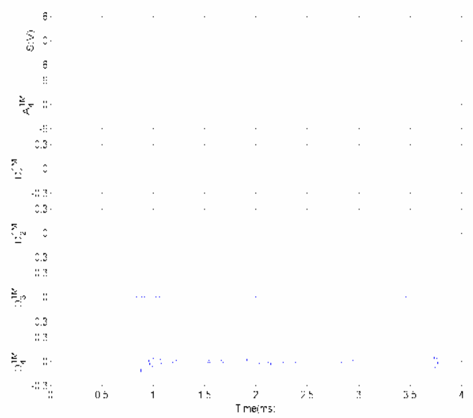
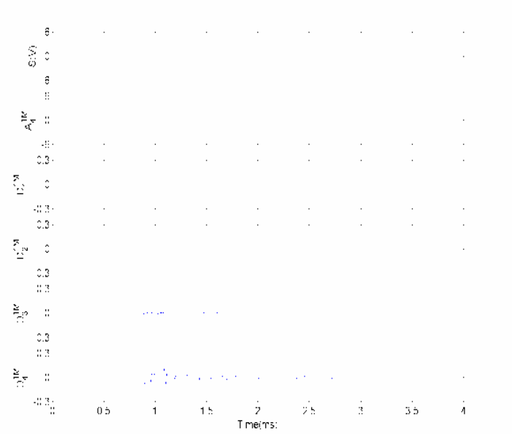


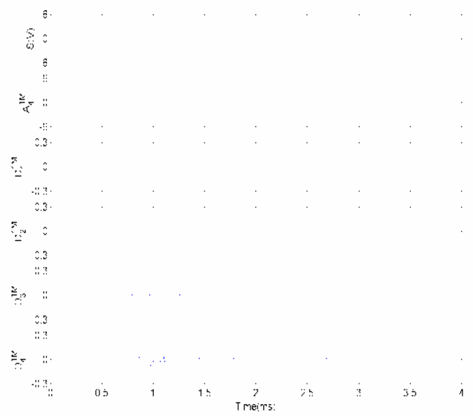
Fig. 3 Investigated delamination in the $[0_2/45_2/\text{-}45_2/90_2]_S$ carbon/epoxy composite plate using C-SCAN.

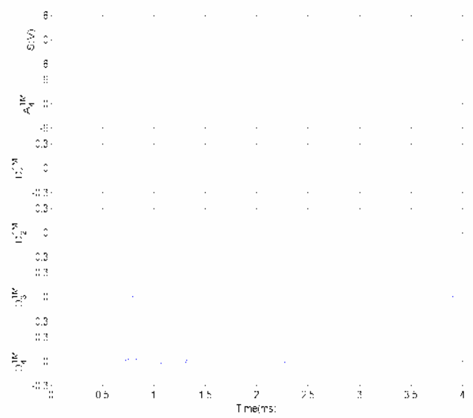
Fig. 4 shows the wavelet-transformed results of AE signals induced by 5.0 *J* impact energy, with different propagation distances. It is known that ultrasonic AE signal over 20 *kHz* are generated when a structural fracture occurs in composite materials. Investigating the wavelet details from D_1^{1M} to D_4^{1M}, ultrasonic AE signals are observed in the wavelet detail components of D_3^{1M} and D_4^{1M}. Because the frequency range occupied by the wavelet detail of D_3^{1M} and D_4^{1M} covers a range of 0 ~ 160 *kHz*, which is coincident with the frequency range of delamination fractures in composite materials; therefore, it is predicted that the AE signal is generated from the delamination between composite laminates. Observing the raw signals *(S)* in Fig. 4, leading wave releases about 0.3 *ms* and shows consistent wave shape with little differences in signal magnitude.





(a) 15 cm (b) 30 cm



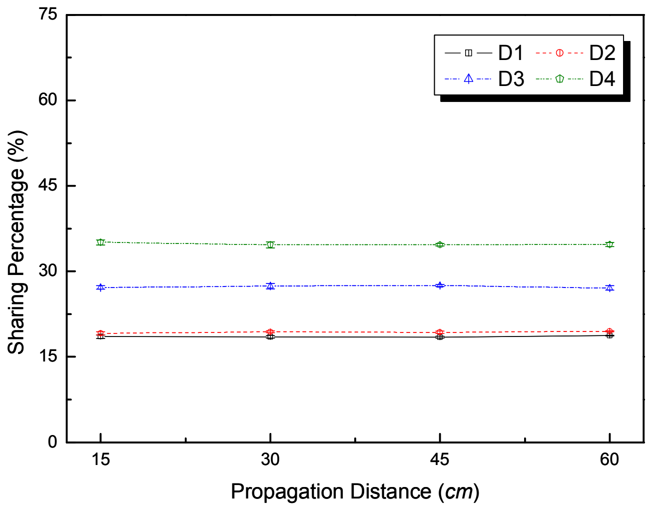


(c) 45 cm (d) 60 cm

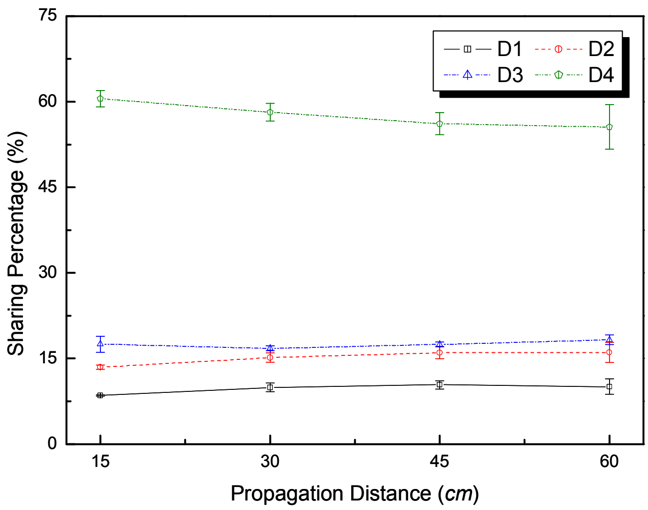
Fig. 4 Wavelet transformed results of 5.0 *J* impact induced signals as the change of propagation length.

The impact signal in Fig. 4(a), which is generated from the impact location 150 *mm* away from the PZT sensor, shows an ultrasonic AE signal in the leading wave region of wavelet details D_3^{1M} and D_4^{1M}, and this AE signal lasts about 0.3 *ms*. These high frequency fracture signals tend to show reduced magnitude in the signal propagation length, while the dispersion time increases with propagation distance. The dispersion time of the AE signal in wavelet detail D_4^{1M} is 0.3 *ms* at 150 *mm* impact location, and it increased to 0.7 *ms* at 600 *mm* impact location.As a result, the intensity of the AE signal decreases with the propagation length due to the signal attenuation property of composite materials; therefore, there is a possibility of misjudgment in damage detection only using the intensity level of AE signals in damage assessment.

Fig. 5 is a comparison of shared portions in wavelet detail components for the different propagation distances. Fig. 5(a) shows the result of 0.1 *J* impact. In this undamaged case, the shared portion of wavelet details is as follows in order, D_4^{1M} is 35 %, D_3^{1M} is 27 %, and D_2^{1M} and D_1^{1M} show similar percentages of 18 ~ 19 %, respectively. Moreover, we can confirm that the sharing percentage of the wavelet details show a consistent result without being influenced by the propagation distance of AE signals within the maximum propagation distance of 600 *mm*. Fig. 5(b) is the signal processing result of 5.0 *J* impact cases, in which the delaminations are generated by the low-velocity impacts. As a result, in the structural damaged case, the wavelet detail component D_4^{1M} shares the portion of 56 ~ 61 %, D_3^{1M} and D_2^{1M} shares 16 ~ 18 % and 13 ~ 16, respectively, and the highest frequency component D_1^{1M} has the smallest sharing percentage of 9 ~ 10 %. From the above results, the frequency portion of wavelet details D_4^{1M} and D_1^{1M} is largely changed in the damaged case compared with the undamaged case. For the D_4^{1M} wavelet component, the shared portion shows an increase of 20 ~ 25 % over the undamaged case, and the portion of D_1^{1M} decreases by 10 % compared with undamaged case. This changing rate of the sharing proportion in wavelet details is sufficient information to discriminate the structural conditions between sound and damaged cases, and these frequency characteristics show consistent tendencies regardless of signal attenuations in composite materials.



(a) 0.1 *J*



(b) 5.0 *J*

Fig. 5 Comparison of shared portion of wavelet detail components $D_1^{1M} \sim D_4^{1M}$ of impact induced signals as the change of propagation length;
(a) 0.1 *J* impact energy (b) 5.0 *J* impact energy.

Fig. 6 is the integrated result of Fig. 5. In Fig 6, every result of each propagation distance is averaged. In the undamaged case, there is not much difference in the shared portion between any of the wavelet details. However, in a case in which a high level of impact energy is applied to composite laminates inducing structural fractures, the shared portion of D_4^{1M} shows an increment of 25 % in the maximum case. Therefore, the comparison of shared portion change in wavelet details D_4^{1M} and D_1^{1M}, largely changing components in the damaged case, can be an effective criterion of the damage assessment in composite laminates from low-velocity impacts.

Summarizing the above results, because the AE signals are largely attenuated in composite materials it is hard to evaluate the structural healthiness by only using the intensity characteristics of impact induced AE signals. However, the shared portion of the wavelet details is scarcely affected by the boundary conditions and signal attenuations; thus, the shared portion is suitable to be applied to detect fracture events in composite structures.

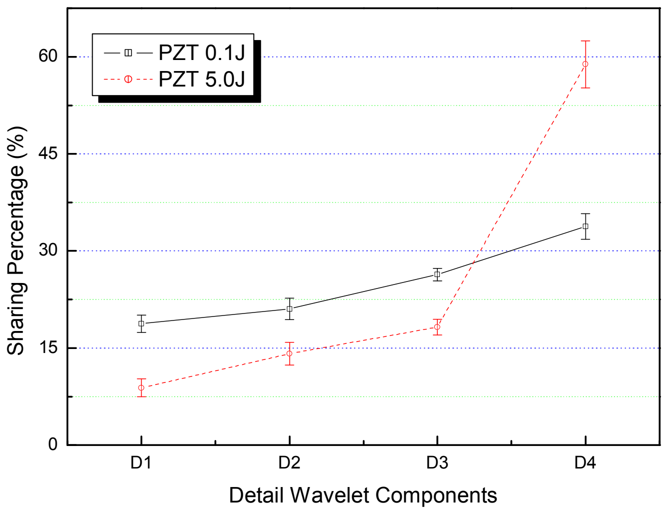


Fig. 6 Comparison of shared portion of wavelet detail components between undamaged case (0.1 J impact) and damaged case (5.0 J impact).

5. Summary and Conclusion

In this study, to know the attenuation characteristics of impact induced AE signals, low velocity impact tests were performed on a composite plate by changing the impact distances from the PZT sensors. Then, to quantify the variation of frequency characteristics of AE signals, the sharing portions of the wavelet details were compared. If impact damage occurs, the most drastically changed wavelet detail component is D_4^{1M} and the shared portion shows an increment of 20 ~ 25 % over the undamaged case. Consequently, the wavelet details of an AE signal show a consistent tendency in the shared portion, regardless of the propagation length in composites medium; thus, this signal processing method can be effectively used as a damage assessment method for applications that use AE sensing for structural health monitoring in composite structures.

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