Cover page

Title: Simultaneous Monitoring of Impact Locations and Damages Using Neural Networks and Wavelet Analysis

Authors: Dae-Un Sung
Chun-Gon Kim
Chang-Sun Hong

ABSTRACT

Low-velocity impact is a major concern in the design of structures made of advanced laminated composites, because it can cause extensive delaminations inside composites that can severely degrade the load-carrying capability. It is necessary to develop the impact monitoring techniques providing on-line diagnostics of smart composite structures susceptible to impacts. In this paper, we report on the simultaneous monitoring of impact locations and damage states. Up to now, the impact problems of composite laminate were classified into two main directions. One was the impact identification and the other was the detection of impact damages such as delaminations. This study focuses on the integrated approach for both two objects by PZT sensors. We discuss the procedures of impact location detection in which the generated acoustic signals are detected using PZT by the improved neural network paradigms. Simultaneously, the sensor output is processed with the Wavelet Transform (WT) to monitor the Acoustic Emission (AE) waves by the occurrence of damages and the result is compared with that of the undamaged case.

INTRODUCTION

Due to recent advances in sensor technology, a new concept of damage diagnostics for monitoring the integrity of in-service structures has been proposed. This concept is generally known as a health monitoring of smart structures. The health monitoring system must estimate structural health by using all of the information provided by the various sensor measurements. The impact monitoring process especially involves in the tracking of impact. The event and location of an impact load can be identified by the propagating acoustic waves. Simultaneously with the impact identification, the diagnostics of impact damages can be carried out to determine whether the incipient damage is initiated or not from the information of the AE waves.

Recently, Chang et al. [1] proposed the techniques for the reconstruction of force history and the determination of impact location by minimizing the difference between modeled response and actual response from built-in piezoceramic sensors. The response comparator

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Korea Advance Institute of Science and Technology (KAIST), 373-1 Kusong-Dong Yusong-Gu, Taejon, 305-701, KOREA.

using an optimization algorithm was applied to compare the responses. However, these techniques are in many cases a time consuming process. Moreover, the response of real complex structures cannot be the same as the modeled response, because the result of this analytical method can be more influenced by boundary conditions, noises, and vibrating conditions of structures. An alternate approach to identify the impact location of a composite structure is to use a neural network [2]. These approaches used several kinds of information as the input data such as the differential signal arrival times of propagating acoustic waves and the integrated real and imaginary parts of the FFT of four strain signals. In this study, neural network paradigms are used for an inverse problem solver. This method may be easily applied when a specific equation or algorithm is not applicable, but when adequate knowledge or data exists to derive a knowledge-based solution.

The Active sensing diagnosis (ASD) was proposed to detect impact damage in in-service composite structures using piezoceramic sensors and actuators to generate and receive diagnostic waves by Chang [3]. The passive sensing diagnosis (PSD) without actuators may be simpler and more lightweight than the ASD system. Recently, the PSD method using the time-frequency analysis has been issued. The WT method can provide the time-frequency localization from sensor signals. The WT itself is a more intuitive decomposition of the data since it provides simultaneous time-frequency localization at multiple resolutions. Being a more flexible method of time-frequency decomposition, wavelets can describe signal characteristics in a much more precise manner and result in more accurate feature extraction. Several researches show that the WT can be a powerful tool for condition monitoring and fault diagnosis by using its ability to "zoom in" on short lived high frequency phenomena for the analysis of transients [4-5]. Though the WT has been applied to the diagnostics of transient vibration signals of machinery, this has been rarely used for damage diagnostic application to composite laminates.

This paper mainly focuses on the integrated approach for both two objects by PZT sensor system. This paper proposed the simultaneous impact monitoring techniques to identify the impact location and to detect the impact damage using the propagation property of acoustic waves and the AE waves. This paper proposed that the PSD method using the WT could be applied to monitor the AE signals due to damage initiation of composite laminates during the low velocity impact. The fundamental researches have been carried out to identify the impact location of composite laminates and the laminates with a circular hole. Then, we investigated the time-frequency characterization of the AE signals in the case of matrix cracks and delaminations respectively.

FUNDAMENTAL APPROACHES

The fundamental researches have been carried out to identify the impact location of composite laminates. Moreover, the time-frequency characteristics of impact damages have been investigated by the WT. The propagating acoustic waves due to impacts have a complex non-linear property on the wave velocities of composite laminates. The neural network using the Levenberg-Marquardt (LM) algorithm with the generalization methods was used for the identification of the impact location using the arrival time differences of acoustic waves. It was found that the AE waves generated by impact damages are undistinguishable from each damage mode and the amount of damage by the conventional analysis methods in time or frequency domain. The Fourier transform decomposes a signal into its various frequency

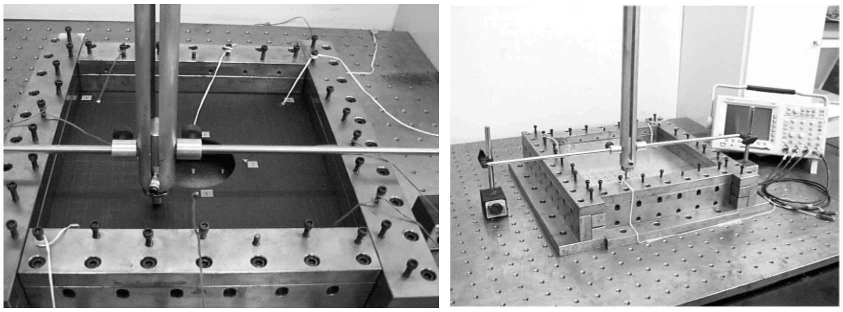


Figure1. The experimental setups for the low-velocity impact test.

components. Because it uses the sinusoidal basis functions that are localized in frequency only, it loses the transient feature of the signal. Therefore, it is necessary to implement the time-frequency analysis for diagnostics of a transient signal such as that induced by damage. The WT can be a powerful tool for condition monitoring and fault diagnosis by using its ability to "zoom in" on short-lived high frequency phenomena for the analysis of transients. The WT can decompose the AE waves in time and wavelet scale domain and catch the differences of these waves. It makes possible to distinguish the damage modes and size by the decomposed wavelet details. The experimental setups are shown in Figure 1.

Impact Identification by Neural Networks

The acoustic wave velocity is dependent on the material property, the wave frequency and

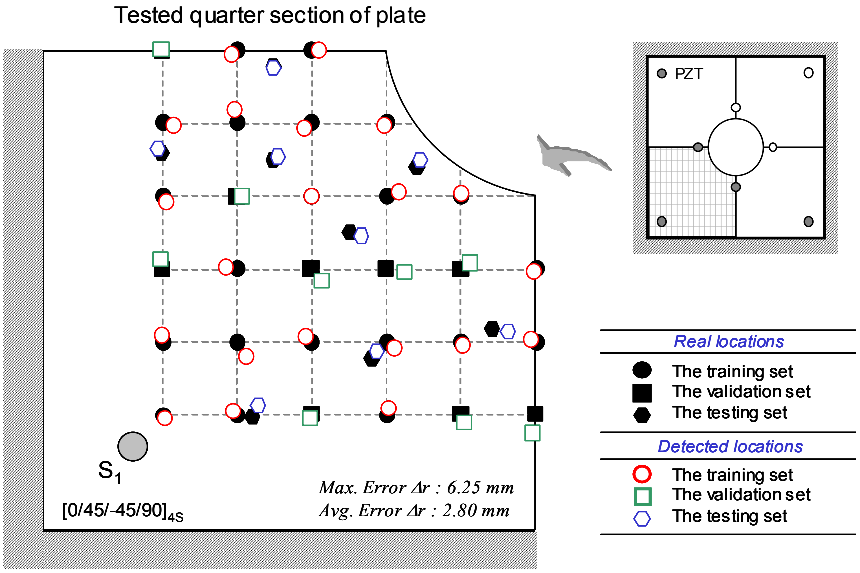
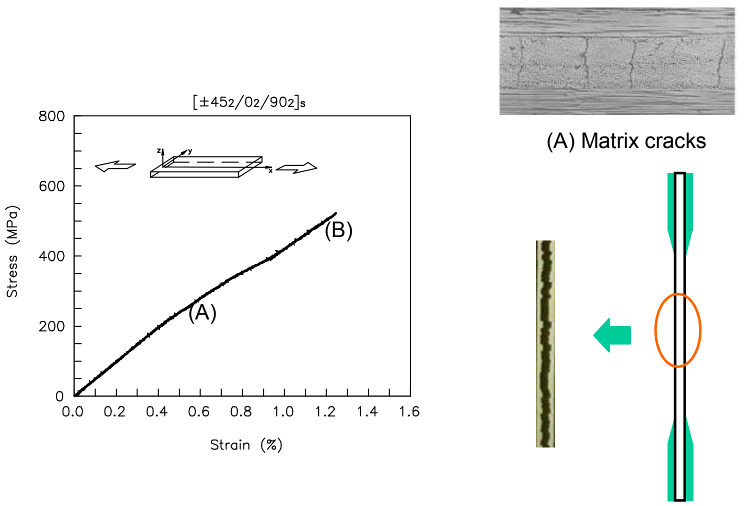


Figure 2. The results of the detection of impact locations of $[0/45/-45/90]_{4S}$ laminates with a circular hole.

the type of waves. In the case of composite laminates, the acoustic wave velocity varies with the direction of propagation because the wave propagates faster along fiber rather than matrix. Neural networks can be applied to make a nonlinear modeling for the differential arrival time of acoustic waves at a certain location of impacts. One inherent advantage in using neural networks is that their performance is independent of a particular system's complexities; the physics of boundary conditions and the velocity of acoustic waves, etc. It was discovered that the backpropagation Multi-Layer Perceptron (MLP) was adequate for the impact location detection. In this paper, the LM algorithm for nonlinear least squares was incorporated into the backpropagation algorithm for training the MLP. The algorithm was tested on many function approximation problems, and was compared with a conjugate gradient algorithm and a variable learning rate algorithm. In general, on networks that contain up to a few hundred weights the LM algorithm will have the fastest convergence. Another problem that occurs during the neural network training is called overfitting. The error on the training set is driven to a very small value, but when new data is presented to the network the error is large. The network has memorized the training examples but it has not learned to generalize to new situations. We used two methods for improving generalization: regularization and early stopping methods. This predicted the location of impact under the error of 6.25 *mm* in radial direction on a 330 *mm*×330 *mm* $[0/45/-45/90]_{4S}$ Graphite/Epoxy laminates with a circular hole, as shown in Figure 2. The influence of boundary condition on the accuracy of impact location was also studied.

Impact Damage Characterization

This research provides the real-time in-service damage monitoring techniques using the time-frequency analysis of PZT sensor signals. PZT sensors were utilized to monitor the impact events. These can be used as wide-band transducers of low-frequency vibrations and high-frequency acoustic emission waves. We chose PZT sensors suitable for detecting the frequency range from 20 *kHz* to 360 *kHz* that is known as the general frequency range of the



(A) Matrix cracks

(B) Free-edge delamination

Figure 3. The evolution of matrix cracks and free-edge delaminations in tension of $[\pm 45_2/0_2/90_2]_S$ beam.

AE during the initiation of damage such as delaminations in composites laminates. These techniques present the simultaneous monitoring of damage at the time of impact events. Time-frequency analysis can be implemented by the STFT and the WT. The STFT cannot be a local spectral density because of the continuing nature of harmonic waves. Moreover, it is impossible to achieve high resolution in time and frequency simultaneously.

The WT decomposes a signal into a set of basis functions that are localized in both time and frequency. Each wavelet function $\Psi_{a,b}(t)$ is a stretched or narrowed version of a prototype wavelet $\Psi(t)$,

$$\Psi_{a,b}(t) = \frac{1}{\sqrt{a}}\Psi\left(\frac{t-b}{a}\right) \tag{1}$$

where $a \in R^{+}$ and $b \in R$ are scale and shift parameters, respectively.

The Continuous Wavelet Transform (CWT) is defined as follow,

$$\begin{aligned} W_{\Psi x}(a,b) &= \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} x(t)\Psi^{*}\left(\frac{t-b}{a}\right)dt \\ &= \left\langle \Psi_{a,b}(t), x(t) \right\rangle \end{aligned} \tag{2}$$

That is, we measure the similarity between the signal $x(t)$ and the shifts, scales of an elementary function. Because the wavelet basis function is localized in both time and frequency, it can act as multi-scale band-pass filters when convoluted with the signal data. From the Discrete Wavelet Transform (DWT), a signal can be represented by its approximations and details. The approximations are the low frequency components of the signal decomposed by the high-scaled wavelet basis function. The details are the high frequency components of the signal decomposed by the low-scaled wavelet basis function. By

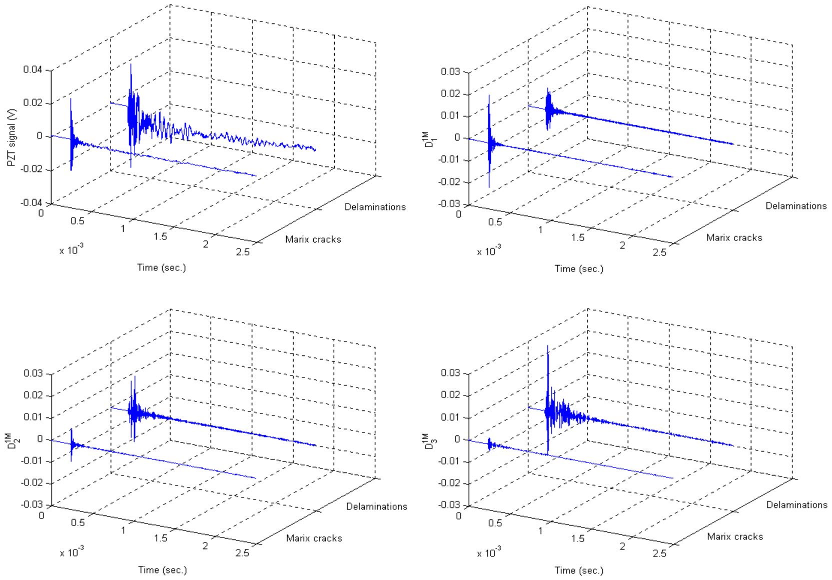


Figure 4. The comparison of details D_1^{1M}~ D_3^{1M} of PZT signals of matrix cracks and free-edge delaminations by DWT.

selecting different dyadic scales, a signal can be broken into many lower-resolution components, referred as the wavelet decomposition tree. The high frequency AE waves of PZT signals can be decomposed into several details 'D_j'.

The characteristics of the PZT signals due to matrix cracks and the evolution of free-edge delamination were analyzed by the WT. Tension tests were performed to investigate the AE waves due to matrix cracks and free-edge delaminations using $[\pm45_2/0_2/90_2]_S$ Gr/Ep specimens. The stress-strain curve and the picture of damage modes are shown in Figure 3. The differences of transient characteristics of the AE waves due to matrix cracks and delaminations can be identified by the time-frequency analysis. The WT can be used to characterize damage modes by measuring the transient decomposed signals of a certain scale level of wavelets. The results are shown in Figure 4. The details are indicated by D_1^{1M} of which the subscript represents the level of decomposition and the superscript represents the sampling frequency. The details D_1^{1M}, D_2^{1M} and D_3^{1M} represent approximately 300~400 *kHz*, 140~240 *kHz*, 80~100 *kHz* signal range respectively from the calculation of approximate frequencies. Therefore, these details can represent the characteristic frequencies of AE signals. As the selection of wavelet functions, these details can show detailed characteristics that could not be represented by the harmonic function based analysis. Figure 3 shows that the AE signals due to matrix cracks are dominantly composed of the detail D_1^{1M}. However, the AE signals due to delaminations are mainly composed of D_2^{1M} and D_3^{1M}. These trends coincide with the frequency characteristics. From these results, delaminations known as the primary damage mode of low velocity impact can be detected by observing the details D_2^{1M} and D_3^{1M}.

SIMULTANEOUS IMPACT MONITORING

From the results of basic researches, these procedures were implemented to the

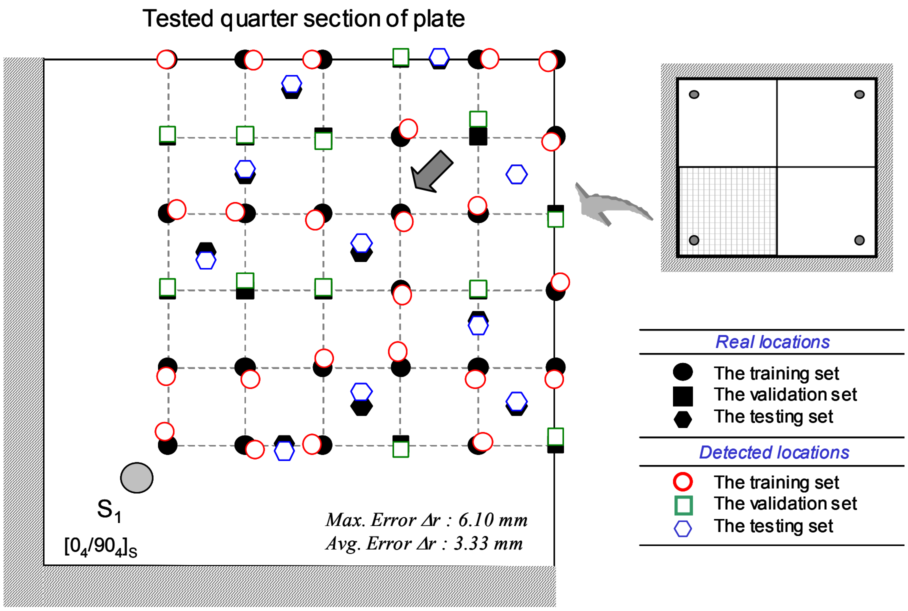


Figure 5. The results of the detection of impact locations of $[0_4/90_4]_S$ laminates.

simultaneous impact monitoring of 330 *mm*×330 *mm* $[0_4/90_4]_S$ Graphite/Epoxy laminates. Firstly, the same neural network paradigm was trained using the arrival time differences of acoustic waves. The energy of impact was fixed to 0.3 *J*. In this case, the acoustic wave velocity much varies with the direction of propagation than the case of quasi-isotropic laminates, because the wave propagates faster along fiber rather than matrix. This non-linear property produced much more error of detection than the case of quasi-isotropic laminates. Figure 5 shows the results of the identification of impact locations. After training of neural network, the drop-weight type impact test was carried out to simulate the low-velocity impact. The arrow in Figure 5 represents the test impact position. The impact energy was chosen to generate delaminations. First, the laminated plate was subjected to 8.0 *J* impact. After impact, delaminations having the dimension of about 40 *mm*×20 *mm* were measured by the C-Scan. Second, after 10.8 *J* impact, the size of delaminations was about 60 *mm*×25 *mm*.

Results of Impact Monitoring

The trained neural network could identify the impact location. The error of detected location was 7.64 *mm* in radial direction. The much more error was produced in the higher energy level of impact. Because the neural networks trained by the fixed 0.3 *J* impact, the much higher energy makes another leading waves slightly different from small energy impact. This affected the accuracy of detection. Simultaneously, the PZT signals were analyzed to decompose the AE waves along time domain by the WT. Figure 6 shows the wavelet details D_1^{1M}~D_3^{1M}. This figure shows that the AE signals of impact damages are dominantly composed of the detail D_1^{1M}. We can detect the occurrence of delaminations. Moreover, we can estimate the time of damage evolution by the WT. We can estimate the matrix cracks was

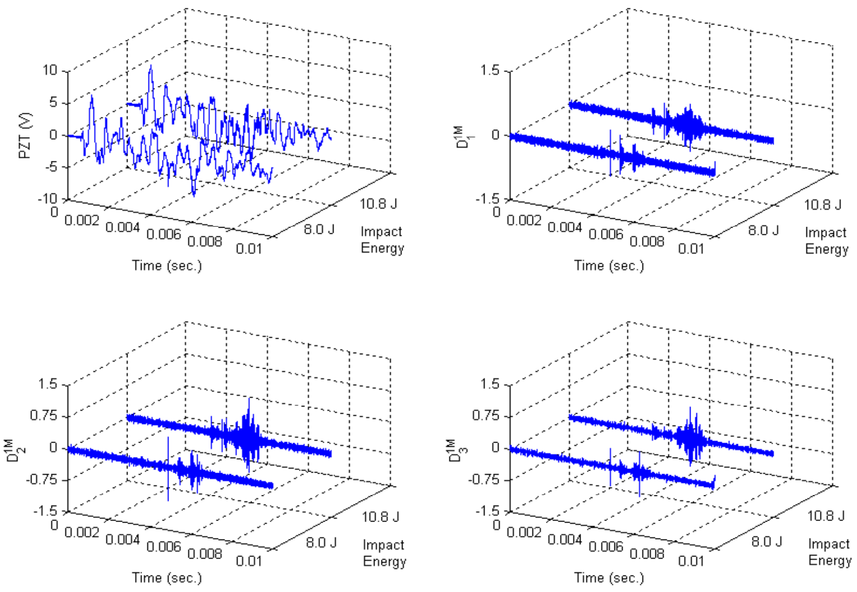


Figure 6. The comparison of details D_1^{1M}~ D_3^{1M} of PZT signals of 8.0 *J* and 10.8 *J* impacts by DWT.

generated at the same time. The higher amplitudes of the details D_1^{1M}~D_3^{1M} were observed in the 10.8 *J* case than the 8.0 *J* case that makes the smaller size of delaminations. These make it possible to monitor the damage state by measuring the interested detail components by adjusting the scale level. Because the voltage resolution of Digital Storage Oscilloscope is 120 mV in the ±4 V, the one-bit noises prevent the PZT signals under 120 mV. The data acquisition board having the higher voltage resolution should be used in the future experimentation. This would help to have a clear detail signals.

CONCLUSION

In this research, we have presented the impact monitoring techniques to detect the location of impact, to determine the occurrence of damage and to estimate the qualitative severity of damage simultaneously. The neural network using the LM algorithm with the generalization methods predicted the location of impact with the accuracy of about 5 *mm* error in radial direction. We also have presented the PSD using the time-frequency analysis like the WT on the determination of the occurrence of damage and the estimation of damage. It can be carried out simultaneously with the detection of impact locations using the same PZT sensor. We can confirm that the WT can be the better monitoring tool for the analysis of the transient signals like damage-induced signals. This makes it possible to examine the interested multi-band frequency range by adjusting the wavelet functions. These results show the possibilities of simultaneous monitoring of impact locations and damages. Future works include the impact monitoring of a stiffened composite plate and real-time data acquisition and processing programming.

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