論文

압전 변환기를 이용한 복합재료 보의 비파괴 평가

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Quantitative Nondestructive Evaluation in Composite Beam Using Piezoelectric Transducers

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초 록

본 연구는 압전 변환기를 이용하여 탄소/에폭시 복합재료 보의 초기 균열 길이에 대한 정량적인 예측방법을 제시하였다. 구조물의 손상에 대한 비파괴평가기술에 대한 관심은 증가하고 있다. 본 연구에서는 시간-주파수 영역에서 웨이블렛 변환에 기초한 신호처리기술로 손상 유무와 손상평가를 위한 방법을 제시하였다.

한 쌍의 피에조 재료를 이용하여 탄소/에폭시 복합재료 보의 동적응답을 제안한 신호처리 기술로 협대역 가진하에서 연구하였다.

ABSTRACT

A quantitative prediction method for initial crack length in a carbon/epoxy (CF/EP) composite beam using active piezoelectric transducers was established in this study. Wavelet Transform (WT)-based signal processing and identification technique in time-frequency domain was developed to facilitate the determination of damage presence and severity. Dynamic response of a CF/EP composites beam containing a continuously expanding crack, coupled with a pair of active piezoelectric disks, was examined under a narrow band excitation, and then applied with the proposed signal processing technique.

Key Words : Piezoelectric Transducer(압전변환기), Wavelet Transform(웨이블렛 변환), Non-Destructive Evaluation(비파괴평가), Damage Detection(결함 검출), Finite Element Analysis(유한요소해석)

1. Introduction

Though serving as competitive candidates to meet current and future challenges imposed on aeronautical vehicles, carbon/epoxy composite structures still run a large risk of losing efficiency under occurrence of structural damage, which can potentially lead to catastrophic failure of the whole system if it does not detect on time. Quantitative nondestructive evaluation (QNDE) therefore plays an essential role in confident acceptance of composite materials and structures.

Amongst them, the detection approaches based on the elastic wave propagation have been attracting more and more attentions from both researchers and engineers, regarded as one of the most promising solutions to the quantitative assessment of the structural deterioration and the prevention for catastrophic failure. On the other hand, signal processing is a key point to make an identification scheme applicable

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and understandable. Wang and Chang [1] discussed the damage detection technique based on the Lamb wave generated by ultrasonic transmitter, and Lemistre et al. [2] reported a structural defect identification method using piezoelectrics. The wavelet transform can also be used to detect the arrival times of the dispersive waves propagating in plates. There has been intense research activity in the application of wavelets in various fields of science and engineering [3-5]. The present work aims developing a practical and effective real-time damage identification technique for Carbon/Epoxy composite materials. For this purpose, a damage diagnosis system incorporated with a piezoelectric transducer, in correlation with an elastic wave propagation model, was developed. The validity of this system was then investigated by applying it to a composites beam bearing a transverse crack with an increasing length, simulating the damage growth. It is shown that the damage parameters, including the damage presence, location and its variable severity, can be identified promptly and accurately using this technique.

2. Experimental Setup

The composite materials used in this study were unidirectional carbon/epoxy laminates. The carbon fibers used were T300 fibers and the epoxy matrix was the CIBA 934.

An active real-time diagnosis system was developed in this work, whose schematic description is given in Fig. 1.

In this system, Piezoelectric Lead Zirconate Titanate (PZT) Wafers(Φ : 6.9mm, thickniss : 0.5mm) acted as both actuators and sensors with the aid of two-way switches.

Agilent® E1441 arbitrary waveform generator was used to produce 5-cycle toneburst with Hanning Window at a central frequency of 0.5MHZ.

The simulated diagnostic signal was then applied on each PZT wafer after amplified with the PZT amplifier(Piezo SYS® PI 151) to generate ultrasonic lamb wave. Response signals were conditioned by Agilent® E3242A and acquired via E1437A digitizer at a sampling rate of 20-48MHZ; Frequency and amplitude are 500kHz and 60V, respectively.

Sampled signals were transmitted into the central control unit(CCU) for further analyses; all the diagnosis control and signal analyses were performed by CCU, supported on the NI Labview© and Matlab© platforms.

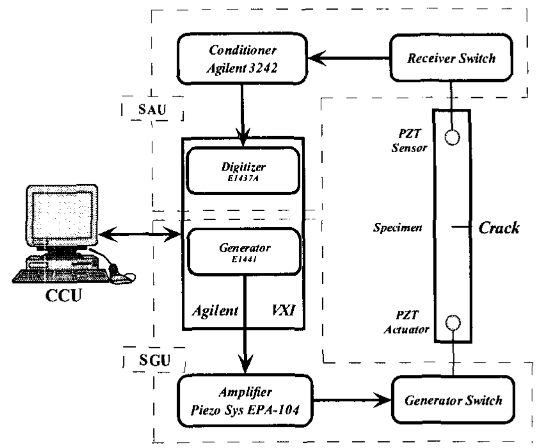


Fig. 1 Configuration of diagnosis system based on VXI platform.

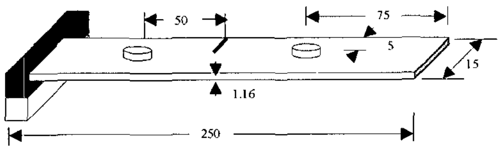


Fig. 2 Experiment setup (dimensions in mm).

In order to evaluate the effectiveness of the proposed model and identification scheme, the diagnosis system was then applied to a defective CF/EP cantilever beam (cross-section of 15mm, 1.16mm) as shown in Fig. 2. The beam has a small crack at edge which is perpendicular to the beam axis. The width of the crack is 0.39mm and its length varied from 0.343mm to 11.720mm gradually long.

3. Numerical Approach

Finite element analysis (FEA) were performed for the elastic wave propagation in a composites beam with a transverse crack using a three-dimensional model. As shown in Fig. 3, the PZT actuator and sensor were assumed to be completely adhered to the composites beam. The physical properties of the composites beam and the PZT actuator and sensor are listed in Table 1.

A very fine mesh was employed in the crack region and the region where the PZT actuator and sensor adhere to the composites beam. The eight-node linear brick element was employed to model both the composite beam and the PZT actuator and sensor, and the total number of elements was

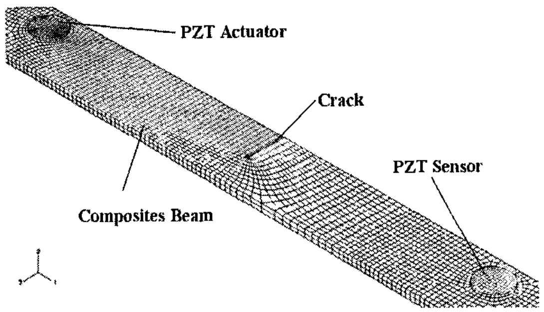


Fig. 3 Geometry of the finite element model.

Table 1 Geometry and physical properties of the materials used in this study

Properties	PZT	Carbon/epoxy[0_8]
Geometry [mm]	ϕ : 6.9, h_{PZT} : 0.5	250×15×1.1
Density, ρ[g/cm^3]	7.8	1.52
Poisson's ratio, υ_{12}	0.3	0.22
Young's modulus, E_{11} [GPa]	66.7	131
Young's modulus, E_{22} [GPa]		10.3
Young's modulus, E_{33} [GPa]	86.2	10.3
Shear modulus, G_{12},G_{13},G_{23} [GPa]		6.9
Charge constant, d_{31} [m/V]	-1.70×10^{-12}	
Charge constant, d_{33} [m/V]	450×10^{-12}	

8940 in the model shown in Fig. 3, for instance. The end close to the PZT sensor was geometrically constrained to simulate the cantilever beam boundary condition. The input electrical signal in experiments was transformed into excitation force which was applied on the PZT actuator in FEA model. The analyses of elastic wave propagation process were carried out based on a dynamic explicit method by using a commercial finite element code ABAQUS/Explicit (Version 6.2).

In order to investigate the effect of crack length on the elastic wave propagation in the composites beam, various crack lengths were modeled, and the averaged stress of the PZT sensor was adopted as an indicator for assessment. The averaged stress of the PZT sensor was calculated, which was then processed by using Wavelet Transformation analysis. First, the analysis of the beam without crack was carried out for comparison. Then the beams with different crack lengths were analyzed and compared with that without crack.

4. Results And Discussion

4.1 Signal Analysis

In Fig. 4, relationship plots of amplitude versus time for tests at different crack length are displayed. Because the raw signals Contain the structural vibration components and diverse bandwidth noises, the acquired raw signals can hardly be used for the evaluation of damage detection. Wavelet transform-based time-frequency spectrographic analyses were employed to extract the useful diagnostic in formation[6-12]. Daubechies function, Ψ(a, b), at level 8 (db10) was chosen as the wavelet transform function and the Continuous Wavelet Transform (CWT) of a function $f(t)$ is defined by [6, 13]:

$$Wf\ (a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} f(t)\cdot\Psi^*\left(\frac{t-b}{a}\right)\cdot dt = \int_{-\infty}^{+\infty} f(t)\cdot\Psi^*_{a,b}(t)\cdot dt \tag{1}$$

where a and b are the scale and time shifting (or translation) parameters, respectively. In addition, derived from Eq. (1), the total energy for sampling signal can be yielded as [6]:

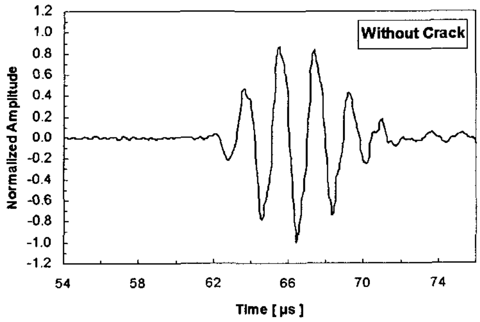
$$E = C\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} | W(a,b) |^2\cdot\frac{da}{a^2}\cdot db \tag{2}$$

The wavelet transform Wf is the wavelet coefficient for the wavelet $\Psi^*(t)$ with dilation a and position b. The function Ψ(t) is termed as the mother (basic) wavelet serving to analyze an arbitrary sampled signal $f(t)$. The $\Psi^*(t)$ denotes the complex conjugate of Ψ(t). If the transform is invertible, the inverse wavelet transform exists:

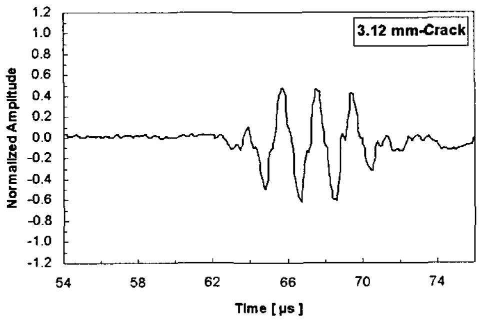
$$f(t) = \frac{1}{C_\Psi}\int_{-\infty}^{+\infty}\int_{a>0}^{+\infty} Wf(a,b)\cdot\frac{1}{\sqrt{a}}\cdot\Psi\left(\frac{t-b}{a}\right)\cdot\frac{da}{a^2}\cdot db \tag{3}$$

where a is positive and C_Ψ is a constant that depends only on Ψ(t).

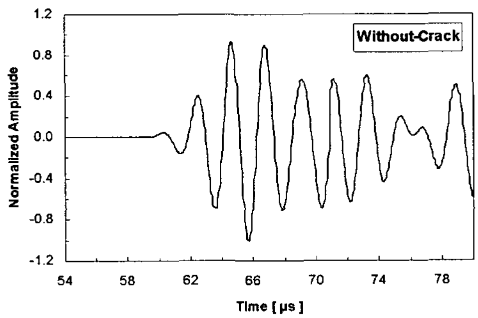
The sampled signal Ψ(t) passes through two complementary filters and can be analyzed into low frequency [Approximations (A's)] and high frequency [Details (D's)] signals. Wavelet transform provides how to analyze the vicinity of location using variable scale. The analytical results by the Discrete Wavelet



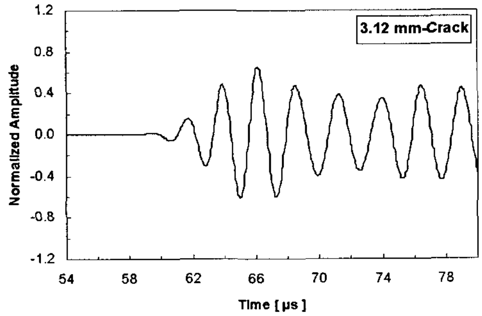
(a) Without-crack from experiment



(b) crack of 3.12 mm from experiment



(c) Without-crack from FEM



(d) crack of 3.12 mm-crack from FEM

Fig. 4 Raw sampled signals via two piezoelectric transducers.

Transform (DWT) at the 8th level for signals via PZT actuator-sensor shown in Fig. 4 is displayed and illustrated in Fig. 5. In this work, the damage degree regarded as a singularity involved in the signal, was determined using the CWT and DWT spectrographic analyses. The damage degree was calibrated upon the relation with the normalized energy. Spectrographic analyses based on the CWT and DWT techniques [14] were accordingly executed. A series of band filters with proposed threshold and different frequency scopes were designed and applied on the sampled signals to suppress the diverse interferences and effectively extract diagnostic components. Thus the interrogation on the sampled signals can be concentrated in a specific frequency scope.

Meanwhile, in this work, the Sampling Point (SP) was hereafter introduced instead of the direct Time Point (TP) in CCU to expedite and facilitate the data processing procedure. The DWT analytical results at level 8 for without crack and 3.12mm cracks are displayed in Fig. 5 for comparison. In the meantime, the 2D and 3D spectrographic analyses via CWT were performed.

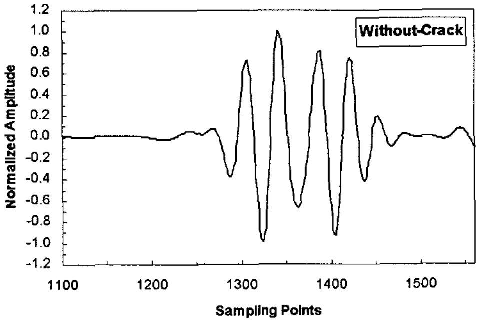
4.2 Damage Diagnosis

The damage diagnostic results were achieved via the proposed identification scheme and the actual damage parameters were compared in Table 2.

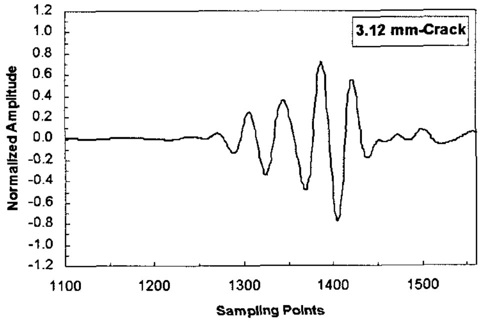
Table 2 Diagnostic results and relative percentage errors for crack severity

Damage Diagnosis [mm]		
Actual Damage Length [mm]	Calculated Value by Integration Method	Minimum Error of Prediction [%]
0.343	0.320	6.70
1.016	1.051	3.44
1.780	1.741	2.19
3.120	3.152	1.02
4.613	4.646	0.72

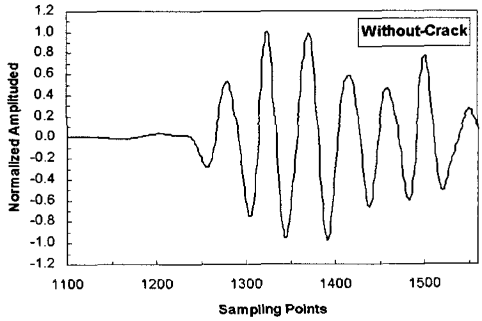
The percentage diagnostic errors are listed in Table 2 and illustrated in Fig. 6. The results imply that the identification accuracy for crack location, in spite of the actual damage severity, is acceptable with a high creditability. The precision in damage severity identification increases with the crack size. Also, a satisfactory precision for the damage severity estimation is maintained until the crack size approaches 5 mm approximately when the transverse damage area occupies around 50% of the entire cross-section of the beam. Considerable errors occur when the crack size exceeds 50% of the height of the beam.



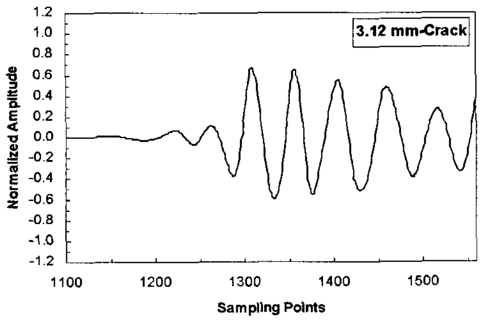
(a) Without-crack from experiment.



(b) crack of 3.12 mm from experiment.



(c) Without-crack from FEM.



(d) crack of 3.12 mm-crack from FEM

Fig. 5 Detail at level 10 by DWT analysis for signals in Fig. 4.

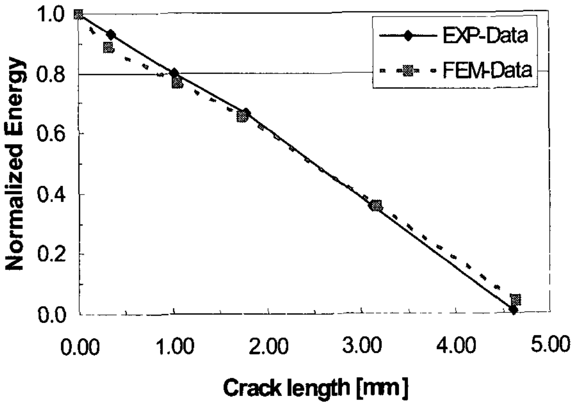


Fig. 6 Relationship between crack length and normalized energy.

5. Conclusions

This paper shows that the wavelet transform to the experimental time-frequency domain analysis has been developed as a damage detection method for the beam structures. The Discrete Wavelet Transform (DWT) analysis are shown to a very effective method in damage detection of a unidirectional carbon/epoxy beam. An identification and monitoring scheme for structural damage has been developed in correlation with the excitation response analysis, and its validity was examined experimentally through a quantitative diagnosis for the size of damage with an increasing depth in a two-dimensional structural beam.

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