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Damage Detection in Composite Plates by Using an Enhanced Time Reversal Method

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ABSTRACT

A damage detection technique, which does not rely on any past baseline signals, is proposed to assess damage in composite plates by using an enhanced time reversal method. A time reversal concept of modern acoustics has been adapted to guided-wave propagation to improve the detectability of local defects in composite structures. In particular, wavelet-based signal processing techniques have been developed to enhance the time reversibility of Lamb waves in thin composite laminates. In the enhanced time reversal method, an input signal at an excitation point can be reconstructed if a response signal measured at another point is reemitted to the original excitation point after being reversed in a time domain. This time reversibility of Lamb waves is violated when wave distortion due to wave scattering is caused by a defect along a direct wave path. Examining the deviation of the reconstructed signal from the known initial input signal allows instantaneous identification of damage without requiring the baseline signal for comparison. The validity of the proposed method has been demonstrated through experimental studies of an anisotropic composite laminate structure with delamination.

Keywords: Composites, Damage detection, Time reversal method, Wavelet-based signal processing, Lamb waves, Time reversibility, Structural health monitoring, Delamination

1. INTRODUCTION

There has been a significant increase in using solid composites in load-carrying structural components, particularly in aircraft and automobile industries. With the advances in actuator and sensor technologies that allow simultaneous excitation and sensing, many studies have been proposed to use Lamb waves for detecting defects in composite structures (Moulin et al. 1997, Sohn et al. 2004, Paget et al. 2003, Kessler et al. 2003, Wang et al. 2003).

Lamb waves are mechanical waves whose wavelength is in the same order of magnitude as the thickness of the plate. The analysis and interpretation of Lamb waves can be complicated due to their dispersive and multimodal natures: Due to dispersion characteristics, the various frequency components of Lamb waves travel at different speeds and attenuate at different rates causing the shapes of wave packets to change as they propagate through a solid medium. In addition, multiple symmetric and anti-symmetric Lamb wave modes are generated as the driving frequency for wave generation increases.

Recently, attention has been paid to the time reversal method developed in modern acoustics to compensate the dispersion of Lamb waves and improve the signal-to-noise ratio of propagating waves (Prada and Fink 1998, Ing and Fink 1996, Ing and Fink 1998, Fink 1999). Though the experimental results showed the spatial focusing and time compression properties of time reversal Lamb waves, the results were not directly usable for damage detection of plates (Ing and Fink 1998). A pulse-echo time reversal method, which is the time reversal method operating in a pulse-echo mode, has been employed to identify the location and size of defects in a plate (Ing and Fink 1996, Ing and Fink 1998, Fink 1999). If there exist multiple defects in a plate, the pulse-echo time reversal method tends to detect only the most distinct defect, requiring more sophisticated techniques to detect multiple defects. Furthermore, the pulse-echo time reversal method might be impractical for structural health monitoring applications, because a dense array of sensors is required to cover a large surface of the plate being investigated.

According to the time reversal concept, an input signal can be reconstructed at an excitation point (point A) if an output signal recorded at another point (point B) is reemitted to the original source point (point A) after being reversed in a time domain as shown in Figure 1. This process is referred to as the time reversibility of waves. This time reversibility is based on the spatial reciprocity and time-reversal invariance of linear wave equations (Draeger et al. 1997, Fink and Prada 2001). However, it should be noted that time reversal acoustic is originally developed for propagation of body waves in an infinite solid media. Additional issues such as the frequency dependency of time reversal operator and signal reflection due to limited boundary conditions should be addressed to successfully achieve the time reversibility for Lamb waves (Sohn et al. 2004, Park et al. 2004). By developing a unique combination of a narrowband excitation signal and wavelet-based signal processing techniques, the authors demonstrated previously that the original input waveform could be successfully reconstructed in a composite plate through the enhanced time reversal method (Park et al. 2004).

This paper takes advantage of this enhanced time reversal method to identify defects in composite plates: Damage causes wave distortions due to wave scattering during the time reversal process and it breaks down the linear reciprocity of wave propagation. Therefore, the time reversibility of waves can allow detecting damage, which causes wave distortions along a direct wave path. It should be noted that the proposed damage detection method leaves out unnecessary dependency on past baseline signals by instantly comparing the known input signal to the reconstructed input signal. By eliminating the need for the baseline signals, the proposed damage detection is immune to potential operational and environmental variations throughout the life span of a structure. The validity of the proposed method has been demonstrated through experimental studies of an anisotropic composite plate with delamination.

This paper is organized as follows: Section 2 deals with the characteristics of Lamb waves and the time reversibility of Lamb waves. In particular, some issues crucial to the time reversibility of Lamb waves are briefly discussed. In Section 3, the enhanced time reversal method is introduced to improve the time reversibility of Lamb waves. In Section 4, damage sensitive features are investigated and extracted for damage identification based on the time reversibility of Lamb waves. A statistical classifier and a damage localization technique are also described. Experimental investigations are presented in Section 5 to demonstrate the validity of the current study. Finally, this paper is concluded in Section 6 with a brief summary and discussions.

2. TIME REVERSAL LAMB WAVES

Dispersive and Multimode Characteristics of Lamb Waves

Lamb waves usually occur on the waveguides such as bars, plates and shells. Unlike body waves, the propagation of Lamb waves is complicated due to two unique features: dispersion and multimode (Viktorov 1967). The dispersion curve in terms of the product of the excitation frequency and the plate thickness versus the group velocity C_g can be determined as follows:

$$C_g = \frac{d\omega}{dk} \tag{1}$$

where ω denotes an angular frequency. For a uniform plate with constant thickness, a typical dispersion curve can be represented as a function of the frequency as shown in Figure 2.

As shown in Figure 2, multiple Lamb wave modes are created as the excitation frequency increases. The dispersive nature of waves causes the different frequency components of Lamb waves to travel at different speeds and attenuate at different rates. Therefore, the shape of the wave packet changes as it propagates through solid media. Note that the dispersive and multimodal characteristics of Lamb waves make it difficult to analyze and interpret output responses for damage identification.

Time Reversibility of Lamb Waves in a Thin Plate

The application of a time reversal method to Lamb wave propagation can compensate the dispersion effect, which has limited the use of Lamb waves for damage detection applications (Ing and Fink 1996, Ing and Fink 1998). Because of the dispersion characteristic of Lamb waves, wave packets traveling at higher speeds arrive at a sensing point earlier than those traveling at lower speeds. However, during the time reverse process at the sensing location, the wave packets, which travel at slower speeds and arrive at the sensing point later, are reemitted to the original source location first. Therefore, all wave packets traveling at different speeds concurrently converge at the source point during the time reversal process, compensating the dispersion.

While a number of experimental evidences have shown that the dispersion of Lamb waves is well compensated through the time reversal process, the time reversibility of Lamb waves has not been fully investigated unlike that of body waves. The authors investigated the time reversibility of Lamb waves exerted by piezoelectric (PZT) patches on a composite plate by introducing the time reversal operator into the Lamb wave equation based on the Mindlin plate theory (Park et al. 2004). The time reversal operator G_{TR} is a frequency kernel, which relates the original input signal I to the reconstructed output signal V at an actuating PZT patch during the time reversal process (Wang et al. 2003):

$$V(\omega) = K_{TR} G_{TR}(\omega) I(\omega) \tag{2}$$

where ω and K_{TR} denote the angular frequency and the electro-mechanical efficiency of PZT, respectively.

As shown in Figure 3, the time reversal operator varies with response to frequency, indicating that wave components at different frequency values are non-uniformly amplified. Therefore, the original input signal cannot be properly reconstructed if the input signal consists of various frequency components such as a broadband input signal. This section briefly presented issues that have to be addressed before time reversal method can be applied to Lamb wave propagation. Theses issues are tackled in the following section.

3. AN ENHANCED TIME REVERSAL METHOD

To alleviate several issues raised in the previous section, a combination of input waveform design and a multi-resolution signal processing are employed so that the time reversibility of Lamb waves could be preserved within an acceptable tolerance in the presence of background noise.

Active Sensing using a Known Input Waveform

First, a carefully designed narrowband input waveform is exerted onto a structure to minimize the frequency dependency of the time reversal operator. When a narrowband frequency input is used, the frequency dependency of the time reversal operator becomes negligible, allowing proper reconstruction of the original input signal. In addition, the use of a known and repeatable input further improves the effective signal-to-noise ratio by allowing time averaging of response signals subject to the same repeatable input and makes subsequent signal processing for the time reversal process much easier.

In this study, a Morlet wavelet function, as defined below, with a driving frequency around a specified narrowband frequency range is adopted as an input waveform (Strang and Nguyen 1997).

$$\Psi(t) = e^{-t^2/2}\cos(5t) \tag{3}$$

Here, a Morlet waveform is employed for excitation because its frequency content is well bounded in a frequency domain. A proper selection of the driving frequency is critical for successful generation of Lamb waves in a given structure. While the input frequency should be high enough to make the wavelength of the Lamb wave comparable to the scale of local damage, the driving frequency also needs to be low so that higher modes do not clutter the fundamental symmetric and anti-symmetric modes. Further discussion on the selection of the driving frequency can be found in Sohn et al. 2004 (Sohn 2004).

Automated Signal Selection Process based on Wavelet Transform

When Lamb waves travel in a thin plate, a response signal consists of several wave modes as illustrated in Figure 4. Some of the modes are symmetric modes associated with the direct path of wave propagation and/or signals reflected off from the edges of the plate. There are also additional anti-symmetric modes reflected off from the edges. Because these reflected modes are very sensitive to the changes in boundary conditions, our primary interest lies in investigating the first flexural A_0 mode corresponding only to the direct path between the actuating PZT and the sensing PZT. Note that this A_0 mode traveling along the direct path between the actuator and the sensor is insensitive to changing boundary conditions. Therefore, only this first arriving A_0 mode portion of the signal needs to be extracted from the raw signal to minimize false warnings of damage due to changing operational conditions of the system. For this purpose, an automated selection procedure based on wavelet analysis is developed. Because this signal component of our interest, the first arriving A_0 mode, is time and frequency limited, the two-dimensional time-frequency representation of the signal can be a useful tool for simultaneous characterization of the signal in time and frequency, in particular for characterizing dispersive effects and analyzing multimodal signals.

The basic concept of this automated selection procedure is as follows: If the signal shape that needs to be extracted for damage detection is known *a priori*, optimal extraction can be achieved using a mother wavelet that matches the shape of the signal component (Das 1991). The automated selection procedure is schematically shown in Figure 5. First, the continuous wavelet transform of the signal, $Wf(u,s)$, is obtained by convolving the signal *f(t)* with the translations (*u*) and dilations (*s*) of the mother wavelet:

$$Wf(u,s) = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{s}} \, \psi^{*}_{u,s}(t) \, dt \tag{4}$$

where

$$\psi^{*}_{u,s}(t) = \frac{1}{\sqrt{s}} \psi\left(\frac{t-u}{s}\right) \tag{5}$$

The Morlet wavelet, same as the previously defined input signal, is used as a mother wavelet $\psi(t)$ for wavelet transform. Then a complete set of daughter wavelets $\psi^{*}_{u,s}(t)$ is generated from the mother wavelet by dilation (*s*) and shift (*u*) operations. Note that each value of the wavelet coefficient $Wf(u,s)$ is normalized by the factor $1/\sqrt{s}$ to ensure that the integral energy given by each wavelet is independent of the dilation *s*.

Because the Morlet wavelet is used as a mother wavelet for wavelet transform and the wavelet coefficient is the correlation between the signal and the mother wavelet by definition, the wavelet coefficient arrives at its maximum value when the shape of the response signal becomes closest to that of the Morlet wavelet. When this search of the maximum wavelet coefficient is performed at the input frequency, the first arrival of the A_0 mode can be easily detected by the temporal shift parameter *u*. Hence, this wavelet transform can be an effective way to reduce noise if the mother wavelet is chosen to be a good representation of the signal to be detected. Furthermore, the continuous wavelet transform is performed instead of the discrete wavelet transform to obtain a better time resolution over the full period of the signal (Burrus et al. 1998). Through this automated selection procedure, only the first arriving A_0 mode of the response time signal is chosen for reemission. This selection procedure also automatically eliminates the portion of the response signal contaminated by electromagnetic interference. A similar approach to noise elimination in ultrasonic signals for flaw detection can be found in (Abbate et al. 1997).

Signal Filtering based on Multi-Resolution Analysis

When a narrowband signal travels through a thin solid media, the dispersive nature of the wave can be compensated through the conventional time reversal process. In other words, the time reversal process compensates a phase difference of each wave packet in frequency domain by reemitting each wave packet with proper time delays. However, the frequency content of the traveling waves smears into nearby frequencies and is non-uniformly amplified during the time reversal process. Therefore, to enhance the time reversibility of the reconstructed signal at the original input point, the measured response signal needs to be processed before reemitting at the response point. In particular, for the time reversal analysis of Lamb waves, it is critical to retain the response components only at the original input frequency value, because of the frequency dependent nature of the time reversal operator shown in Figure 3. To achieve this goal, a multi-resolution analysis is adopted to filter out the measurement noise in response signals and to keep only the response component at the driving frequency value. Multi-resolution signal processing based on wavelet transform has been extensively studied especially for perfect reconstruction of signals using quadrature mirror filters (Akansu and Haddad 1992).

Once the wavelet coefficients are computed from Eq. (4), the original signal can be reconstructed via the following inverse continuous wavelet transform (Akansu and Haddad 1992):

$$f(t) = \frac{1}{C_\varphi} \int_{-\infty}^{\infty} \int_{0}^{\infty} Wf(u,s) \, \frac{1}{\sqrt{s}} \, \psi\left(\frac{t-u}{s}\right) \frac{1}{s^2} \, ds \, du \tag{6}$$

where C_φ is a constant determined by

$$C_\varphi = \int_0^\infty \frac{|\psi|}{\omega} \, d\omega \tag{7}$$

In this study, the integration operation with respect to the scale parameter *s* in Eq. (6) is restricted only to near the driving frequency in order to filter out the frequency components outside the driving frequency before transmitting the response signal back to the original input location:

$$f(t) = \frac{1}{C_\varphi} \int_{-\infty}^{\infty} \int_{a}^{b} Wf(u,s) \, \frac{1}{\sqrt{s}} \, \psi\left(\frac{t-u}{s}\right) \frac{1}{s^2} \, ds \, du \tag{8}$$

where *a* and *b* are the lower and upper limits of the narrowband excitation frequency. The choice of the frequency limits is dictated by the fact that the filter must cover the frequency range of interest so that useful information is not lost. In fact, the wavelet transform is used as a matched filter to improve the signal-to-noise ratio without any loss in time resolution or accuracy and in many cases with improvements. This filtering processing is repeated for the reconstructed input signal obtained by the time reversal process.

4. STATISTICAL DAMAGE CLASSIFICATION

Extraction of Damage Sensitive Feature

Intact composites possess atomic linear elasticity as water and copper do. The atomic elastic material is well described by the classical linear elastic constitutive law and linear wave propagation equations. However, it should be noted that the atomic elastic materials demonstrate nonlinear mesoscopic elasticity that appears to be much like that in rock or concrete if they have been damaged. Nonlinear mesoscopic elastic materials have hysteretic nonlinear behaviors yielding acoustic and ultrasonic wave distortion, which gives rise to changes in the resonance frequencies as a function of drive amplitude, generation of accompanying harmonics, nonlinear attenuation, and multiplication of waves in different frequencies (Guyer and Johnson 1999, Abeele et al. 2000). It has been also shown that cracks and delamination with low-aspect-ratio geometry are the scattering sources creating nonclassical nonlinear waves, which arise from hysteresis in the wave pressure-deformation relation (Kazakov et al. 2002). Wave scattering can be also caused by either horizontal or vertical mode conversion in which the energy of the incident Lamb waves at a specified driving frequency is redistributed into neighboring Lamb wave modes as shown in Figure 2. Because delamination changes the internal geometric boundary conditions in a composite plate, diffraction and reflection of the waves can also produce wave scattering when the incident Lamb waves pass through delamination.

Because the time reversibility of waves is fundamentally based on the linear reciprocity of the system (Draeger et al. 1997, Fink and Prada 2001), the linear reciprocity and the time reversibility break down if there exists any source of wave distortion due to wave scattering along the wave path. Therefore, by comparing the discrepancy between the original input signal and the reconstructed signal, damage such as crack opening-and-closing, delamination and fiber breakage could be detected.

Data Normalization

In most of conventional damage detection techniques, damage is inferred by comparing newly obtained data sets with baseline data previously measured from an initial condition of the system. Because there might have been numerous variations since the baseline data were collected, it would be difficult to blame structural damage for all changes in the measured signals. For instance, there might have been operational and environmental variations of the system once the baseline data have been collected. The importance of data normalization, which attempts to distinguish signal changes originated from structural damage from those caused by natural variations of the system, has been addressed by Sohn (Sohn 2004). In this study, the dependency on the baseline data measured at some previous time point is completely eliminated by instantly comparing the original input signal and the reconstructed input signal. By eliminating the need for some past baseline signals, the enhanced time reversal process also alleviates the data normalization problem.

Definition of Damage Index

Damage classification is based on the comparison between the original input waveform and the reconstructed signal.

$$DI = 1 - \sqrt{\left\{ \int_{t_0}^{t_1} I(t)V(t)\,dt \right\}^2 \Big/ \left\{ \int_{t_0}^{t_1} I(t)^2\,dt \int_{t_0}^{t_1} V(t)^2\,dt \right\}} \qquad (9)$$

where the $I(t)$ and $V(t)$ denote the known input and reconstructed signals. t_o and t_1 represent the starting and ending time points of the baseline signal's first A_o mode. The value of DI becomes zero when the time reversibility of Lamb waves is preserved. Note that the root square term in Eq. (9) becomes 1.0 if and only if $V(t) = \beta I(t)$ for all t where $t_0 \le t \le t_1$ and β is a nonzero constant. Therefore, a simple linear attenuation of a signal will not alter the damage index value. If the reconstructed signal deviates from the input signal, the damage index value increases and approaches 1.0, indicating the existence of damage along the direct wave path. Once the damage index value exceeds a pre-specified threshold value, the corresponding signal is defined as damaged.

Establishment of a Decision Boundary

The establishment of the decision boundary [or the threshold] is critical to minimize false-positive and false-negative indications of damage. Although data are often assumed to have a normal distribution for building a statistical model for damage classification, it should be noted that a normal distribution weighs the central portion of data rather than the tails of the distribution. Therefore, for damage detection applications, we are mainly concerned with extreme (minimum or maximum) values of the data because the threshold values will reside near the tails of the distribution. The solution to this problem is to use a statistical tool called extreme value statistics (EVS) (Sohn et al. 2003), which is designed to accurately model behavior in the tails of a distribution.

In this study, the damage index value is computed from various normal conditions of the composite plate. Then, the statistical distribution of the damage index is characterized by using a Gumbel distribution, which is one of three types of extreme value distributions. From this fitted cumulative density function (CDF) for the Gumbel distribution, a threshold value corresponding to a one-sided 99.9% confidence interval was determined. More details on the threshold establishment can be found in (Sohn et al. 2004).

It should be noted that the computation of the threshold value based on EVS requires training data only from the undamaged conditions of a structure, classifying the proposed statistical approach as one of the unsupervised learning methods. Another class of statistical modeling is supervised learning where training data from both undamaged and damaged conditions are required. When a SHM system is deployed to real-world applications, it is often difficult to collect training data from various damage cases. Therefore, an unsupervised learning method such as the one presented here will be more practical in field applications. Furthermore, by properly modeling the maximum distribution of the damage index, false alarms have been minimized.

5. EXPERIMENTAL STUDY

Experimental Test Setup

The overall test configuration of this study is shown in Figure 6 (a). The test setup consists of a composite plate with a surface mounted sensor layer, a personal computer with a built-in data acquisition system, and an external signal amplifier. The dimension of the composite plates is 60.96 cm x 60.96 cm x 0.6350 cm (24 in x 24 in x 1/4 in). The layup of this composite laminate contains 48 plies stacked according to the sequence [6(0/45/-45/90)]s, consisting of Toray T300 Graphite fibers and a 934 Epoxy matrix.

A commercially available thin film with embedded piezoelectric (PZT) sensors is mounted on one surface of the composite plate as shown in Figure 6 (b) (Acellent@1999). A total of 16 PZT patches are used as both sensors and actuators to form an “active” local sensing system. Because the PZTs produce an electrical charge when deformed, the PZT patches can be used as dynamic strain gauges. Conversely, the same PZT patches can also be used as actuators, because elastic waves are produced when an electrical field is applied to the patches. In this study, one PZT patch is designated as an actuator, exerting a predefined waveform into the structure. Then, the adjacent PZTs become strain sensors and measure the response signals. This actuator-sensor sensing scheme is graphically shown in Figure 6 (b). This process of the Lamb wave propagation is repeated for different combinations of actuator-sensor pairs. A total of 66 different path combinations are investigated in this study. The data acquisition and damage identification are fully automated and completed in approximately 1.5 minutes for a full scan of the plate used in this study. These PZT sensor/actuators are inexpensive, generally require low power, and are relatively non-intrusive.

The personal computer shown in Figure 6 (a) has built-in analog-to-digital and digital-to-analog converters, controlling the input signals to the PZTs and recording the measured response signals. Increasing the amplitude of the input signal yields a clearer signal, enhancing the signal-to-noise ratio. On the other hand, the input voltage should be minimized for field applications, requiring as low power as possible. In this experiment the optimal input voltage was designed to be near 45 V, producing 1-5 V output voltage at the sensing PZTs. PZTs in a circular shape are used with a diameter of only 0.64 cm (1/4 in). The sensing spacing is set to 15.24 cm (6 in). A discussion on the selection of design parameters such as the dimensions of the PZT patches, sensor spacing, and a driving frequency can be found in (Kessler 2002).

Actual delamination is seeded to the composite plate by shooting a 185 gram steel projectile into the composite plate as shown in Figure 7. Cables were attached to one side of the plate so that the plate could hang from the test frame in a free-free condition. Several impact tests were repeated varying the impact speed of the steel projectile around 31 m/s to 46 m/s. The data collection using the active sensing system was performed before and after the impact test.

Experimental Results

In this study, typical results only from one of severe impact tests are presented due to the space limitation. First, the surface damage on the composite plate is visually inspected after each impact test. Figure 8 (a) shows the surface damage on the impact side of the composite plate. A very small (about 5 mm diameter) dent was barely visible on the impact side of the plate. On the backside of the plate shown Figure 8 (b), there was a very small crack (less than 1 mm thickness and about 2 cm long), but it was difficult to spot this crack without a magnifying glass. However, the existence of an internal delamination was confirmed by the ultrasonic scan of the composite plate.

Next, the active sensing system and the proposed damage identification algorithms were employed to identify the internal delamination. Figure 9 (a) shows the actual impact location. The identification of the damaged paths shown in Figure 9 (b) is based on the premise that if there is any defect along the wave propagation path, the time reversibility of Lamb waves breaks down. Therefore, by examining the deviation of the reconstructed signal from the known original input signal for each path as shown in Eq. (9), damaged paths can be identified.

The final goal is to pinpoint the location of delamination and to estimate its size based on the damaged paths identified in Figure 9 (b). To identify the location and area of the delamination, a damage localization algorithm is also developed in (Sohn et al. 2004). The delamination location and size estimated by the active sensing system was presented in Figure 9 (b), and the estimate from the proposed damage identification matched well with the ultrasonic scan results.

Figure 10 demonstrates the time reversibility of Lamb wave and the violation of the time reversibility due to delamination: Figure 10 (a) shows that the reconstructed signal (the dotted line) is very close to the original input signal (the solid line) except near the tails of the A_o mode. Figure 10 (b) further illustrates the distortion of the reconstructed signal due to the internal delamination.

6. SUMMARY AND DISCUSSION

A time reversal concept in modern acoustics has been further extended to Lamb wave propagations for detecting defects in a composite plate. First, the enhanced time reversal method is employed to improve the time reversibility of Lamb waves: A carefully designed narrowband waveform is used to address the frequency dependency of the time reversal operator and an automated signal selection process based on wavelet transform is employed to retain only a segment of a raw response signal that is more sensitive to damage and less responsive to changing boundary conditions.

Then, the time reversibility of Lamb waves is utilized to identify the defects: Because the reconstructed signal is expected to be identical to the original input signal for a intact plate and wave scattering induced by damage results in wave distortion, the time reversibility is violated when there is a defect along the wave propagation path. This time reversibility allows detecting damage by comparing a known input waveform to a reconstructed signal. It should be noted that no past baseline signals is necessary for the presented damage detection method thanks to the instantaneous comparison between the original and reconstructed signals.

A rigorous statistical classifier based on extreme value statistics is used to identify the probable wave propagation paths affected by defects, and a damage localization technique is used to pinpoint the locations of the defects. An experimental case study is performed to demonstrate the validity of the proposed method. Actual delamination is seeded to a composite plate by shooting a steel projectile into a composite plate. Though damage on the plate surface is almost indiscernible by naked eyes, the actual size and location of delamination are successfully identified through the proposed damage detection method.

Further research is warranted to optimally design the parameters of the active sensing system such as the spacing between the PZT patches, the actuating frequency, and power requirement for the PZTs. It should be pointed out that the procedure developed in this study has only been verified on relatively simple laboratory test specimen. To fully verify the proposed approach, it will be necessary to apply the proposed approach to different types of representative structures and to investigate how delamination physically affects the Lamb wave propagation.

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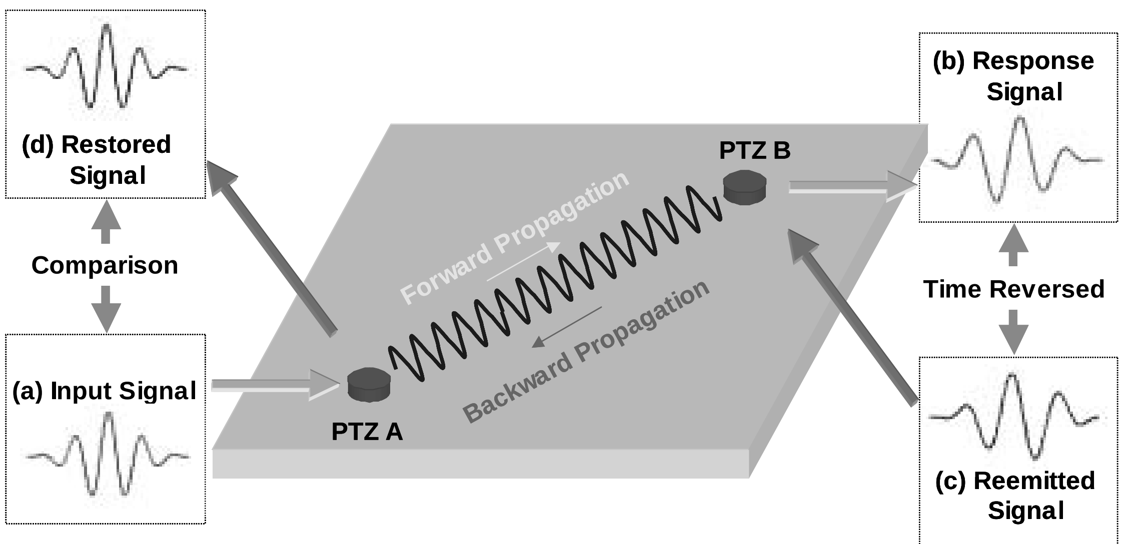


Figure 1: Schematic concepts of damage identification in a composite plate through time reversal processes.

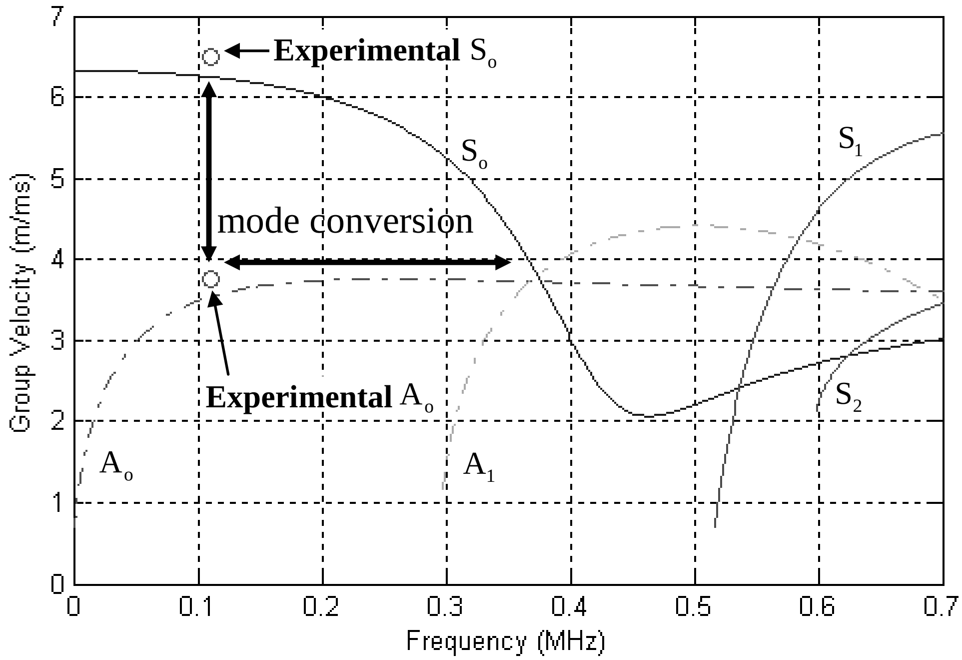


Figure 2: A dispersion curve for an idealized isotropic composite plate (the abscissa is presented in term of the frequency with the given plate thickness (0.64 cm) rather than the frequency-thickness product)

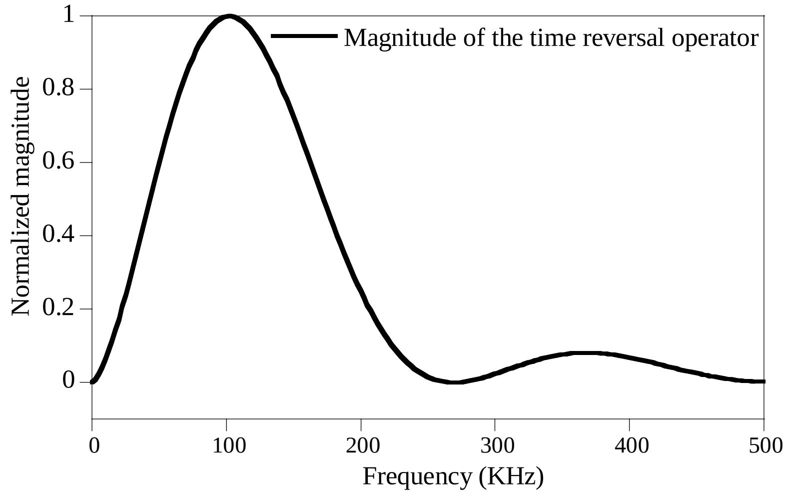


Figure 3: Normalized time reversal operator of the A_0 mode

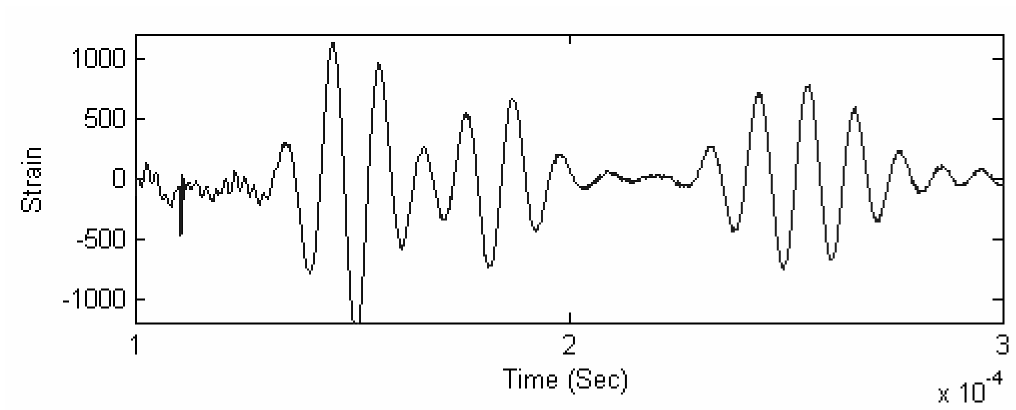


Figure 4: A typical dynamic strain response measured at one of the piezoelectric sensors

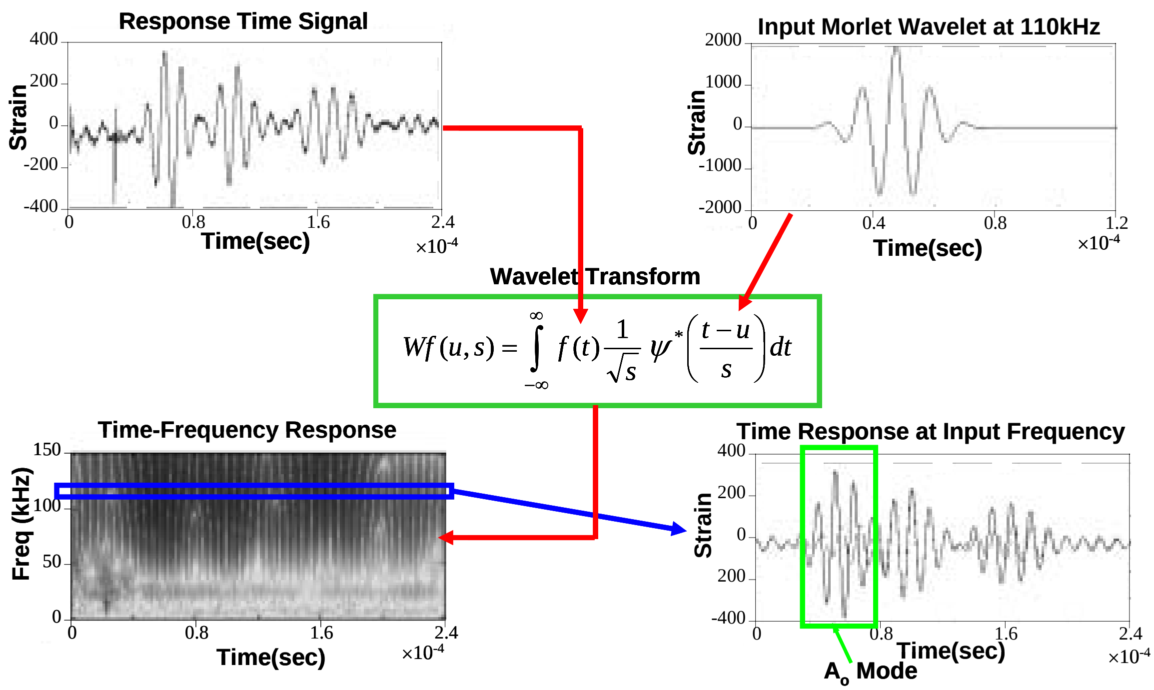
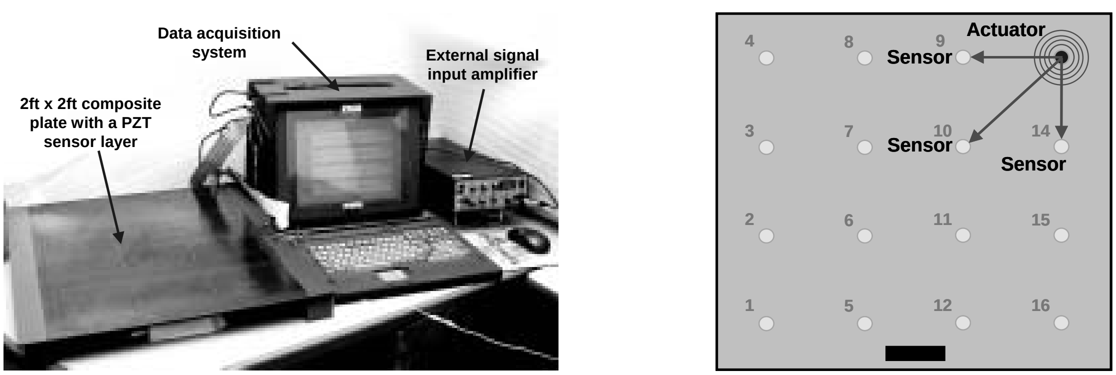


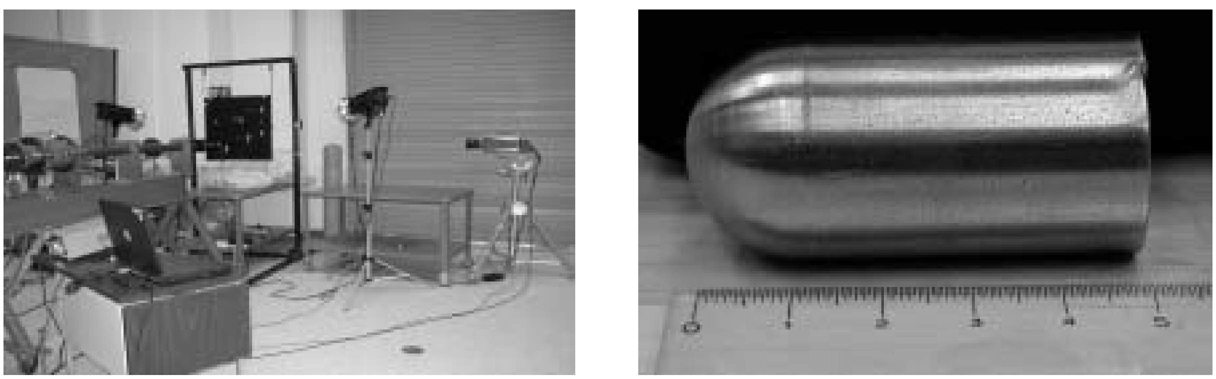
Figure 5: A wavelet analysis procedure to extract a damage sensitive feature



(a) Testing configuration

(b) A layout of the PZT sensors/actuators

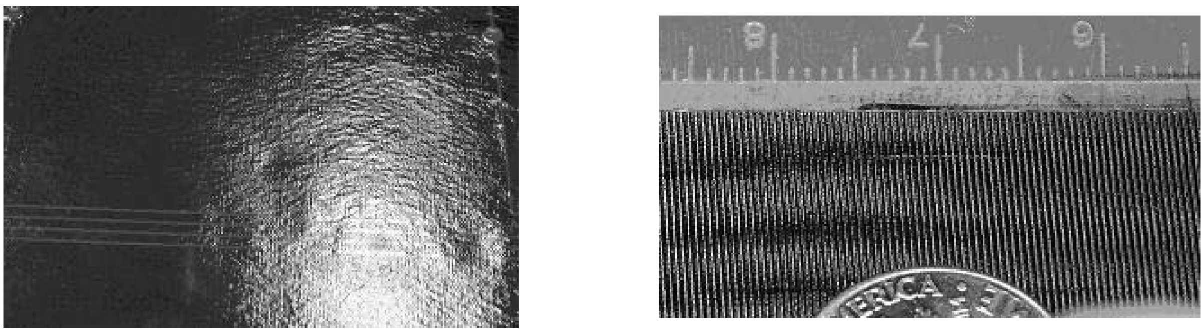
Figure 6: An active sensing system for detecting delamination on a composite plate



(a) A gas gun chamber is used to shoot a steel projectile to the composite plate

(b) A 185 gram steel projectile is shot at varying speeds (30 – 40 m/s)

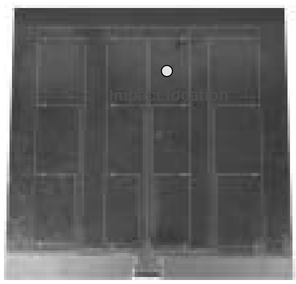
Figure 7: An impact test setup used to seed internal delamination in the composite plate



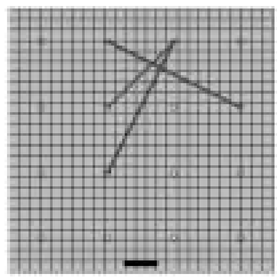
(a) Dent on the impact side of the plate

(b) Crack damage on the back side of the plate

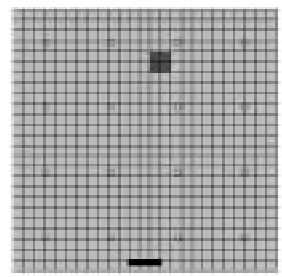
Figure 8: Visual inspection of surface damage after impact test



(a) Actual impact location

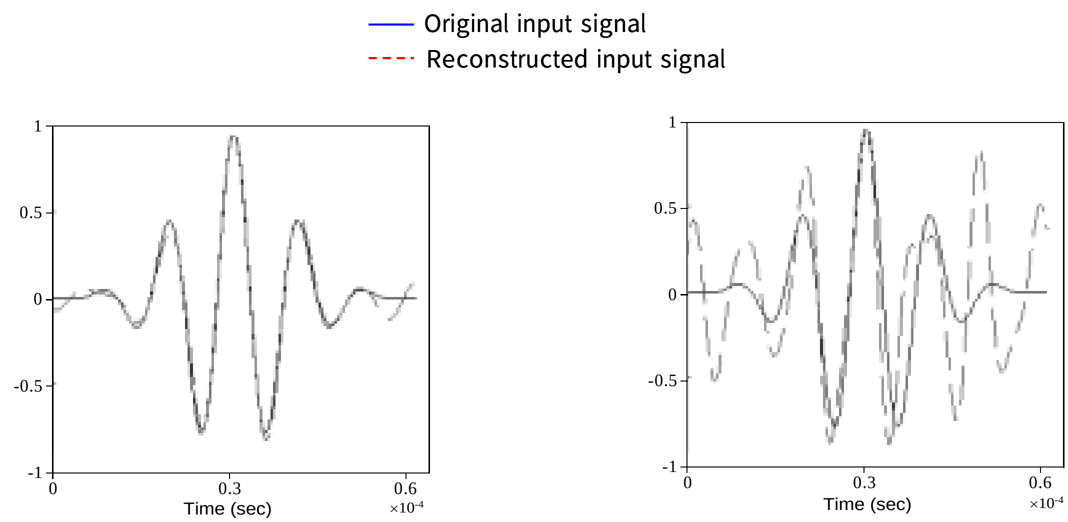


(b) Actuator-sensor paths affected by the internal delamination



(c) The damage size and location identified by the proposed method

Figure 9: Detection of different sizes of damage using the wavelet-based approach



(a) The time reversibility of Lamb waves for the intact composite plate

(b) The break-down of the time reversibility due to the internal delamination

Figure 10: Comparison between the original input signal (solid) and the restored signal (dotted) during the TRA process between actuating PZT # 6 and sending PZT #9