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 is based on linear reciprocity of elastic waves, and it is violated when nonlinearity 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 exemplified through experimental studies on a quasi-isotropic laminate with delamination.

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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; Strei et al. 2003; Rose 1995; Thomson and Chimenti 2002; Alleyne and Cawley 1992; Seale et al. 1998; McKeon and Hinders 1999; Castaings and Cawley 1996; Mal et al. 2005; Staszewski et al. 2004). All elastic waves including body and guided waves are governed by the same set of partial differential equations. The primary difference is that, while body waves are not constrained by any boundaries, guided waves need to satisfy the boundary conditions imposed by the physical systems as well as the governing equations. Lamb waves are one type of guided waves that exist in thin plate-like structures, and they are plane strain waves constrained by two free surfaces (Rose 1999). 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 antisymmetric 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, 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, 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. Further, 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 Fig. 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 opera-
tor, dispersion, multimodes, 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. 2006). By developing a unique combination of a narrowband excitation signal and wavelet-based signal processing techniques, Park et al. (2006) demonstrated previously that the original input waveform could be successfully reconstructed in a composite plate through the enhanced time reversal method when only the fundamental antisymmetric mode is considered.

This paper takes advantage of this enhanced time reversal method to identify defects in composite plates: Certain types of damage cause nonlinear responses during the time reversal process, and it breaks down the linear reciprocity of elastic waves. Therefore, damage may be detected by examining the distortion of the time reversibility. 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 becomes less vulnerable 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: The next section 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 the following section, the enhanced time reversal method is introduced to improve the time reversibility of Lamb waves. Next, damage sensitive features are investigated and extracted for damage identification based on the time reversibility of Lamb waves. Then, a statistical classifier and a damage localization technique are described. Experimental investigations are presented in the penultimate section to demonstrate the validity of the current study. Finally, this paper is concluded with a brief summary and discussions.

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 characteristics: 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:

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

where $\omega =$ 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 Fig. 2.

As shown in Fig. 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.

Time Reversibility of Lamb Waves in a Thin Plate

The time reversibility of Lamb waves becomes complicated due to the aforementioned dispersive and multimodal characteristics of Lamb waves, and these unique characteristics have limited the use of Lamb waves for damage detection applications (Sohn et al. 2004; Park et al. 2006).

Although a number of experimental evidence has shown that the time reversal process can be used to focus Lamb wave energy in a time domain, the time reversibility of Lamb waves has not been fully investigated unlike that of body waves. Park et al. (2006) investigated the time reversibility of Lamb waves on a composite plate and introduced the time reversal operator into the Lamb wave equation based on the Mindlin plate theory. The time reversal operator $G_{TR}$ is a frequency kernel, which relates the original input signal $I$ to the reconstructed output signal $V$ at a given frequency during the time reversal process (Wang et al. 2003)

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

where $\omega$ and $K_{TR} =$ angular frequency and the electromechanical efficiency of piezoelectric (PZT), respectively.

As shown in Fig. 3, the time reversal operator varies with respect to frequency, indicating that wave components at different frequency values are nonuniformly amplified. Therefore, the
original input signal cannot be properly reconstructed if the input signal consists of multiple frequency components such as a broadband input signal. To avoid this issue, a narrowband excitation at 110 kHz is used in this study. It should be noted that the time reversal operator in Eq. (2) is based on the Mindlin plate theory, and it considers only the fundamental antisymmetric mode. In reality, the existence of multimodes complicates Lamb wave time reversal.

To justify the use of a narrowband excitation for the time reversal process, a numerical example of the time reversal process based on the Mindlin plate theory is provided in Fig. 4. In particular, broadband (a Gaussian pulse [Fig. 4(a)]) and narrowband (a 100 kHz tone burst [Fig. 4(d)]) input signals are employed to numerically simulate the time reversal process. The specification of a composite plate and a PZT pair used in this numerical simulation are identical to those described in the section entitled “Experimental Study.” The distance between the PZT pair is assumed to be long enough (5 m) so that the velocity dispersion of Lamb waves can be observed at the response PZT [Figs. 4(b and e)]. When the response signals are reversed in a time domain and reemitted to the input PZT, the velocity dispersion of Lamb waves is compensated [Figs. 4(c and f)]. As demonstrated here, dispersion within a single Lamb wave mode can be compensated during the time reversal process. Some wave components within the single Lamb wave travel at higher speeds and arrive at a sensing point earlier than those traveling at lower speeds. However, during the time reversal process at the sensing location, the wave components, which travel at slower speeds and arrive at the sens-

Fig. 3. Normalized time reversal operator of the $A_0$ mode

Fig. 4. Reconstruction of input signals using broadband and narrowband input signals through a numerically simulated time reversal process: (a) Original input signal—Gaussian pulse; (b) response signal—Gaussian pulse; (c) original input (dotted) and reconstructed input (solid) signals—Gaussian pulse; (d) original input signal—100 kHz tone burst; (e) response signal—100 kHz tone burst; and (f) original input (dotted) and reconstructed input (solid) signals—100 kHz tone burst
Fig. 5. Effect of multimodes on the time reversal process. (Note: $S_0/A_0$ denotes $S_0$ mode produced at PZT A due to $A_0$ mode input at PZT B. $A_0/S_0$, $S_0/S_0$, and $A_0/A_0$ are similarly defined.)

The narrowband excitation is selected so that only the first symmetric modes are generated at PZT B in Fig. 5. When a tone-burst signal is exerted to PZT A, the response signal is reversed in a time domain and reemitted to the original source location first. Therefore, all wave components traveling at different speeds concurrently converge at the source point during the time reversal process, compensating the dispersion within the mode. In addition, there is a signal processing technique that can remove the dispersion effect of Lamb waves (Wilcox et al. 2000).

The shape of the original pulse is, however, not fully recovered when the Gaussian input is used [Fig. 4(e)]. This is because the various frequency components of the Gaussian input are differently scaled and superimposed during the time reversal process as indicated in Fig. 3. On the other hand, the shape of the reconstructed tone burst waveform is practically identical to that of the original input tone burst because the amplification of the time reversal operator is almost uniform for a limited frequency band [Fig. 4(f)].

Effect of reflections on the time reversal process (TRP). (Note: P1 and P2 are waves propagating along the direct path between PZTs A and B, and P3 and P4 are waves reflected at one end of the plate in forward and backward directions. P3/P2 denotes a signal arrived at PZT A through a direct path, when the reflected signal, P2, is emitted back to PZT B after time reversal. P4/P2, P3/P1, and P4/P1 are similarly defined.)

Fig. 6. Effect of reflections on the time reversal process (TRP). (Note: $S_0/A_0$ denotes $S_0$ mode produced at PZT A due to $A_0$ mode input at PZT B. $A_0/S_0$, $S_0/S_0$, and $A_0/A_0$ are similarly defined.)

Next, the effect of the multimode characteristic is investigated in Fig. 5. When a tone-burst signal is exerted to PZT A [Fig. 5(a)], multimodes are generated at PZT B [Fig. 5(b)]. In this example, the narrowband excitation is selected so that only the first symmetric ($S_0$) and antisymmetric ($A_0$) modes are generated. When the response signal is reversed in a time domain and reemitted to PZT B [Fig. 5(c)], each of $A_0$ or $S_0$ modes creates $S_0$ and $A_0$ modes resulting in a total of four modes in the reconstructed signal [Figs. 5(d and e)]. In Fig. 5, $S_0/A_0$ denotes the $S_0$ mode measured at PZT A due to the $A_0$ mode input at PZT B. $A_0/S_0$, $S_0/S_0$, and $A_0/A_0$ are similarly defined. After superposition of Figs. 5(d and e), the reconstructed signal consists of the main peak at the middle ($S_0/A_0$) and two sidebands ($A_0/S_0$ and $S_0/A_0$) around the main peak [Fig. 5(f)]. Note that the main peak in the middle is the superposition of $A_0/A_0$ and $S_0/S_0$ modes and “symmetric” side bands are produced as a result of $A_0$ and $S_0$ mode coupling. There will be additional sidebands if more modes are generated during wave propagations. However, the shape of the main peak should be always identical to that of the original input signal (Kim et al. 2005).

The actual implementation of the TRP is further complicated due to reflection when Lamb waves propagate along a finite medium. The effect of reflections from boundaries on the TRP is illustrated in Fig. 6. Assuming that a single mode wave is generated at PZT A and travels to PZT B [Fig. 6(a)], the wave will take two different paths to arrive at PZT B [Fig. 6(b)]. In Fig. 6, P1 and P2 denote modes produced along direct and reflection paths in a forward propagation direction. P3 and P4 are defined in a similar fashion for the reversed wave propagation direction. When the mode due to the reflection, P2, is emitted back to PZT A [Fig. 6(c)], this wave generates two response modes, P3/P2 and P4/P2, in the reconstructed signal due to the two different wave propagation paths [Fig. 6(d)]. Similarly, when P1 is reemitted, it creates additional two modes, P3/P1 and P4/P1 [Fig. 6(e)]. Finally, the reconstructed signal is composed of the main peak in the middle, which is the superposition of P3/P1 and P4/P2, and two symmetric sidebands due to P3/P2 and P4/P1 [Fig. 6(e)]. Note that the symmetry of the reconstructed signal is irrelevant to the symmetry of neither the structure nor the boundary condition. In the example presented in Fig. 6, there is only one finite boundary where waves can be reflected, but the reconstructed signal is still symmetric. The number of sidebands will increase if there are additional wave reflections.

Ultimately, the reconstructed signal will have multiple peaks due to multimodes and reflections. Note that $S_0$ modes traveling along the direct path in both directions ($P_3/P_1$) and along the indirect (reflection) path in both directions ($P_4/P_2$) converge with $A_0$ modes propagating through the same paths, creating energy concentration on the main peak in the reconstructed signal. Then, several sidebands are produced due to the interaction of $A_0$ and $S_0$ modes and the coupling of the direct and reflection paths (Fig. 7). Note that the waveform of the main peak response is identical to that of the original input signal, and the symmetry of the reconstructed signal is irrelevant to the symmetry of neither the structure nor the boundary condition.

In the composite plate experiment presented in this study, the size and placement of the PZT sensors are optimized for the generation of the antisymmetric mode (Giurgiutiu and Lyshchevski 2004). In addition, it has been reported that antisymmetric modes are predominantly generated when the PZT patches are attached on the one surface of the plate (Kessler 2002; Wilcox et al. 2000). Therefore, our study focuses on mainly examining the fundamen-
Enhanced Time Reversal Method

To alleviate several issues raised in the previous section, a combination of input waveform design and a multiresolution 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 in the following, with a specified narrowband frequency (110 kHz for the experiments presented later in this paper) is adopted as an input waveform (Strang and Nguyen 1997)

\[
\psi(t) = e^{-\pi t^2/2}\cos(5t)
\]  

(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. Although 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 antisymmetric modes. Further discussion on the selection of the driving frequency can be found in Sohn et al. (2004). Note that the Morlet waveform used in this study is similar to the Gaussian-modulated toneburst waveform commonly used in ultrasonic testing. However, the use of the Morlet wavelet is more advantageous for the following wavelet transform.

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 Fig. 8. Some of the modes are antisymmetric modes associated with the direct path of wave propagation and/or signals reflected off from the edges of the plate. There are also additional 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. This time gating is a common practice in conventional ultrasonic testing. For this purpose, an automated selection procedure based on wavelet analysis is developed. Because this sig-

Fig. 7. A typical reconstructed signal when the TRP is applied to Lamb wave propagations. The time reversibility and symmetry of the reconstructed input signal are expected to be preserved through the TRP even in the presence of multimodes and dispersion. These characteristics will be used to extract damage sensitive features. See Figs. 5 and 6 for descriptions of \(S_0/S_0, A_0/A_0\), Paths 1 and 4, and Paths 2 and 3.

Fig. 8. Typical dynamic strain response measured at one of the piezoelectric sensors.
nal 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 Fig. 9. 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

\[
Wf(u,s) = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{s}} \psi^*(\frac{t-u}{s}) \, dt
\]

where

\[
\psi^*(t) = \frac{1}{\sqrt{s}} \psi\left(\frac{t-u}{s}\right)
\]

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 \( \psi^*_u(t) \) 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. Further, 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 Multiresolution 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 the 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 nonuniformly 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 Fig. 3. To achieve this goal, a multiresolution analysis is adopted to filter out the measurement noise in response signals and to keep only the response component at the driving frequency value. Multiresolution 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)

\[
f(t) = \frac{1}{C_\psi} \int_{-\infty}^{\infty} \int_{0}^{\infty} Wf(u,s) \frac{1}{\sqrt{s}} \psi\left(\frac{t-u}{s}\right) \frac{1}{s} \, ds \, du
\]

where \( C_\psi = \text{constant determined by} \)
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

\[
f(t) = \frac{1}{C_s} \int_{-\infty}^{\infty} Wf(u, s) \frac{1}{s^2} \frac{1}{\sqrt{2\pi}} e^{-\frac{(t-u)^2}{2s^2}} ds du
\]

where \( a = \text{lower} \) and \( b = \text{upper} \) 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.

**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 hysteric 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).

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 nonlinearity 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 might be detected.

**Data Normalization**

In most 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 (2006). 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

\[
DI = 1 - \sqrt{\left( \int_{t_0}^{t_1} I(t)V(t)dt \right)^2 \left/ \left( \int_{t_0}^{t_1} I(t)^2dt \int_{t_0}^{t_1} V(t)^2dt \right) \right.}
\]

where the \( I(t) \) and \( V(t) \) are input and reconstructed signals and \( t_0 \) and \( t_1 \) are starting and ending time points of the baseline signal’s first \( A_0 \) 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 \( V(t) = I(t) \) for all \( t \) where \( t_0 < t < t_1 \) and \( \beta = 0 \), 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 prespecified 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. 2005), 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 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. (2005).

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 structural health monitoring 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. Further, by properly modeling the maximum distribution of the damage index, false alarms have been minimized.

Experimental Study

Experimental Test Setup

The overall test configuration of this study is shown in Fig. 10(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 $\times$ 60.96 $\times$ 0.6350 cm ($24 \times 24 \times 1/4$ 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 PZT sensors is mounted on one surface of the composite plate as shown in Fig. 10(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 Morlet waveform defined in Eq. (3) into the structure at a driving frequency of 110 kHz. Then, the adjacent PZTs become strain sensors and measure the response signals. This actuator–sensor sensing scheme is graphically shown in Fig. 10(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 min for a full scan of the plate used in this study. These PZT sensor/actuators are inexpensive, generally require low power, and are relatively nonintrusive.

The personal computer shown in Fig. 10(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

![Fig. 10. Active sensing system for detecting delamination on a composite plate](image)

(a) Testing configuration (b) A layout of the PZT sensors/actuators

(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)

![Fig. 11. Impact test setup used to seed internal delamination in the composite plate](image)
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 g steel projectile into the composite plate as shown in Fig. 11. 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 31–46 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. The findings from the other damage cases were consistent with the one presented here. First, the surface damage on the composite plate is visually inspected after each impact test. Fig. 12(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 reverse side of the plate shown in Fig. 12(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 as shown in Fig. 12(c).

Next, the active sensing system and the proposed damage identification algorithms were employed to identify the internal delamination. Fig. 13(a) shows the actual impact location. The identification of the damaged paths shown in Fig. 13(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 Fig. 13(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 were presented in Fig. 13(c), and the estimate from the proposed damage identification matched well with the ultrasonic scan results.

Fig. 14 demonstrates the time reversibility of Lamb waves and the violation of the time reversibility due to delamination: Fig. 14(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 $A_0$ mode. Fig. 14(b) further illustrates the distortion of the reconstructed signal due to the internal delamination.

**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 an intact plate and delamination results in nonlinear response, the time reversibility is violated when there is delamination 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 are 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 specimens. 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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