Baseline-free damage visualization using noncontact laser nonlinear ultrasonics and state space geometrical changes

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2015 Smart Mater. Struct. 24 065036

(http://iopscience.iop.org/0964-1726/24/6/065036)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 143.248.122.199
This content was downloaded on 23/06/2015 at 23:34

Please note that terms and conditions apply.
Baseline-free damage visualization using noncontact laser nonlinear ultrasonics and state space geometrical changes

Peipei Liu, Hoon Sohn and Byeongjin Park

Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daejeon, 305-701, Korea

E-mail: hoonsohn@kaist.ac.kr

Received 22 December 2014, revised 1 April 2015
Accepted for publication 16 April 2015
Published 18 May 2015

Abstract
Damage often causes a structural system to exhibit severe nonlinear behaviors, and the resulting nonlinear features are often much more sensitive to the damage than their linear counterparts. This study develops a laser nonlinear wave modulation spectroscopy (LNWMS) so that certain types of damage can be detected without any sensor placement. The proposed LNWMS utilizes a pulse laser to generate ultrasonic waves and a laser vibrometer for ultrasonic measurement. Under the broadband excitation of the pulse laser, a nonlinear source generates modulations at various frequency values due to interactions among various input frequency components. State space attractors are reconstructed from the ultrasonic responses measured by LNWMS, and a damage feature called Bhattacharyya distance (BD) is computed from the state space attractors to quantify the degree of damage-induced nonlinearity. By computing the BD values over the entire target surface using laser scanning, damage can be localized and visualized without relying on the baseline data obtained from the pristine condition of a target structure. The proposed technique has been successfully used for visualizing fatigue crack in an aluminum plate and delamination and debonding in a glass fiber reinforced polymer wind turbine blade.

Keywords: nonlinear wave modulation, noncontact laser ultrasonics, state space attractor, baseline-free damage diagnosis, damage visualization

(Some figures may appear in colour only in the online journal)

1. Introduction

There have been increasing demands to reduce exorbitant maintenance costs, enhance safety and extend residual service life of structural components. These demands have been driving the development of non-destructive evaluation (NDE) and structural health monitoring (SHM) techniques that enable more accurate component failure diagnosis and prediction. Among various techniques explored for NDE and SHM, ultrasonic techniques have been widely studied for damage detection and they have proven their effectiveness in achieving a reasonable compromise between resolution, practicality and detectability [1–4]. Most existing ultrasonic techniques detect damage by measuring variations of the amplitude, phase and mode conversion of ultrasonic waves that are either transmitted or reflected from the damage [5–9]. These techniques, which rely on linear features, are often used to evaluate only gross damage (e.g., through-hole, open crack and void) with dimensions comparable to the ultrasonic wavelength. However, when dealing with small damage (e.g., fatigue crack), linear ultrasonics may lose their effectiveness and practicability.

Indeed, damage evolution is often a nonlinear process that causes a structure with predominantly stationary and linear dynamic response properties in its intact condition to exhibit non-stationary and nonlinear properties. Examples of such damages include fatigue crack, fiber debonding and delamination, etc [10]. Recently, many nonlinear ultrasonic techniques have been proposed to take advantage of the nonlinear features created by damage. It has been shown that
the sensitivity of nonlinear features to small damage is much higher than what can be achieved by conventional linear features [11–14]. Nonlinear ultrasonic techniques view damage as an active nonlinear radiation source at frequencies different from excitation frequencies, while conventional linear techniques consider damage as a passive scatter source only at the excitation frequencies. More specifically, nonlinearity due to damage evolution can distort ultrasonic waves, create accompanying harmonics and modulations of different frequencies, and change resonance frequencies as the amplitude of the driving input changes. For intact structures, these nonlinear features are weak, but they become remarkably strong for damaged structures [11–15].

Nonlinear wave modulation spectroscopy (NWMS) is one of the nonlinear ultrasonic techniques based on nonlinear mixing of two distinctive input signals [15]. Generally, a low-frequency pumping input and a high-frequency probing input are used in NWMS to create modulation. Here, the amplitude of modulation heavily depends on the choice of the probing and pumping frequencies, which needs to obey certain binding conditions [16, 17]. However, because this selection of two input frequencies can be affected by environmental and operational conditions (e.g., temperature and loading) of the structure and even by damage configurations [16–19], it is challenging to find the optimal combinations of probing and pumping frequencies that can maximize the modulation amplitude.

To address this problem, frequency-swept probing signals and a frequency-fixed pumping signal are used [18]. Similarly, a first sideband spectrogram is created by sweeping both pumping and probing signals over specified frequency ranges to study the effect of pumping and probing frequencies on the modulation amplitude [19]. In addition, a laser nonlinear wave modulation spectroscopy (LNWMS) utilizes a pulse laser excitation instead of two distinct frequency inputs to create a broadband input [20]. Then, damage is detected by counting the number of spectral peaks above a moving threshold, based on the premise that a spectral signal obtained from a nonlinear system would have more spectral peaks compared to a linear system.

When it comes to generation and sensing of ultrasonic waves, various types of contact transducers, such as accelerometers, piezoelectric stack actuators, surface-bonded piezoelectric wafer transducers or mechanical shakers are available [11–15, 18, 19]. One common issue with all aforementioned contact transducers is that a dense array of transducers is often required to achieve good spatial resolution and cover a large inspection area for damage localization or visualization. Moreover, the installation of contact transducers under harsh environments such as high temperature and radioactive conditions is a daunting task, and the bonding layer between the contact transducer and the host structure can also be a source of nonlinearity.

A potential solution to this problem is to use noncontact laser scanning techniques so that high spatial resolution can be achieved, unnecessary nonlinearity due to the bonding layer can be eliminated, and damage can be visualized. Previous examples include the detection of fatigue crack from the variation of the ultrasonic amplitude profile [21] and the visualization of delamination in composites using a standing wave filter [22]. However, with only a few exceptions [23], to date there have been no laser ultrasonic scanning techniques that visualize damage using nonlinear features.

This study develops an LNWMS system with laser scanning capability and defines a nonlinear damage feature named Bhattacharyya distance (BD) so that certain types of damage can be detected and visualized without any reference to the baseline data obtained from the intact condition of the target structure. The proposed technique offers the following advantages: (1) A single pulse excitation rather than two distinctive sinusoidal inputs is used so that binding conditions for nonlinear wave modulation can be more easily matched; (2) BD, the nonlinear damage feature extracted from a reconstructed state space, is shown to be very sensitive to even small incipient damages; (3) baseline-free damage visualization is achieved without relying on baseline data obtained from the pristine condition of a target structure, minimizing false alarms due to operational and environmental variations of the target structure; (4) the proposed technique is fully noncontact, nondestructive and nonintrusive; and (5) various types of damage such as fatigue crack, delamination and debonding can be successfully detected and visualized.

This paper is organized as follows: in section 2, the working principle of nonlinear wave modulation using a pulse excitation input is briefly reviewed, and the proposed damage feature, BD, is defined. Section 2 also describes how damage can be visualized using the BD values obtained only from the current state of the target structure. In sections 3 and 4, the effectiveness of the proposed techniques is demonstrated by visualizing a fatigue crack in an aluminum plate, and delamination and debonding in a glass fiber reinforced polymer (GFRP) wind turbine blade. The paper concludes with a brief summary and discussion in section 5.

2. Theoretical background

2.1. Nonlinear wave modulation using a single pulse excitation

When two waves with different frequencies \( \omega_a \) and \( \omega_b \) (\( \omega_a < \omega_b \)) propagate through a stress-free plate in the x-direction with a thickness of \( 2h \) (\( -h \leq z \leq h \)) and a localized damage located at \( x = 0 \), the solution for the total particle displacement after passing the damage, \( u \), can be written as the summation of the linear responses, harmonics and modulations (figure 1(a)) [16, 17]:

\[
\begin{align*}
\mathbf{u} &= u_a e^{i(k_a z - \omega_a t + \theta_a)} + u_b e^{i(k_b z - \omega_b t + \theta_b)} \\
&+ u_{2a} e^{2i(k_a z - \omega_a t + \theta_a)} + u_{2b} e^{2i(k_b z - \omega_b t + \theta_b)} \\
&+ u_{2a2b} e^{2i((k_a + k_b) z - (\omega_a + \omega_b) t + (\theta_a + \theta_b))} + \text{c.c.}
\end{align*}
\]

(1)

where c. c. stands for complex conjugate, \( u_a \) and \( u_b \) are the amplitudes of the linear waves at \( \omega_a \) and \( \omega_b \), \( u_{2a} \) and \( u_{2b} \) are the amplitudes of the nonlinear harmonics at \( 2\omega_a \) and \( 2\omega_b \), and \( u_{2a2b} \) is the amplitudes of the modulation responses at \( \omega_a + \omega_b \). \( k_a, \omega_a, \theta_a \) and \( k_b, \omega_b, \theta_b \) are the wavenumbers and phases.
corresponding to waves \( a \) and \( b \), respectively. For simplicity, the higher-order harmonics and modulations are omitted.

For the creation of modulated waves, the combination of two input frequencies should be carefully selected. The binding conditions for nonlinear modulation in the case of a localized nonlinear source such as fatigue crack have been theoretically and experimentally investigated: First, the wave (or vibration) applied to the structure should perturb the localized damage (e.g., crack opening/closing) [17]. For example, if a fatigue crack is located in one of the vibrational nodes produced by the inputs, no nonlinear component is generated because the applied inputs do not cause crack opening and closing. Furthermore, the type of vibration mode (in-plane or out-of-plane) should be carefully determined so that the damage can be perturbed effectively. Second, the amplitude of the modulation component can be further amplified when the modulation frequency coincides with one of the resonance frequencies of the structure [16, 18].

In practice, it is challenging to find the optimal combination of two input frequencies, which satisfies all the binding conditions. In order to tackle this issue, a broadband excitation is used instead of two distinct input frequencies as an input signal [20, 24]. In Liu et al, the broadband excitation is realized with a pulse laser and it is called LNWMS [20]. When a broadband pulse signal is used as the input signal, nonlinear wave modulation can occur among various frequency components of the input signal, and multiple frequency peaks are generated as shown in figure 1(b). Here, some of the frequency peaks in figure 1(b) could have been the result of higher-order nonlinear modulations (cascade cross modulations) in the presence of damage [25].

A sideband peak count (SPC) technique has been previously proposed to keep track of the relatively weak peaks in the neighborhood of the strong peaks generated by the material nonlinearity and/or the anomalies in the material. A feature called maximum SPC difference is extracted from the frequency domain response to identify the existence of fatigue cracks [20]. In this study, a new damage feature, BD, is extracted from a reconstructed state space attractor, and applied to all time signals obtained from laser scanning for damage visualization.

2.2. Computation of BD from reference and current state space attractors

Recently, the geometric variations of data-driven dynamic state space attractors under deterministic or stochastic excitations have been shown to be sensitive to nonlinear damage [26–29]. An attractor is first reconstructed in the state space from a scalar vibration response. Then, damage features representing geometrical changes of the attractor, such as prediction error, average local attractor variance ratio and correlation dimension of attractors, are extracted by comparing the attractors across the intact and damaged conditions.

This study also uses the geometric variation of the reconstructed state space attractors to detect damage. The major departure of this study from the aforementioned ones is that the state space attractor is applied to ultrasonic signals, the frequency band of which is far above the frequency ranges explored by the previous studies. Also, in conjunction with laser scanning, it is used for baseline-free damage visualization.

Assume a dynamical system described by a first order differential equation:

\[
\dot{x} = f(x, t). \tag{2}
\]

The solution to this problem with an initial value \( x(0) \) (boldface type denotes a vector) will trace out a trajectory in

![Figure 1. Illustration of nonlinear wave modulation using: (a) two distinct sinusoidal inputs, intact (left), damaged (right), (b) a pulse input, intact (left), damaged (right).](image-url)
state space defined by the system variables $x$. As transients die out, the trajectory will approach the system dynamical attractor, which is a geometric object in a state space to which all trajectories belong [26]. The state space attractor is the geometric representation of the dynamical system, and thus will reflect a loss of dynamical similarity due to damage, especially in the nonlinear one [27].

In practice, it is difficult to gain access to each of the system variables. Instead, based on the mathematical embedding proposed by Takens [30], the dynamics of the unobserved variables can be qualitatively reconstructed from a single time series of the system response data. The reconstruction procedure is accomplished by concatenating lag copies of the single measured time series $x(n)$ ($n = 1, 2, ..., N$). Here $n$ is the discrete time index corresponding to the value of $x$ sampled at time $n\Delta t$ and $\Delta t$ is the sampling interval. Each discrete time instance of the attractor $X$ at time $n\Delta t$ can be expressed as:

$$X(n) = [x(n), x(n + T), ..., x(n + (m - 1)T)]$$

where $T$ is the time lag and $m$ is the embedding dimension. With proper time lag $T$ and embedding dimension $m$, a state space attractor, which preserves the ‘true’ underlying system dynamics, can be reconstructed. For the selection of time lag $T$, there are two common techniques: one uses an auto-correlation function and the other uses the average mutual information (AMI) function. As for the selection of embedding dimension $m$, two commonly used methods are the singular system analysis and the false nearest neighbors (FNNs) method. Details on the aforementioned methods can be found in Overbey et al [28].

Once the state space attractor has been reconstructed, BD is extracted from the reconstructed state space attractor as described in Figure 2 [26, 28]. In the first step, a set of $Q$ fiducial points $Y(i)$ ($1 \leq i \leq N - (m - 1)T$) is randomly selected from a reference attractor $Y$. The number of fiducial points should be chosen so that the feature extraction results are insensitive to the addition of successive fiducial points.

In the second step, a set of $P$ nearest neighbors $X_{ej}(j)$ ($1 \leq j \leq N - (m - 1)T$) to each fiducial point $Y(i)$ is selected from the current attractor $X$. Here, $P$ should be selected so that the local dynamics of the attractor can be captured, and it also should be large enough to be insensitive to noise. To prevent temporal correlations between the fiducial point and the selected neighbors, a Theiler window with step $2T$ is adopted so that any selected neighbor point will be separated from the fiducial point by at least $T$ points in time. Then, the fiducial points and neighbors are evolved in time with a time step $L$, and the mass centroid of the time-evolved neighborhood in the current attractor is computed by:

$$\hat{Y}_c(i + L) = \frac{1}{P} \sum_{1 \leq j \leq N - (m - 1)T} X_{ej}(j + L).$$

The error for each chosen fiducial point becomes:

$$e_{ci} = \hat{Y}_c(i + L) - Y(i + L)$$

where $\| \|$ denotes the Euclidean norm, and the total number of $e_{ci}$ is $Q$. Next, the reference attractor itself is treated as the current attractor and a set of $P$ nearest neighbors $X_{ej}(j)$ to each fiducial point are selected from the reference attractor itself. Similarly, the time-evolved error $e_{cj}$ for each chosen fiducial point can be calculated using equations (4) and (5).

In the last step, BD is computed to statistically estimate the difference between $e_{ci}$ and $e_{cj}$ obtained from the reference and current attractors:

$$BD = \frac{1}{4} \frac{(\mu_c - \mu_r)^2}{\sigma_c^2 + \sigma_r^2} + \frac{1}{2} \ln \left[ \frac{\sigma_c^2 + \sigma_r^2}{2\sigma_c\sigma_r} \right]$$

where $\mu_c$, $\sigma_c$ and $\mu_r$, $\sigma_r$ represent the mean and standard deviation of $e_{ci}$ and $e_{cj}$, respectively. Here, a large BD value implies a big geometrical difference between the current attractor and the reference attractor, and the current condition of the structure significantly deviates from the reference condition of the structure.

2.3. Baseline-free damage visualization

The majority of existing damage detection techniques detect damage by comparing the data obtained from the current state of the structure with the baseline data obtained from the intact condition. However, the varying operational and environmental conditions of the structure can adversely influence the collected data and cause false alarms. To address this problem, the ultrasonic response obtained from a specific spatial point is compared with the other responses obtained from spatially adjacent points. In this way, damage can be detected and even visualized without relying on the baseline data obtained from the intact condition. Figure 3 shows the overall schematics of the nonlinear laser ultrasonic system and how raster scanning of the target area is performed [31]. Here, the sensing laser beam is fixed at a single point and the excitation laser beam is scanned over the target area with a constant pitch. When the excitation laser beam is aimed at a specific excitation point, ultrasonic waves are generated and measured at a fixed sensing point using a sensing laser. The resultant time response is stored and assigned to the coordinate of the corresponding excitation point. The scanning process continues until the scanning covers the whole target area.

The BD value for each excitation point is computed by comparing the current attractor obtained from the current excitation point with the reference attractors reconstructed from the adjacent points as shown in Figure 4. The calculation of BD here is based on the premise that the waves from spatially adjacent points are similar unless there is anomaly (e.g., damage) among these points. Therefore, the BD value increases when the state space attractor reconstructed from the center point deviates from its spatially adjacent attractors due to damage. Except the points at the boundary of the scanning area, there are in total eight adjacent points for each point, and multiple BD values can be calculated using equation (6) as shown in Figure 4. The mean value of these BD values is...
chosen as the damage index for each point:

$$\text{BD} = \frac{1}{n} \sum_{i=1}^{n} \text{BD}_i$$  \hspace{1cm} (7)

where \( n \) is the number of adjacent points for each point. This mean BD value can be visualized for the entire target area, and spatial points with high BD values indicate the location of the damage. Thus, baseline-free damage visualization is realized. Also, note that the damage visualization method presented here is different from traditional phased array ultrasonic imaging techniques, in which time-of-flight or wave attenuation characteristics are used to image damage in a structure [32, 33].

3. Visualization of fatigue crack in an aluminum plate

3.1. Description of a test specimen and fatigue testing

To examine the performance of the proposed damage visualization technique, a 3 mm thick aluminum plate specimen, fabricated using 6061-T6 aluminum alloy, was prepared. All the geometrical information of this specimen can be found in figure 5. A notch was introduced in the middle of one edge of
the specimen so that fatigue crack could initiate from this notch. A fatigue crack was introduced using an INSTRON 8801 system as shown in figure 6(a). The specimen was tested under tension–tension cycling of a maximum load of 25 kN and a minimum load of 2.5 kN at a frequency of 10 Hz. A 15 mm long crack was produced after 18,793 loading cycles. The width of the fatigue crack was overall less than 10 μm and even less than 5 μm near the crack tip as shown in figure 6(b). This crack is hardly detectable using traditional linear ultrasonic techniques.

\[
BD_i = \frac{1}{4} \frac{(\mu_{ci} - \mu_{ri})^2}{\sigma_{ci}^2 + \sigma_{ri}^2} + \frac{1}{2} \ln \left( \frac{\sigma_{ci}^2 + \sigma_{ri}^2}{2\sigma_{ci}\sigma_{ri}} \right)
\]

\[
BD = \frac{1}{n} \sum_{i=1}^{n} BD_i
\]

Figure 3. Raster scanning of the target inspection area using a noncontact laser ultrasonic measurement system.

Figure 4. Illustration for spatially adjacent ultrasonic response comparison.

Figure 5. Dimensions of the aluminum plate, crack location, and laser sensing and excitation scanning arrangement.
3.2. Experimental setup and measurement

In order to operate raster scanning on the aluminum plate, a complete noncontact laser ultrasonic system was adopted in this study [31]. This system is composed of an excitation unit, a sensing unit and a control unit, as shown in figure 3. The excitation unit comprises a Q-switched Nd:YAG pulse laser, a galvanometer and a focal lens. The Nd:YAG laser (Quantel Ultra Laser) employed in this study has a wavelength of 1064 nm and a maximum peak power of 3.7 MW, and generates a pulse with 8 ns pulse duration at a repetition rate of 20 Hz. When a pulse laser beam is shot at an infinitesimal area on the specimen, a localized heating of the surface causes thermoelastic expansion of the material and creates ultrasonic waves [34]. Parameters for the laser ultrasonic generation, such as the peak power, pulse duration and beam size, should be carefully selected to avoid surface damage such as ablation. Although the available maximum peak power of the Nd:YAG laser is 3.7 MW, a peak power of around 0.2 MW is used in this study. Note that GFRP used for the wind turbine blade in the following experiment is more vulnerable to ablation due to its lower thermal conductivity. The galvanometer (Scanlab Scancube 10), with an angular resolution of $7.4 \times 10^{-5}$° and equivalent spatial resolution of 0.026 mm at 2 m focal distance, is installed in front of the Nd:YAG laser so that the pulse laser can be shot at the desired target excitation points on the specimen.

For the sensing unit, a commercial scanning laser Doppler vibrometer (LDV) (Polytec PSV-400-M4) with a built-in galvanometer and an auto-focal lens is used. The laser source of this LDV is a helium–neon (He–Ne) laser with a wavelength of 633 nm. This one-dimensional LDV measures the out-of-plane velocity in the range of 0.01 um s$^{-1}$ to 10 m s$^{-1}$ over a target surface based on the Doppler frequency-shift effect of light [34]. However, the accuracy of velocity measurement highly depends on the intensity of the returned laser beam. Thus, the incident angle of the LDV laser beam should be carefully controlled to maximize the intensity of the returned beam and minimize speckle noises [35]. Occasionally, a special surface treatment is also necessary for increasing the measurement accuracy.

The control unit consists of a personal computer (PC), a velocity decoder with a maximum velocity sensitivity of 1 mm s$^{-1}$ and a 14-bit digitizer with a maximum sampling frequency of 5.12 MHz. In this experiment, the ultrasonic responses were measured with a sampling frequency of 2.56 MHz for 25.6 ms. The PC sends out a trigger signal to launch the excitation laser beam and to simultaneously start the data collection. Also, the PC generates control signals to aim the excitation and sensing laser beams to the desired target positions.

For raster scanning, two scanning schemes are available: (1) fixed laser excitation and scanning laser sensing and (2) scanning laser excitation and fixed laser sensing. There is no difference between the two schemes with regard to the dynamic linear reciprocity. However, in practice, scanning laser excitation is more effective than scanning laser sensing because the ultrasonic generation by the Nd:YAG laser is less affected by the surface irregularity and the incident angle of the laser beam. Typically, the allowable incident angle for an excitation laser is up to ±70° whereas it is ±20° for a sensing laser [31]. Hence, in this experiment, the scanning laser excitation and fixed laser sensing scheme were employed. The laser excitation scanning area was a 35 mm × 35 mm square area, located close to one edge of the specimen and covering the entire fatigue crack, as shown in figure 5. A total of 361 (19 × 19) scanning points were assigned within this scanning area, achieving a spatial resolution of less than 2 mm. The fixed sensing point was located outside the scanning area and was 25 mm away from the closest excitation point. Here, a retro-reflective tape was pasted on the fixed sensing point to enhance the intensity of the returned laser beam.

Figure 7 shows the actual hardware components used in this experiment. The distances between the Nd:YAG laser head and the target specimen and between LDV and the target specimen were set to 1 m. Also, to improve the signal to noise ratio, the responses corresponding to a single excitation point
were measured 100 times and averaged in the time domain during the scanning.

3.3. Fatigue crack visualization results

Before calculating the BD values and visualizing the fatigue crack, the parameters for the reconstruction of a state space attractor are selected. In this study, the AMI and FNNs functions are used to choose the optimal time lag \( T \) and the embedding dimension \( m \), respectively.

The AMI function measures the average amount of information learned about \( x(n + T) \) from \( x(n) \) [36]:

\[
AMI(T) = \sum_n \frac{\hat{p}(x(n), x(n + T)) \log_2 \frac{\hat{p}(x(n)) \hat{p}(x(n + T))}{\hat{p}(x(n), x(n + T))}}
\]

where \( \hat{p}(x(n)) \) and \( \hat{p}(x(n + T)) \) are the estimated probability densities of \( x(n) \) and \( x(n + T) \), respectively, and \( \hat{p}(x(n), x(n + T)) \) is the estimated joint density. When AMI value becomes zero, \( x(n + T) \) is completely independent of \( x(n) \) and the coordinate independence is ensured for the reconstructed attractor. Figure 8(a) shows the AMI values of ten randomly selected ultrasonic responses with response to time lag \( T \). When the time lag \( T \) reaches 5, the AMI values for all the responses approach close to zero. Therefore, \( T = 5 \) is selected in this experiment.

The FNNs function calculates the percentage of false neighbors when a state space attractor is reconstructed with dimension \( m \). A false neighbor is defined as a pair of closely positioned points whose distance substantially increases as the dimension increases from \( m \) to \( m + 1 \). As the embedding dimension expands, the percentage of FNNs will decline to a suitably small value. The detailed calculation procedure can be found in [37]. The lowest embedding dimension, which corresponds to the first near zero percentage of FNNs, is often chosen as the optimal embedding dimension. The FNNs functions for ten randomly selected ultrasonic responses are depicted in figure 8(b). The percentage of FNNs functions declines rapidly and approaches the minimum values when \( m = 5 \). Therefore, the embedding dimension is selected as 5 or higher. Note that the FNNs value does not converge to zero even after \( m \) increases over 5. That is because the laser pulse excitation used in this study is neither a purely stochastic process nor a fully deterministic sequence. There is still some information retained in higher dimensions but the majority of information is retained in the first few dimensions [28].

Once the parameters are selected for state space attractor reconstruction, the BD value for each scanning point is calculated by comparing its attractor with the reference attractors obtained from its adjacent excitation points. Here, the effect of the embedding dimension \( m \) is investigated as well. The state space attractors are reconstructed with varying dimensions \((m = 1, 2, 3, 4, 5 \text{ and } 10)\) and corresponding BD values are calculated and used for fatigue crack visualization.

The results are summarized in figure 9. When \( m = 1 \) or 2, the FNNs function shows a percentage for false neighbors...
Figure 9. Fatigue crack visualization using different embedded dimensions for $m$ ($m = 1, 2, 3, 4, 5$ and $10$).
over 50%; the corresponding visualization result cannot indicate the fatigue crack, but produces a false indication of the fatigue crack. As the percentage of false neighbors decreases below 20% ($m$ is equal or larger than 3), the visualization results are improved. Furthermore, it is clearly demonstrated that the strongest nonlinearity is observed near the crack tip [23]. The damage visualization results demonstrate that the proposed technique can successfully localize the fatigue crack and is quite sensitive to nonlinear damage.

4. Visualization of delamination and debonding in a GFRP wind turbine blade

4.1. Description of a GFRP wind blade specimen, delamination and debonding

An actual 10 kW wind turbine blade (figure 10) was fabricated for additional validation of the proposed visualization technique. The wind turbine blade is made of GFRP material, has rough dimensions of 3500 mm × 450 mm × 3 mm, and consists of 6 piles with a layup of [0/± 45]$. The elastic modulus $E_1$, shear modulus $G_{12}$, and poisson ratio $\nu_{12}$ of the GFRP material are 24.65 GPa, 8.53 GPa, and 0.476, respectively [22].

Since composite structures are fabricated by bonding multilayers of laminates with resins, they are inherently vulnerable to delamination and debonding. These two types of damage were intentionally produced in this wind turbine blade as shown in figure 10. For simulating internal delamination, a circular Teflon tape with 15 mm diameter was inserted between the third and fourth ply during fabrication of the blade. For debonding, some of the glue used to attach a stiffener to the blade skin was removed, introducing a small localized gap (debonding) between the stiffener and the blade skin. Close views of these two types of damage are shown in figure 11.

4.2. Experimental setup and measurement

As shown in figure 11, a 50 mm × 50 mm square area was scanned with 400 (20 × 20) scanning points for both delamination and debonding detection, achieving a spatial resolution
of around 2.5 mm. The fixed sensing point was located 20 mm away from the closest excitation point. Figure 12 shows the actual experimental setup. The ultrasonic responses from each excitation point were measured with a sampling frequency of 2.56 MHz for 0.4 ms and averaged 100 times in the time domain for improving the signal to noise ratio. The rest of the experimental setup was identical to that in the previous experiment.

4.3. Delamination and debonding visualization results

The parameters for state space attractor reconstruction are first selected. Figure 13 shows the selections of time lag $T$ using the AMI function and embedding dimension $m$ using FNNs function, respectively. The AMI values of ten randomly selected ultrasonic responses from two scanning areas are shown in response to time lag $T$ in figure 13(a). The AMI values approach almost zero when time lag $T$ reaches 30. Hence, $T = 30$ is selected in this experiment. Figure 13(b) displays the FNNs values for the same ten randomly selected ultrasonic responses. The FNNs values decline to the minimum values when $m = 6$. Therefore, the embedding dimension is set to 6.

The BD values for two scanning areas are then calculated from the reconstructed state space attractors with the selected parameters. The corresponding damage visualization results are shown in figure 14. It can be seen that if the scanning is performed in the middle of the damaged area, BD value does not increase much since the other adjacent points are also affected by the damage. However, as the scanning moves toward the edge of the damaged area, the BD value increases significantly as demonstrated in figure 14. The proposed technique again successfully visualizes both delamination and debonding in the GFRP wind turbine blade.

5. Conclusions

In this study, a laser nonlinear wave modulation spectroscopy (LNWMS) system with scanning capability and a damage-sensitive feature called Bhattacharyya Distance (BD) is presented to detect various types of damages in metallic and composite structures. The damage-sensitive feature BD is obtained by reconstructing state space attractors from the ultrasonic responses acquired by LNWMS. By examining the spatial distribution of the BD values over the inspection area using laser scanning, damages are visualized without referencing temporal baseline ultrasonic signals corresponding to the pristine condition of the target structure. Fatigue crack in an aluminum plate and delamination and even hidden debonding in a GFRP wind turbine blade are successfully detected using the proposed technique. However, additional studies are warranted before the proposed technique can be applied to real structures. For example, the time for laser scanning can be prohibitively long, especially for scanning large structures. In addition, the high power laser used for ultrasonic generation should be treated with extreme caution to avoid laser-induced damage.
Acknowledgments

This research was supported by the Climate Change Research Hub of KAIST (Grant No. N01150138).

References

[7] Cai J, Shi L, Yuan S and Shao Z 2011 High spatial resolution imaging for structural health monitoring based on virtual time reversal Smart Mater. Struct. 20 055018
[34] Scruby C B and Drain L E 1990 Laser Ultrasonics: Techniques and Applications (London: Taylor and Francis)