Damage detection using sideband peak count in spectral correlation domain

Peipei Liu, Hoon Sohn*

Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daejeon, 34141, South Korea

ARTICLE INFO

Article history:
Received 13 June 2017
Received in revised form 13 August 2017
Accepted 30 August 2017

Keywords:
Damage detection
Nonlinear wave modulation
Sideband peak count
Spectral correlation
Laser ultrasonics

ABSTRACT

Nonlinear ultrasonic techniques have been proven to be more sensitive to the presence of an early-stage damage than linear techniques. Among various nonlinear techniques, laser nonlinear wave modulation spectroscopy (LNWMS) utilizes a pulse laser to exert a broadband input and a damage on the target structure exhibits nonlinear wave modulation among various input frequency components. A sideband peak count (SPC) technique in the spectral frequency domain was proposed to estimate the damage-induced nonlinearity. In this study, the SPC operation is conducted in the spectral correlation domain so that noise has less influence on damage detection performance and a higher sensitivity to damage can be achieved. In addition, through spatial comparison of SPC over an inspection area, damage can be detected without relying on the baseline data obtained from a pristine condition. The performance of the proposed technique is validated using a numerical simulation performed on an aluminum plate with a simulated crack, and experiments performed on an aluminum plate with a fatigue crack and a carbon fiber reinforced polymer plate with delamination.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Damage evolution in a structure is often a nonlinear process that causes a linear structure to exhibit nonlinear properties. Examples of such damages include fatigue cracks, fiber debonding and delamination, etc [1,2]. Among various ultrasonic techniques, it has been shown that the sensitivity of nonlinear ultrasonic techniques to an early-stage damage is much higher than what can be achieved by linear ultrasonic techniques [3–6]. Specifically, the linear ultrasonic techniques detect the presence and location of a damage by measuring variations of amplitude, phase and mode conversion of ultrasonic waves that are either transmitted or reflected from the damage [7–9]. However, these linear features are not sensitive to early-stage damages whose dimensions are comparable to the ultrasonic wavelength. Furthermore, the interpretation of linear features becomes complex in plate-like structures due to dispersion and multimode characteristics [10], and even more challenging in inhomogeneous materials like composites [11,12].

On the other hand, nonlinear ultrasonic techniques detect a damage by investigating accompanying harmonics, modulations (sidebands) of different frequencies, or changing resonance frequencies as the amplitude of the driving input changes. These nonlinear features are observed in the course of structural degradation processes much sooner than any changes of linear features can be detected, making the nonlinear ultrasonic features more attractive for early-stage damage detection.

* Corresponding author.
E-mail address: hoonsohn@kaist.ac.kr (H. Sohn).

http://dx.doi.org/10.1016/j.jsv.2017.08.049
0022-460X/© 2017 Elsevier Ltd. All rights reserved.
For nonlinear wave modulation spectroscopy (NWMS) which is one of the nonlinear ultrasonic techniques, a low-frequency pumping input and a high-frequency probing input are simultaneously applied on a damaged structure to create modulation [13]. For the generation of nonlinear modulation using NWMS, there are certain binding conditions should be satisfied in addition to the existence of a damage [14,15]: (1) The strain (displacement) at the damage location should be oscillated by both inputs; and (2) The motion induced by one of the two inputs should modulate the other input at the damage location. That is, the generation of nonlinear modulation also depends on the choice of input frequencies and can be easily affected by the configuration of the damage as well as by variations in the environmental and operational conditions (e.g., temperature and loading) of the target structure [16].

To ensure that the binding conditions be satisfied and damage be detected, frequency-swept probing signals and a frequency-fixed pumping signal were used to find input frequency combinations that could amplify the amplitude of damage-induced modulation [17]. Similarly, fatigue cracks in aircraft fitting-lug mock-up specimens were detected by sweeping both low-frequency pumping and high-frequency probing inputs [18]. In another study, instead of using two distinct frequency inputs, a pulse signal was designed as an input to reveal reduction of the nonlinear modulation behavior in glass fiber reinforced cement material with aging [19]. A laser nonlinear wave modulation spectroscopy (LNWMS) utilized a pulse laser signal to excite multiple frequency components simultaneously into a target structure [20,21]. The basic premise is that nonlinear wave modulation can occur among frequency components excited by the pulse input at the existence of a damage, as illustrated in Fig. 1. The broadband nature of the pulse laser input guarantees that the binding conditions can be satisfied among a subset of frequency combinations within the excited frequency band. The pulse excitation also can reduce the data collection time compared to the sweeping of input frequencies within the same frequency band. Note that, because the nonlinear modulation (sideband) and the linear response components overlap in the spectral frequency domain, a sideband peak count (SPC) was developed to detect the spectral peaks created by a damage [20,21]. LNWMS experiments were conducted on simple aluminum plates and aircraft fitting-lugs with a complete noncontact laser ultrasonic system, and the test results demonstrated that an increased number of weak spectral peaks appeared when fatigue cracks were formed [22].

This study develops a new SPC technique by conducting the SPC operation in a spectral correlation domain for damage detection rather than the conventional spectral frequency domain. The proposed technique offers the following advantages: (1) The new SPC technique is robust against noise interferences; (2) The new SPC technique has a higher sensitivity to damage than the conventional SPC technique conducted in the spectral frequency domain; (3) The new SPC technique is realized in a fully noncontact manner; and (4) By spatial comparison through laser scanning, damage can be detected without relying on baseline data obtained from the pristine condition of a target structure.

This paper is organized as follows. Section 2 briefly reviews the working principle of the SPC technique. Then, Section 2 presents the new spectral correlation based SPC technique and its advantages over the conventional SPC technique. In addition, a baseline-free damage detection strategy is proposed by spatial comparison through laser scanning. In Section 3, the proposed technique is numerically validated by detecting a simulated crack in an aluminum plate model. In Sections 4 and 5, the performance of the proposed technique is examined by detecting a fatigue crack in an aluminum plate, and delamination in a carbon fiber reinforced polymer (CFRP) plate. Finally, a conclusion is provided in Section 6.
2. Theoretical background

2.1. Sideband peak count (SPC)

When a broadband pulse laser signal is used as an input for LNWMS and there is a damage within an inspection area, nonlinear wave modulation can occur among various frequency components excited by the input signal as shown in Fig. 1. A SPC technique was proposed to identify the presence of damage-induced nonlinearity [20,21]. First, the spectral density distribution \( P_x(f) \) of the response signal \( x(t) \) is computed in the spectral frequency domain:

\[
P_x(f) = E\{X(f)X^*(f)\}
\]

where \( f \) is the spectral frequency, \( X(f) \) is the Fourier transform of \( x(t) \), * denotes the complex conjugate, and \( E \) is the expectation operation. \( P_x(f) \) within a specified spectral frequency range is then selected and normalized to fit its values within unity. The SPC is defined as the ratio of the number of spectral peaks \( N_p \) over a threshold \( T \) to the total peak number \( N_t \) in \( P_x(f) \) within the specified spectral frequency range (Fig. 2). When \( T \) moves from 0 to 1, the SPC value can be plotted as a function of \( T \):

\[
SPC(T) = \frac{N_p(T)}{N_t}
\]

A SPC difference is defined as the difference between the SPC plots obtained from the current and reference conditions. As the level of nonlinearity increases, more sideband peaks show up in the spectrum or the sideband energy grows as a consequence. Therefore, the SPC plot will show larger values for the damage case than for the intact case, and the SPC difference becomes positive for the damage case. The maximum SPC difference (MSPCD) is selected as a nonlinear damage feature for damage detection:

\[
MSPCD = \max(\text{SPC}_c(T) - \text{SPC}_r(T))
\]

where \( \text{SPC}_c \) and \( \text{SPC}_r \) are the SPC plots obtained from the current and reference conditions, respectively. Here, the maximum operation is performed with respect to the moving threshold \( T \). Since the energy of the damage-induced sideband peaks is much smaller than that of the linear spectral peaks, this MSPCD is often obtained when \( T \) is relatively low.

Though the effectiveness of this SPC technique has been demonstrated by detecting damages in different target specimens [20,21], there is still a technical hurdle that needs to be overcome before it can make transitions to real field applications. In general, the amplitude of the damage-induced modulation components is at least one or two orders of magnitude smaller than that of the linear components. Test noises, varying with environmental and operational conditions, can deteriorate the performance of the SPC technique. Fig. 3 compares a signal before and after contaminated with simulated white noise in the spectral frequency domain. The signal-to-noise ratio (SNR) of the noise contaminated signal is set to 30 dBW. Here, the SNR is defined as:

\[
\text{SNR} = 10\log_{10} \frac{E_s}{E_n} \text{ (dBW)}
\]

where \( E_s \) and \( E_n \) are the energy of the signal and the added white noise, respectively. Because of the added noise, more spectral peaks appear in the spectrum and these increased spectral peaks may cause false alarms of damage.

2.2. SPC in spectral correlation domain

In this study, ultrasonic signals measured from a specimen are transformed into a new spectral correlation domain instead of the spectral frequency domain [23]:

Fig. 2. Sideband peak count (SPC) above a moving threshold \( (T) \) in the spectral frequency domain.
When \( f_a = f_b = f \), \( S_x(f_a, f_b) = E[X(f_a)X^*(f_b)] \) equals to its spectral density function \( S_x(f) = P_x(f) = E[X(f)X^*(f)] \). If SPC is conducted in \( E[X(f)X^*(f)] \), the results will be identical to the results obtained from Section 2.1. When the specified range of \( f \) varies from \( f_1 \) to \( f_2 \), the corresponding spectral correlation region for \( E[X(f_a)X^*(f_b)] \) can be shown in Fig. 4(a), given that \( f_0 > f_b \).

The new SPC operation is conducted in \( E[X(f_a)X^*(f_b)] \) by considering all the spectral correlation values within the corresponding spectral correlation region, as shown in Fig. 4(b). The SPC in Eq. (2) is redefined as the ratio of the number of the spectral correlation peaks over a moving threshold plane to the total peak number within a specified spectral correlation region. Then, we can calculate the SPC difference and obtain the MSPCD value as defined in Eq. (3).

Two notable properties of spectral correlation are as follows [24]: (1) Noise exhibits no spectral correlation (for \( f_a \neq f_b \)); and (2) Two statistically weak-linked components exhibit weak spectral correlation (for \( f_a = f_b \)). For the first property, since most of the test noises are stationary or do not show cyclostationary features, the spectral correlation values \( (f_a \neq f_b) \) caused by the test noises become zero and they have little effect on the test results when the SPC operation is conducted in the spectral correlation domain. Hence, the new spectral correlation based SPC technique has a high robustness against noise.

**Fig. 3.** Comparison of noise-free and noise-contaminated signals in the spectral frequency domain.

**Fig. 4.** New sideband peak count (SPC) technique: (a) spectral correlation region corresponding to a spectral frequency range from \( f_1 \) to \( f_2 \). (b) SPC in the spectral correlation domain.
For the second property, let us consider two components at frequencies \(f_a\) and \(f_b\) \((f_a > f_b)\) extracted from a broadband response signal. For the first-order nonlinear modulations caused by these two components, their amplitudes \(m_+\) at \(f_a \pm f_b\) are proportional to the amplitudes \(a\) and \(b\) at \(f_a\) and \(f_b\) based on the classical two-fold nonlinear interaction \([13]\):

\[
m_+ \sim \beta_{a,b}^+ a b \sqrt{E[X(f_a + f_b)X^*(f_a - f_b)]} \sim \beta_{a,b}^+ \sqrt{E[X(f_a)X^*(f_a)]} E[X(f_b)X^*(f_b)]
\]

where \(E[X(f_a \pm f_b)X^*(f_a \pm f_b)]\) is the spectral density value at the modulation frequencies \(f_a \pm f_b\), \(E[X(f_a)X^*(f_a)]\) and \(E[X(f_b)X^*(f_b)]\) are the spectral density values at frequencies \(f_a\) and \(f_b\), and \(\beta_{a,b}^+\) is the classical nonlinear coefficient between \(f_a\) and \(f_b\), respectively. For the corresponding spectral correlation \(E[X(f_a + f_b)X^*(f_a - f_b)]\) between the two modulation components, it can be estimated as \([24]\):

\[
E[X(f_a + f_b)X^*(f_a - f_b)] \\
\sim c_{a+b,a-b} \sqrt{E[X(f_a + f_b)X^*(f_a + f_b)]} E[X(f_a - f_b)X^*(f_a - f_b)]
\]

where \(c_{a+b,a-b} (\leq 1)\) is the correlation coefficient, reflecting the statistical link between the two modulation components at \(f_a \pm f_b\). Furthermore, the statistical link between the two modulation components is determined by the correlation level between their amplitude coefficients \(m_+\) and \(m_-\) \([25]\). Substituting Eq. (6) into Eq. (7) results in the following equation:

\[
E[X(f_a + f_b)X^*(f_a - f_b)] \\
\sim c_{a+b,a-b} \beta_{a,b}^+ \beta_{a,b}^- E[X(f_a)X^*(f_a)] E[X(f_b)X^*(f_b)]
\]

Comparison of Eqs. (6) and (8) shows that the spectral density value \(E[X(f_a \pm f_b)X^*(f_a \pm f_b)]\) is influenced only by the nonlinear coefficient \(\beta_{a,b}^+\), while the spectral correlation value \(E[X(f_a + f_b)X^*(f_a - f_b)]\) is affected by both the nonlinear coefficient \(\beta_{a,b}^+\) and the correlation coefficient \(c_{a+b,a-b}\).

Given that the frequency resolution of Fourier transform is \(\Delta f\), the two frequency components in the spectral frequency domain are centered at \(f_a\) and \(f_b\) with a frequency band of \(\Delta f\) (Fig. 5). These narrowband components can be represented as a summation of pure sinusoidal signals with varying frequencies around \(f_a\) and \(f_b\):

\[
a(t) \cdot e^{i2\pi f_a t} = \sum_p a_p e^{i2\pi (f_a + f_p) t} \\
b(t) \cdot e^{i2\pi f_b t} = \sum_q b_q e^{i2\pi (f_b + f_q) t}
\]

where \(f_a\) and \(f_q\) are frequencies within the range of \(-1/2 \cdot \Delta f \leq f_{p/q} < 1/2 \cdot \Delta f\) and \(a_p\) and \(b_q\) are the amplitudes of the corresponding components at \(f_a + f_p\) and \(f_b + f_q\), respectively. Based on the classical two-fold nonlinear interaction \([13]\), we can also get the corresponding modulation components and their amplitude coefficients \(m_+ (t)\) and \(m_- (t)\):

\[
m_+ (t) \cdot e^{i2\pi (f_a + f_b) t} = \sum_p \sum_q \beta_{p,q}^+ a_p b_q e^{i2\pi (f_a + f_b + f_p + f_q) t} \\
m_- (t) \cdot e^{i2\pi (f_a - f_b) t} = \sum_p \sum_q \beta_{p,q}^- a_p b_q e^{i2\pi (f_a - f_b + f_p - f_q) t}
\]

![Fig. 5](https://example.com/Fig5.png) Two narrowband components centered at \(f_a\) and \(f_b\) with a frequency band of \(\Delta f\) from a broadband response signal.
\[ m_+(t) = \sum_p \sum_q \beta_{p,q}^+ a_p b_q e^{i2\pi (f_a + f_b) t} \]
\[ m_-(t) = \sum_p \sum_q \beta_{p,q}^- a_p b_q e^{i2\pi (f_a - f_b) t} \]

where \( \beta_{p,q}^+ \) is the nonlinear coefficient of the modulation component at the sum frequency of \( f_a + f_b \) and \( f_a + f_b \) \( (f_a + f_b + f_p + f_q) \), and \( \beta_{p,q}^- \) is the nonlinear coefficient at the difference frequency between \( f_a + f_b \) and \( f_a + f_b \) \( (f_a - f_b + f_p - f_q) \).

Here, the absolute variations of \( \beta_{p,q}^\pm \) value over \(-1/2 \cdot \Delta f \leq f_p/q < 1/2 \cdot \Delta f\) are insignificant, and the \( \beta_{a,b}^\pm \) value can be seen as the average value of \( \beta_{p,q}^\pm \).

It is worth mentioning that the same frequency component \( f_a + f_b \) has different amplitudes \( \beta_{p,q}^+ a_p b_q \) and \( \beta_{p,q}^- a_p b_q \) in \( m_+(t) \) and \( m_-(t) \), respectively. For the intact case, there is little modulation and the values of \( \beta_{p,q}^\pm \) are close to zero. Then, the variations of \( \beta_{p,q}^\pm \) over \(-1/2 \cdot \Delta f \leq f_p/q < 1/2 \cdot \Delta f\) become relatively large when the variations are normalized by the values of \( \beta_{p,q}^\pm \). For the damage case, since \( f_a + f_p \) and \( f_b + f_q \) vary within a narrow frequency band, all \( \beta_{p,q}^\pm \) will increase if \( f_a \) and \( f_b \) satisfy the binding conditions. In this case, the relative variations of \( \beta_{p,q}^\pm \) with respect to the increased values of \( \beta_{p,q}^\pm \) become smaller than the intact case. Note that the correlation level between \( m_+(t) \) and \( m_-(t) \) is proportional to the product of \( \beta_{p,q}^+ a_p b_q \) and \( \beta_{p,q}^- a_p b_q \) for all \( f_p + f_q \) in the frequency domain normalized by the energies of \( \beta_{p,q}^+ a_p b_q \) and \( \beta_{p,q}^- a_p b_q \) [26]. Consequently, \( m_+(t) \) and \( m_-(t) \) become more correlated and the corresponding correlation coefficient \( \gamma_{a:b,a-b} \) will increase in return for the damage case, enhancing the contrast between intact and damage cases in the spectral correlation domain Eq. (8).

Note, if we consider the whole broadband response signal, there must exist some linear components \( E[X(f_a + f_b)]X^*(f_a + f_b)]_l \) overlapped with the modulation components at \( f_a + f_b \). However, since the linear components are not sensitive to early-stage damages, the variation of the linear components is negligible compared to their amplitudes. The corresponding correlation coefficient \( \gamma_{a:b,a-b} \) and spectral correlation value \( E[X(f_a + f_b)]X^*(f_a + f_b)]_l \) vary little between intact and damage cases, no matter these two linear components are statistically linked or not. Therefore, the contrast of the spectral correlation between intact and damage cases is affected only by the damage-induced modulations, and the sensitivity of the SPC technique to damage is increased in the spectral correlation domain. In summary, compared with the SPC technique in the spectral frequency domain, this new SPC technique owns the following advantages: (1) It is more robust against noise interferences; and (2) It owns a higher sensitivity to damage.

2.3. Baseline-free damage detection by spatial comparison

The developed SPC technique is realized in a fully noncontact manner by introducing a complete noncontact laser ultrasonic system [22], which utilizes a Q-switched Nd:YAG pulse laser for excitation and a commercial laser Doppler vibrometer (LDV) for sensing. Note that, because the pulse excitation is induced by the Nd:YAG pulse laser, a broadband response below the cutoff frequency of LDV is measured. This complete noncontact laser ultrasonic system allows to scan a large area with high spatial resolution based on two major scanning strategies, namely, fixed laser excitation and scanning laser sensing, and scanning laser excitation and fixed laser sensing. As for the fixed laser excitation and scanning laser sensing, the excitation laser is fixed at a single point and the sensing laser is scanned over equidistantly distributed spatial points within a scanning area. For the scanning laser excitation and fixed laser sensing, the roles of the excitation and sensing laser beams are switched. By controlling the gap between two sequential scanning points, the spatial resolution can be adjusted.

Fig. 6. Illustration of spatial comparison via laser scanning.
As shown in Fig. 6, the SPC is calculated for all spatial points within the scanning area, and the MSPCD value for each spatial point is computed by comparing the SPC plot obtained from the current point with the reference SPC plots obtained from its adjacent points. Slightly different from Eq. (3), the MSPCD here is redefined as:

$$
\text{MSPCD}_n = \max(|\text{SPC}_c(T) - \text{SPC}_{r,n}(T)|)
$$

$$
\text{MSPCD} = \frac{1}{N} \sum_{n=1}^{N} \text{MSPCD}_n
$$

(12)

Fig. 7. Description of numerical simulation: (a) circular specimen model and selected scanning area, (b) crack formation modeling.

As shown in Fig. 6, the SPC is calculated for all spatial points within the scanning area, and the MSPCD value for each spatial point is computed by comparing the SPC plot obtained from the current point with the reference SPC plots obtained from its adjacent points. Slightly different from Eq. (3), the MSPCD here is redefined as:

$$
\text{MSPCD}_n = \max(|\text{SPC}_c(T) - \text{SPC}_{r,n}(T)|)
$$

$$
\text{MSPCD} = \frac{1}{N} \sum_{n=1}^{N} \text{MSPCD}_n
$$

(12)

Fig. 8. The SPC and SPC difference values obtained from spectral frequency domain are compared between the intact (solid) and damage (dashed) conditions of the simulation model: (a) Point A, (b) Point B, and (c) Point C.
where $SPC_{r,n}$ is the reference SPC plot from each adjacent point, and $N$ is the totally number of the adjacent points. Except the points at the edges of the target scanning area, a total of 8 adjacent points are used for the calculation of MSPCD at each scanning point. The calculation of MSPCD is based on the premise that the waves from spatially adjacent points are similar unless there is a sudden change of the wave propagation characteristics (e.g., damage) among these points [27]. Therefore, the MSPCD value increases when the SPC plot from the current scanning point deviates from the SPC plots obtained from its adjacent points. In this way, damage can be detected and even visualized without relying on the baseline data obtained from the pristine condition of a target structure, which frees the developed SPC technique from the adverse influence caused by varying operational and environmental conditions of the target structure. Note that, with only a few exceptions [27,28], there have been no laser ultrasonic scanning techniques that visualize damage using nonlinear features. Previous examples include the detection of fatigue crack from the variation of ultrasonic amplitude profile [29], and visualization of delamination in composites with a standing wave filter [30].

3. Numerical validation

3.1. Description of numerical simulation

This section validates the new SPC technique using a simulation model developed with a commercial finite element analysis software COMSOL Multiphysics. A 3D model is built to simulate a circular aluminum plate with a radius of 75 mm and a thickness of 3 mm, as shown in Fig. 7(a). A pulse laser beam with 1 mm radius is exerted onto the center of the plate. The pulse laser delivers 10 mJ of energy for 8 ns. To represent multi-physical phenomena occurring after the impingement of the laser beam on the plate, the model is divided into two regions, namely, the thermal wave region and the ultrasonic wave region [31]. First, thermoelasticity analysis is performed to model ultrasonic waves generated from the thermal stress induced by a pulse laser. Second, elastic wave analysis is performed to simulate ultrasonic wave propagation with the specimen. The entire model is meshed with tetrahedral elements, and multi-scale elements are used to reduce the computation burden. A crack is introduced in the 3D model. The crack shape is modeled as the intersection of two circles, and then stretched in its length direction as shown in Fig. 7(b). In this way, the simulated crack will have an extremely narrow width at the crack tips, allowing crack opening and closing during wave propagation. The simulated crack is 10 mm long and 10 μm wide at its center. The details on the 3D modeling and the nonlinearity of the simulated crack are reported in Ref. [31].

![Fig. 9](image)

Fig. 9. The SPC and SPC difference values obtained from spectral correlation domain are compared between the intact (solid) and damage (dashed) conditions of the simulation model: (a) Point A, (b) Point B, and (c) Point C.
To validate the developed technique, a target scanning area of 40 mm x 35 mm was defined, covering the entire crack as shown in Fig. 7 (a). A total of 1400 (40 x 35) scanning points were assigned within this scanning area, achieving a spatial resolution of 1 mm. A 100 μs long out-of-plane velocity response was obtained from each scanning point with a sampling interval of 150 ns.

3.2. Damage detection results

First, three representative scanning points from the scanning area were selected, named Points A, B and C, respectively. As shown in Fig. 7 (a), Point B is located near the simulated crack tip, while Points A and C are relatively far away from the crack. The velocity responses from these three selected points were acquired from the intact and damage conditions of the simulation model. Then, the SPC plots are obtained for both the intact and damage conditions, and the SPC difference is computed by treating the SPC plot from the intact condition as a reference. Fig. 8 shows the SPC plots and the corresponding SPC difference conducted for a spectral frequency band of 20–350 kHz (the upper limit of the frequency range in the model is 350 kHz). The SPC plots and the SPC differences within the corresponding spectral correlation region are also computed and presented in Fig. 9. Both Figs. 8 and 9 show that the difference of the SPC plots between the intact and damage conditions is negligible at Points A and C. On the other hand, the difference of the SPC plots between the intact and damage conditions becomes noticeable at Point B, and the MSPCD shows up when the threshold value is relatively low. Table 1 along with comparison of Figs. 8 (b) and 9 (b) show that the sensitivity of the SPC technique (i.e. the MSPCD between the intact and damage conditions) increases almost by 16% when the SPC operation is conducted in the spectral correlation domain rather than the spectral frequency domain.

To investigate the noise effect on the MSPCD value calculated in the spectral correlation domain, simulated white noises with varying SNRs were added to the velocity response signals acquired from the damage condition. Here, the SNR is defined in Eq. (4) and was varied from 40 to 20 dBW, with 2 dBW decrement. The noise contaminated signals were used to calculate the MSPCD values in both the spectral correlation and spectral frequency domains. Fig. 10 shows that the MSPCD values calculated in the spectral correlation domain are less affected by the added white noise.

Then, the SPC plots were calculated for all the scanning points within the scanning area, and the corresponding MSPCD value for each scanning point was computed using Eq. (12). The SPC plots and the MSPCD values were also computed both in the spectral correlation and frequency domains for comparison. Crack visualization results are shown in Fig. 11. Higher MSPCD values were observed near the crack, and the highest MSPCD value obtained from the spectral correlation domain (0.85 in Fig. 11 (a)) was larger than the one obtained from the spectral frequency domain (0.74 in Fig. 11 (b)).

4. Fatigue crack detection in an aluminum plate

4.1. Experimental setup

To experimentally examine the performance of the new SPC technique, a 3 mm thick aluminum plate specimen was fabricated using 6061-T6 aluminum alloy. A notch was introduced in the middle of one side of the specimen so that fatigue crack can initiate from this notch during a cyclic loading test (Fig. 12 (a)). The specimen was tested under tension-tension

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison of the MSPCD values obtained from the spectral frequency and spectral correlation domains.</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>MSPCD in the spectral frequency domain (Fig. 8)</td>
</tr>
<tr>
<td>MSPCD in the spectral correlation domain (Fig. 9)</td>
</tr>
</tbody>
</table>

Fig. 10. Variation of MSPCD value with respect to SNR: (a) spectral correlation domain, (b) spectral frequency domain.
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 below 5 μm near the crack tip, as shown in Fig. 12(b).

The previously mentioned noncontact laser ultrasonic system was used in this experiment. As shown in Fig. 13, the system is composed of an excitation unit (a Q-switched Nd:YAG pulse laser, a galvanometer and a focal lens), a sensing unit (a commercial scanning LDV) and a control unit [22]. For excitation, the Nd:YAG laser has a wavelength of 512 nm and a maximum peak power of 3.7 MW, and generates a pulse input with 8 ns pulse duration at a repetition rate of 20 Hz. A peak power of around 0.2 MW was selected for this experiment, which is low below an ablation limit to avoid damaging of the specimen, but still high enough to cause crack opening and closing during wave propagation. Ultrasonic waves are created by the thermal expansion of an infinitesimal area heated by the pulse laser. The laser source used for the sensing 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 μm/s to 10 m/s over a target surface based on the Doppler frequency-shift effect of light [32]. In this experiment, each ultrasonic response was measured with a sampling frequency of 2.56 MHz for 25.6 ms, and the responses were measured 100 times and averaged in the time domain to improve the signal-to-noise ratio. Both the excitation and sensing lasers can be aimed at the desired target positions using galvanometers.

4.2. Fatigue crack detection results

First, six pairs of excitation and sensing laser beam points were selected as shown in Fig. 14. In the intact condition of the specimen, ultrasonic responses were recorded three times from each path. One of them was used as the reference signal, and the other two as the test signals acquired from the intact case (Intacts I and II). To take into account variations caused by resetting of the laser ultrasonic system and the specimen after fatigue test, the laser ultrasonic system was reconfigured every time for the acquisition of each response signal. After crack formation, ultrasonic signals were collected again for the damage case (Damage).

**Fig. 11.** Baseline-free crack visualization using MSPCD values obtained from the simulation model: (a) the spectral correlation domain, (b) the spectral frequency domain.

**Fig. 12.** Fatigue test and microscopic image of an aluminum plate with fatigue crack: (a) fatigue test setup, (b) microscopic image of crack tip.
A spectral frequency range of 20—400 kHz was selected to ensure that nonlinear modulation took place in the damage case, and the corresponding spectral correlation region was used for computing SPC plots and calculating the MSPCD values. Fig. 15 compared the MSPCD values obtained from the six paths shown in Fig. 14 for the intact and damage cases. In Fig. 15 (a) and (b), the MSPCD values obtained from the spectral correlation and frequency domains are shown respectively. The MSPCD values increased when the ultrasonic waves passed through the crack (Paths 1 and 2 in Fig. 14). In particular, the MSPCD value reached its maximum value at Path 2, which is closest to the crack tip. It is speculated that the pulse laser excitation activates the crack opening and closing, and this crack breathing becomes most prominent near the crack tip where the crack width is minimum. Comparison of Fig. 15 (a) and (b) reveals that the contrast of the MSPCD values between the paths passing through the crack (Paths 1, 2) and the other paths (Paths 3 to 6) is enhanced when the SPC operation was conducted in the spectral correlation domain.

Second, the crack was visualized using the proposed baseline-free damage detection technique. The scanning laser excitation and fixed laser sensing strategy was selected with a 35 mm × 35 mm square area covering the entire fatigue crack for laser excitation scanning, as shown in Fig. 16. 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, 25 mm away from the closest excitation point. The total scanning time was about 30 min with 100 time averaging. This second experiment was conducted when a 15 mm long crack was produced after 18,793 loading cycles.
By comparing the SPC plots obtained from adjacent spatial points Eq. (12), the MSPCD values were calculated and visualized over the scanning area in Fig. 17. Fig. 17 (a) and (b) show the visualization results obtained from the spectral correlation and frequency domains, respectively. Higher MSPCD values were observed near the crack tips than the remaining intact areas, and the highest MSPCD value obtained from the spectral correlation domain (0.72) was larger than the one obtained from the spectral frequency domain (0.37). Furthermore, the contrast $k$ of the MSPCD values between the area near the crack location and the remaining intact area is estimated as follows:

$$k = \frac{\max(MSPCD_d)}{\text{mean}(MSPCD_i)}$$

(13)

where MSPCD$_d$ and MSPCD$_i$ are the MSPCD values obtained from the damage and intact areas, respectively. The contrast $k$ is estimated as 7.35 and 2.64 for Fig. 17 (a) and (b), respectively, and this observation suggests that the SPC technique performed in the spectral correlation domain might be less affected by noises in field applications.

5. Delamination detection in a carbon fiber reinforced polymer (CFRP) plate

5.1. Experimental setup

A CFRP plate is also tested using the proposed technique, as shown in Fig. 18. The plate is composed of IM7 graphite fibers with 97703 resin material and 12 piles with a layup of $[0/\pm45/0/\pm45]$. A 1 cm diameter delamination was introduced at the center of the plate through impact testing. The noncontact laser ultrasonic system identical to the previous experiment was used in this experiment (Fig. 13). Each ultrasonic response was 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. A 60 mm $\times$ 60 mm square area covering the delamination was scanned, as shown in Fig. 18. A total of 1225 (35 $\times$ 35) scanning points were assigned within the scanning area with a total scanning time about 100 min, achieving a spatial resolution of less than 2 mm. The fixed sensing point was located outside the scanning area and was 20 mm away from the closest excitation point. The rest of the experimental setup was identical to that of the previous experiment.
5.2. Delamination detection results

Since the frequency content of the response signals spans up to 100 kHz, the SPC plots and MSPCD values were computed for a spectral correlation region corresponding to a frequency band of 20–100 kHz. The delamination visualization results are shown in Fig. 19. As before, the highest MSPCD value observed near the delamination from the spectral correlation domain (0.71) was larger than the one obtained from the spectral frequency domain (0.63), and the contrast $k$ in Eq. (13) between the delamination area and the intact area was better in the spectral correlation domain ($k = 5.92$ in Fig. 19 (a) and $k = 2.85$ in Fig. 19 (b)). Fig. 19 once again illustrates that the MSPCD values calculated in the spectral correlation domain is more sensitive to damage and more robust against noise. Another interesting finding is that high MSPCD values were observed near the boundaries of the delamination.

6. Conclusions

In this study, a new SPC technique for LNWMS is developed by analyzing ultrasonic responses in the spectral correlation domain rather than the conventional spectral frequency domain. The major advantages of the new SPC technique over the conventional SPC technique are as follows: (1) The new spectral correlation based SPC technique is more robust against noise interferences; and (2) It owns a higher sensitivity to structural damage. By spatial comparison through laser scanning, the developed SPC technique can detect damage without relying on the baseline data obtained from a pristine condition of the target structure. The effectiveness of the developed technique was validated using a numerical simulation and experimental tests performed on an aluminum plate with a fatigue crack (crack width less than 10 μm) and a CFRP plate with delamination. The new SPC technique was able to successfully detect structural damage and showed a higher sensitivity to damage than the SPC technique conducted in the spectral frequency domain. Moreover, the performance of the new SPC technique was validated using the noise contaminated simulation signals with different SNRs. For the given test cases, the new SPC technique showed high robustness against noise even when the SNR deteriorated from 40 to 20 dBW. A follow-up study is warranted to quantify structural damage and estimate the remaining life of the target structure.
Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2017R1A5A1014883), and GCORE Research Project hosted by Ministry of Science and ICT, organized by OUI C KAIST.

References