Accelerated damage visualization using binary search with fixed pitch-catch distance laser ultrasonic scanning

Byeongjin Park$^1$ and Hoon Sohn$^2$

$^1$Composites Research Division, Korea Institute of Materials Science, 797 Changwondaero, Seongsan-gu, Changwon, Gyeongnam 51508, Republic of Korea

$^2$Department of Civil and Environmental Engineering, KAIST, 291 Daeharko, Yuseong-gu, Daejeon 34141, Republic of Korea

E-mail: hoonsohn@kaist.ac.kr

Received 21 March 2017, revised 16 May 2017
Accepted for publication 19 May 2017
Published 9 June 2017

Abstract

Laser ultrasonic scanning, especially full-field wave propagation imaging, is attractive for damage visualization thanks to its noncontact nature, sensitivity to local damage, and high spatial resolution. However, its practicality is limited because scanning at a high spatial resolution demands a prohibitively long scanning time. Inspired by binary search, an accelerated damage visualization technique is developed to visualize damage with a reduced scanning time. The pitch-catch distance between the excitation point and the sensing point is also fixed during scanning to maintain a high signal-to-noise ratio (SNR) of measured ultrasonic responses. The approximate damage boundary is identified by examining the interactions between ultrasonic waves and damage observed at the scanning points that are sparsely selected by a binary search algorithm. Here, a time-domain laser ultrasonic response is transformed into a spatial ultrasonic domain response using a basis pursuit approach so that the interactions between ultrasonic waves and damage, such as reflections and transmissions, can be better identified in the spatial ultrasonic domain. Then, the area inside the identified damage boundary is visualized as damage.

The performance of the proposed damage visualization technique is validated excusing a numerical simulation performed on an aluminum plate with a notch and experiments performed on an aluminum plate with a crack and a wind turbine blade with delamination. The proposed damage visualization technique accelerates the damage visualization process in three aspects: (1) the number of measurements that is necessary for damage visualization is dramatically reduced by a binary search algorithm; (2) the number of averaging that is necessary to achieve a high SNR is reduced by maintaining the wave propagation distance short; and (3) with the proposed technique, the same damage can be identified with a lower spatial resolution than the spatial resolution required by full-field wave propagation imaging.

Keywords: laser ultrasonic scanning, binary search, fixed pitch-catch distance scanning, accelerated damage visualization, noncontact damage visualization

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

1. Introduction

Laser ultrasonic techniques are gaining their popularity in the field of nondestructive testing (NDT) because of their noncontact nature, long working distance and sensitivity to local damage [1–6]. Ultrasonic waves can be generated and measured in a noncontact manner using a pulse laser and a laser interferometer, respectively. Their generation and measurement locations are also freely controllable to the desired target points using mirrors or mechanical scanning stages. However,
these techniques have certain limitations. First, the quality of the measured ultrasonic signals is highly dependent on
the surface condition of the target specimen and the incident
angle of the sensing laser beam [7]. Second, a high-power
pulse laser used for ultrasonic excitation may induce
impairments on the specimen surface, and impose a safety
concern particularly for human eyes [8].

Among various laser ultrasonic techniques, laser ultra-
sonic full-field wave propagation imaging techniques visu-
alyze damage by constructing time-sequential images of full-
field ultrasonic wave propagation in the target inspection
region [9–15]. Wave-damage interactions including reflection
and scattering are intuitively identified from the constructed
wavefield images. Damage can be visualized by automated
identification of wave-damage interactions including standing
wave energy [16], wavenumber changes [17], or sudden
changes in the wavefield [18]. However, full-field wave
propagation imaging requires a prohibitively long scanning
time to achieve a high spatial resolution and a good signal-to-
noise ratio (SNR) required for damage visualization. For
example, 40 min was required to scan a 5 cm × 5 cm square
area of an aluminum plate with a spatial resolution of 1 mm,
time averaging of 100 and a pulse laser with a repetition rate
of 100 Hz. Compressed sensing techniques [19–22] are
recently proposed to construct ultrasonic wavefield images
with a reduced number of measurements, and continuous-
scanning laser Doppler vibrometry (LDV) [23] quickly
measures local wavenumbers in the inspection region by
continuously scanning a sensing laser beam. Though these
techniques reduce scanning time, they still require contact
actuators for ultrasonic generation and do not work in a fully
noncontact manner.

In this study, a damage visualization technique based on
accelerated laser ultrasonic scanning is developed so that
damage can be located and visualized by using a reduced
number of measurements, a reduced number of averaging,
and a lower spatial resolution addressing the aforementioned
scanning time issue. The pitch-catch distance between the
excitation point and the sensing point during scanning is fixed
to maintain a high SNR for measured ultrasonic responses and
to reduce the number of averaging. First, the approximate
damage boundary is identified by examining the interactions
between ultrasonic waves and damage at the sparse scanning
points that are selected by a binary search algorithm [24].
Here, a time-domain laser ultrasonic response is transformed
into a spatial ultrasonic domain response using a basis pursuit
approach so that the interactions between ultrasonic waves
and damage, such as reflections and transmissions, can be
better identified in the spatial ultrasonic domain. Then, the
region inside the identified damage boundary is visualized as
damage.

The proposed damage visualization technique reduces
scanning time in three aspects: the number of measurements,
the number of averaging, and the required spatial scanning
resolution. First, the number of measurements that is neces-
sary for damage visualization is dramatically reduced from
$N \cdot M$ to $4 \log_2 N \cdot \log_2 M$ even for the worst case scenario. $N$
and $M$ represent the number of equally spaced scanning grids
required to obtain full-field wave propagation images of the
target inspection region in the $x$ and $y$ directions, respectively.
Second, the number of averaging that is necessary for
achieving a high SNR is dramatically reduced from $n_1$ to
$n_1 e^{-\alpha (N^2 + M^2/2 - k) \Delta x}$, $n_1$, $\alpha$, $K$, $\Delta x$ denotes the number
of averaging required to obtain full-field wave propagation
images, the attenuation coefficient of the specimen, the
number of scanning grids corresponding to the fixed pitch-
catch scanning distance, and the size of a single scanning
grid, respectively. Finally, the acceptable spatial scanning
resolution can be lowered for the proposed technique than full-
field wave propagation imaging.

This paper is organized as follows. Section 2 provides
a brief overview of the laser ultrasonic scanning system
and various scanning strategies. In section 3, an accelerated
damage visualization technique is proposed using a binary
search and fixed pitch-catch distance scanning. The effec-
tiveness of the proposed technique is validated using the
numerical simulation described in section 4 and the experi-
mental tests performed on an aluminum plate specimen with
a crack in section 5 and a 10 kW wind turbine blade with
delamination in section 6. This paper concludes with a brief
summary and discussions in section 7.

2. Laser ultrasonic scanning system and fixed pitch-
catch distance scanning

Figure 1 shows a schematic of the laser ultrasonic scanning
system used in this study. The system is composed of an
excitation unit, a sensing unit and a control unit. In the
excitation unit, a pulse laser is used for noncontact ultrasonic
generation. When a pulse laser beam radiates to an infinite-
simal area of a target specimen, a localized heating of the
surface causes thermoelastic expansion of the material and
generates ultrasonic waves [8]. An excessive temperature
increase due to a high-power pulse laser beam may cause
surface impairments, which are referred to as ablation [25].
Parameters for the laser ultrasonic generation, such as the
peak power, beam size and pulse duration, should be carefully
designed to prevent ablation. In the sensing unit, the ultra-
sonic response is measured by a LDV. When a laser beam is
reflected from a vibrating surface, the frequency of the
reflected laser beam is shifted. A LDV measures this fre-
quency shift and relates it to the out-of-plane velocity of the
target surface based on the Doppler effect [26]. The perform-
ance of the LDV is highly dependent on the intensity of the
returned laser beam, which can be affected by the incident
angle of the sensing laser beam and the surface roughness of
the target specimen [7]. A special surface treatment is often
necessary to improve the reflectivity of the surface [27], and
the incident angle is typically limited to $\pm 20^\circ$. The positions
of the laser beams on the target specimen are controlled by
adjusting the angles of the two mirrors inside a galvanometer.
The measured responses are collected and analyzed in the control unit. All units are synchronized and controlled by a personal computer in the control unit.

Three different scanning strategies for fully noncontact scanning are represented in figure 2. The first strategy (figure 2(a)) generates ultrasonic waves at a fixed point, and...
measures the corresponding responses at predetermined points in the inspection region. This is called as fixed excitation and scanning sensing (FE/SS) strategy. The second strategy (figure 2(b)) works in reciprocal to FE/SS strategy. Ultrasonic waves are sequentially generated at predetermined points and the corresponding responses are measured at a fixed sensing point. This is called as fixed sensing and scanning excitation (FS/SE) strategy. These two strategies are commonly used for full-field wave propagation imaging [16]. Theoretically, FE/SS and FS/SE provide identical results based on the linear reciprocity of the ultrasonic waves [28]. However, the FS/SE is preferred in practice because the performance of the LDV measurement is substantially affected by the incident angle of the laser beam.

The last strategy is referred to as fixed pitch-catch distance scanning strategy (FDS). Ultrasonic waves are sequentially generated and measured at predetermined points by controlling both laser beams together, while maintaining a consistent pitch-catch distance between the ultrasonic generation and measurement points. While FDS cannot visualize wave propagation, it can be considered an extended version of the conventional pitch-catch techniques used in the NDT community [29–32]. This strategy is more vulnerable to surface conditions than FS/SE because the sensing laser needs to be scanned as well as the excitation laser. However, FDS offers a better SNR than FS/SE or FE/SS, because a short wave propagation distance between the excitation and sensing points alleviates the effect of signal attenuation and assures large amplitudes for measured ultrasonic responses.

3. Accelerated damage visualization

3.1. Binary search with fixed pitch-catch distance scanning

In this section, a binary search algorithm is adopted to reduce the number of measurements and to visualize damage. Figure 3 provides an overview of the proposed binary search with fixed pitch-catch distance scanning.

Step 1: First, the inspection region is divided into \( N \) (width) \( \times M \) (height) grids. The excitation and sensing beams are always positioned at the center of each grid. Each grid is referred to as an inspection point, and the \( n \)th row of \( N \times M \) grids is referred to as the \( n \)th inspection line. The middle inspection line, \( [M/2] \)th row is selected first for damage visualization. The selected inspection line is divided into equally spaced divisions of \( K \) grids. Here, \( K \) is the number of grids corresponding to the fixed pitch-catch scanning distance, and is determined to be as large as possible while maintaining a good SNR.

Step 2: Initially, the ultrasonic waves are generated from the right end of the leftmost division using a pulse laser and measured at the left end of the division using a LDV. Then, the measured ultrasonic response is transformed into the spatial ultrasonic domain to verify whether damage exists within the direct wave propagation path or not. Here, the direct wave propagation path is defined as the grids between the current excitation and sensing points. The details on this dichotomous decision process are provided in section 3.3. If damage does not exist within the division, the corresponding division is marked in green and named as an intact division. If damage exists within the division, the corresponding division is marked in yellow and named as a damage division. This dichotomy process is repeated for all divisions. Then, the damage region, if any, is identified between the leftmost and the rightmost damage divisions, and marked with a dashed box. Next, the corresponding inspection line is named as a damage inspection line and this step is followed by Steps 3 and 4. However, when there is no damage within the selected inspection line, the corresponding inspection line is named as an intact inspection line and Steps 3–4 are skipped.

Step 3: The left damage boundary point is identified by adopting the binary search algorithm to the leftmost damage division. First, the excitation point is placed to the center of the leftmost damage division and the sensing point is placed at the \( K \)th left grid point from the excitation point. If there is no damage within the direct wave propagation path, the grids between the next right grid to the current excitation point and the very last (far right) grid in the current division are considered for the next excitation point selection. If damage exists within the direct wave propagation path, the grids before the current excitation point to the very first (far left) grid are considered for the next excitation point selection. Then, the next excitation point is moved to the center of the grids in consideration. This binary search is repeated until no considerable grid remains for the next excitation point selection, and the excitation point of the leftmost direct wave propagation path with damage is defined as the left damage boundary point and is marked with a red cross.

Step 4: Step 3 is repeated in the rightmost damage division to find the right damage boundary point. Here, the sensing point is moved by adopting the binary search algorithm. Then, the sensing point of the rightmost direct wave propagation path with the damage is defined as the right damage boundary point and is marked with a red cross.

Step 5: Steps 1–4 are repeated for the next inspection line. The next inspection line is selected using the binary search concept in both upward and downward directions, and Steps 1–5 are repeated until the uppermost and lowermost damage boundary points have been identified.

Step 6: The damage boundary is identified by connecting all damage boundary points after cubic interpolation, and the area inside this boundary is visualized as damage.

3.2. Comparison of scanning speed with the conventional full-field wave propagation imaging

3.2.1. The number of measurements. The proposed binary search with fixed pitch-catch distance scanning requires a fewer number of measurements to visualize the damage than conventional full-field imaging techniques. Let \( q_d \) be the number of measurements that are required for damage region approximation (Step 2 in figure 3) within a single inspection
Step 1: Select an inspection line and divide it into equally spaced divisions

Step 2: Identify the damage region by scanning each division

Step 3 & 4: Binary search for the left and the right damage boundary points

Step 5: Select the next inspection line using binary search concept and repeat Steps 1–4 until the uppermost and the lowermost damage boundary points have been identified.

Step 6: Visualize damage by interpolating identified damage boundary points

Figure 3. Schematic flow of the binary search with fixed pitch-catch distance scanning.

line. Then, $q_a$ can be calculated as

$$q_a = \frac{N}{K}$$

If a damage region exists, additional number of measurements $q_b$ are required for boundary point identification using the binary search [25] (Steps 3–4 of figure 3).

$$q_b = 2 \log_2 K$$

Note that the logarithm term is multiplied by 2, as this approach searches both left (Step 3) and right (Step 4) boundary points.
Then the number of measurements $q (= q_d + q_b)$ that is required by the binary search with fixed pitch-catch distance scanning for a single inspection line becomes:

$$q = N \frac{K}{K} + 2 \log_2 K \leq 2 \log_2 \frac{N}{K} + 2 \log_2 K = 2 \log_2 N \text{ (damage)},$$

$$q = N \text{ (intact)}. \tag{3}$$

Here, $N \leq 2 \log_2 N$ when $\frac{N}{K}$ is smaller than five, and this approximation is valid for most cases including the numerical and experimental validations in sections 4–6.

This process is repeated for other inspection lines. The binary search is adopted in the heightwise direction to select the next inspection line to find the uppermost damage boundary point(s). If the current inspection line is a damage inspection line, the rows that are higher than the current damage inspection line are considered for the next inspection line selection. On the other hand, if the current inspection line is an intact inspection line, the rows higher than the highest damage inspection line and lower than the current intact inspection line are considered for the next inspection line selection. Then, the middle row among the rows in consideration is selected as the next inspection line. This binary search is repeated until no considerable row exists for the next inspection line selection. A similar process is also employed to select the next inspection line for finding the lowermost damage boundary point(s). The required number of inspection lines $l$ is presented as follows, where $M$ is the size of the inspection region in the vertical direction, as defined in Step 1 of Figure 3:

$$l = 2 \log_2 M \text{ (damage)},$$

$$l = M \text{ (intact)}. \tag{4}$$

Then, the total number of measurements $p$ and the reduction rate $R$ is calculated as follows:

$$p = q \cdot l \leq 4 \log_2 N \cdot \log_2 M \text{ (damage)},$$

$$p = q \cdot l = \frac{N \cdot M}{K} \text{ (intact)}, \tag{5}$$

$$R = \left(1 - \frac{p}{N \cdot M}\right) \times 100\% \leq \left(1 - \frac{4 \log_2 N \cdot \log_2 M}{N \cdot M}\right) \times 100\% \text{ (damage)},$$

$$R = \left(1 - \frac{p}{N \cdot M}\right) \times 100\% = \left(1 - \frac{1}{K}\right) \times 100\% \text{ (intact)}. \tag{6}$$

### 3.2.2. The number of averaging

The proposed binary search with fixed pitch-catch distance scanning requires a fewer number of averaging to have the same level of SNR as the conventional full-field wave propagation imaging. The ultrasonic waves attenuate as they propagate through the specimen [33].

$$s_i(t) = s_0(t) e^{-\alpha t}/2, \tag{7}$$

where $s_i$, $s_0$, $\alpha$ denote the measured ultrasound signal at the distance $x_i$ from the ultrasonic generation point, the initial ultrasound signal at the ultrasonic generation point, and the attenuation coefficient respectively.

If we assume that the noise in the signal is a random noise with a zero mean and a variance of $\sigma^2$, the SNR of $s_i$ is defined as [34]

$$\text{SNR}_i = \frac{\text{Signal power}}{\text{Noise power}} = \frac{\int_0^T E[s_i(t)^2] \, dt}{\sigma^2} = \frac{\int_0^T E[s_0(t)^2 e^{-\alpha t}] \, dt}{\sigma^2} = \frac{e^{-\alpha t} E[s_0(t)^2]}{\sigma^2} \text{SNR}_0, \tag{8}$$

where $E[s_i(t)^2]$ denotes the expectation of $s_i(t)^2$, and $\text{SNR}_0$ is the SNR of $s_0$, the signal measured at the ultrasonic generation point. $\text{SNR}_i$ is improved by collecting $s_i$ signals $n$ times and averaging the collected signals.

$$\text{SNR}_{i, averaged} = \frac{\int_0^T E[s_i(t)^2] \, dt}{\sigma^2/n} = n \text{SNR}_i = ne^{-\alpha t} \text{SNR}_0. \tag{9}$$

For an inspection region of $N$ (width) $\times M$ (height) grids, the conventional full-field wave propagation imaging technique requires $n_\ell$ times of averaging to achieve an acceptable level of SNR defined as $\text{SNR}_a$ on average.

$$\text{SNR}_a = n_\ell e^{-\alpha (\sqrt{N^2 + M^2}/2)(\Delta x)} \text{SNR}_0,$$

$$n_\ell = \frac{\text{SNR}_a}{\text{SNR}_0} \text{SNR}_0 \delta^2 e^{\alpha (\sqrt{N^2 + M^2}/2)(\Delta x)}, \tag{10}$$

where $\Delta x$ is the size of a single grid. The proposed binary search and fixed pitch-catch distance scanning requires a fewer number of averaging $n_b$ as the average wave propagation distance is decreased from $(\sqrt{N^2 + M^2}/2)\Delta x$ to $K\Delta x$.

$$\text{SNR}_a = n_b e^{-\alpha K \Delta x} \text{SNR}_0,$$

$$n_b = \frac{\text{SNR}_a}{\text{SNR}_0} \delta^2 e^{\alpha K \Delta x}. \tag{11}$$

Then, the reduction rate in terms of the number of averaging is calculated as follows.

$$R_a = \left(1 - \frac{n_b}{n_\ell}\right) \times 100\% = \left(1 - \frac{e^{\alpha K \Delta x}}{e^{\alpha (\sqrt{N^2 + M^2}/2)(\Delta x)}}\right) \times 100\%$$

$$= (1 - e^{-\alpha (\sqrt{N^2 + M^2}/2 - K)\Delta x}) \times 100\%. \tag{12}$$

Note that, as the wave propagation distance for the proposed fixed pitch-catch distance scanning decreases (a smaller $K$ value), a fewer averaging is required (a higher $R_a$) but more
spatial points need to be scanned (a lower reduction rate \( R \) in terms of the number of measurement points in equation (6)).

3.2.3. Acceptable spatial scanning resolution. For the conventional full-field wave propagation imaging, a high spatial scanning resolution is required to visualize wave propagation within the inspection region. Typically, the grid size for spatial scanning (\( \Delta x \)) should be at most half of the wavelength of interest according to the Nyquist theorem [19, 35]. If not, the wave propagation images are not successfully constructed and it becomes difficult to visualize the wave-damage interactions from the images. It also affects the performance of the widely used frequency-wavenumber analysis [16, 17] as the low spatial scanning resolution leads to the low resolution in the wavenumber domain. The scanning resolution should meet the Nyquist criterion for proper visualization of wave propagation, even when such a high resolution is not required for damage visualization. On the other hand, a lower spatial scanning resolution is allowed for the proposed binary search and fixed pitch-catch distance scanning if a lower damage visualization resolution is acceptable. The aforementioned three issues in section 3.2 are illustrated in section 4.4 using a numerical simulation example.

3.3. Identifying the location of damage with respect to the direct wave propagation path using spatial ultrasonic transformation

The binary search algorithm in section 3.1 is based on the decision whether damage exists between the current excitation and sensing points or not. This problem entails locating damage with respect to the current direct wave propagation path [36].

To determine the damage location with respect to the direct wave propagation path, the measured time-domain ultrasonic signal \( \mathbf{s} \) (\( T \times 1 \) vector) is represented as a weighted linear combination of bases via the following transformation [37].

\[
\mathbf{s} = \mathbf{D} \mathbf{\alpha},
\]

\[
\mathbf{D} = [\mathbf{d}_1, \mathbf{d}_2, \ldots, \mathbf{d}_L],
\]

(13)

where \( \mathbf{\alpha} \) is a representation of \( \mathbf{s} \) in the transformed domain and has a dimension of \( L \times 1 \). \( \mathbf{D} \) is a \( T \times L \) dictionary matrix and consists of \( \mathbf{d}_i \) bases \((i = 1, \ldots, L)\). Each basis \( \mathbf{d}_i \) is a time-domain signal with the same dimensions as \( \mathbf{s} \).

In this study, a dictionary coined as a spatial ultrasonic dictionary is created for effective representations of ultrasonic responses. For a given specimen, each basis in the spatial ultrasonic dictionary represents an ultrasonic response measured at the fixed sensing point when the excitation point is located a specific distance from the fixed sensing point. For example, \( \mathbf{d}_i \) denotes the ultrasonic response when the distance between the fixed sensing point and the excitation point is \( x_i = x_0 + (i - 1) \Delta x \), \( x_0 \) denotes the distance from the sensing point to the first (closest) excitation point, and \( \Delta x \) is the spacing between two adjacent excitation points.

\[
\mathbf{d}_i = A e^{-jk(x_i - ct)} = f(x_i - ct),
\]

(14)

where \( A, k \) and \( c \) represent the amplitude, wavenumber and wave speed, respectively, of the propagating ultrasonic waves in the specimen, and \( t \) denotes time. A smaller \( \Delta x \) generates a higher spatial resolution in the spatial ultrasonic domain, and increases the dimension \( L \) of the dictionary \( \mathbf{D} \).

Because a large \( L \) value is preferred to achieve a high resolution in the transformed domain, equation (13) typically represents an underdetermined system of equations (\( L > T \)), which creates non-unique solutions for \( \mathbf{\alpha} \). A unique solution for \( \mathbf{\alpha} \) can be obtained via the assumption that the actual solution has the sparsest representation, minimizing the number of nonzero entities in \( \mathbf{\alpha} \) [38]. Based on this assumption, Chen and Donoho proposed the basis pursuit approach to solve the underdetermined system in equation (13) [39]. The sparsest representation is obtained by solving the following problem with a given dictionary \( \mathbf{D} \).

\[
\min \| \mathbf{\alpha} \|_{1, \infty} \text{ s. t. } \mathbf{s} = \mathbf{D} \mathbf{\alpha},
\]

(15)

where \( \| \mathbf{\alpha} \|_{1, \infty} \) denotes the \( \ell_1 \) norm of \( \mathbf{\alpha} \). Time-domain ultrasonic signals can be sparsely represented using the designed spatial ultrasonic dictionary.

When waves encounter a discontinuity, such as damage, some energy is transmitted through the discontinuity, and other energy is reflected [40]. The incident \( u_i \), reflected \( u_R \), and transmitted \( u_T \) waves can be represented as

\[
u_i(x, t) = A_R e^{-jk(x-ct)},
\]

\[
u_R(x, t) = A_R e^{jk(x+ct)} = C_R A_i e^{jk(x+ct)},
\]

\[
u_T(x, t) = A_T e^{-jk(x-ct)} = C_T A_i e^{-jk(x-ct)},
\]

(16)

(17)

(18)

where \( A_i, A_R, \) and \( A_T \) represent the amplitudes of the incident waves, reflected waves, and transmitted waves, respectively. \( k_d \) and \( c_d \) denote the wavenumber and wave speed, respectively, in the discontinuity. \( C_R \) and \( C_T \) are the reflection coefficient and transmission coefficients, respectively.

If no damage is introduced to the specimen after the dictionary is composed (figure 4(a)), the ultrasonic response \( \mathbf{s} \) generated at \( x_0 \) distance from the sensing point can be represented with only a single basis. This is the only nonzero element in \( \mathbf{\alpha} \), and a sparse representation of the time-domain signal is possible in the spatial ultrasonic domain. Then, \( \mathbf{s} \) can be represented as

\[
\mathbf{s} = f(x_0 - ct) = \mathbf{d}_a = \mathbf{d}_a \alpha_a,
\]

(19)

where \( \alpha_a \) is the amplitude of the basis \( \mathbf{d}_a \) in the transformed domain and its value is equal to one when no damage exists in the specimen.

Next, the time-domain responses obtained from a damage specimen are represented in the spatial ultrasonic domain. Let us assume a damage is located outside the direct wave propagation path (figure 4(b)). Then, the measured signal \( \mathbf{s} \) can be represented as the superposition of the direct incident waves and the damage reflected waves.

\[
\mathbf{s} = f(x_0 - ct) + g(x_0 + \Delta x_d - c(t - \Delta t_0))
\]

\[
= f(x_0 - ct) + g(x_0 + \Delta x_d - ct + c \Delta t_0)
\]

\[
= f(x_0 - ct) + g((x_0 + 2 \Delta x_d) - ct)
\]

\[
= f(x_0 - ct) + C_R f((x_0 + 2 \Delta x_d) - ct)
\]

\[
= f(x_0 - ct) + C_R f(x_0 - ct)
\]

\[
= \mathbf{d}_a + C_R \mathbf{d}_b = \mathbf{d}_a \alpha_a + \mathbf{d}_b \alpha_b,
\]

(20)
The first term \( f \) represents the direct incident waves generated at \( x_a \) distance from the sensing point, and the second term \( g \) represents the reflection from the damage. The term \( \Delta t_D \) is included in \( g \) as the waves are reflected from the damage \( \Delta t_D \) after the initial ultrasonic generation from the excitation point. \( \Delta t_D = \Delta t_D/c \) is the time-of-flight of the ultrasonic waves from the excitation point to the damage, and \( \Delta x_D \) is the distance between the excitation point and the damage. The signal is represented with two bases: \( d_a \) and \( d_b \). The first base corresponds to the incident waves with a travel distance of \( x_a \), and the second corresponds to the reflected waves with a travel distance of \( x_a = x_a + 2\Delta x_D \). \( \alpha_b \) is the amplitude of the basis \( d_b \) in the transformed domain, and its value is equal to the reflection coefficient of the damage \( C_r \).

A similar analysis can be performed for the other case, where damage is located between the excitation and sensing points (figure 4(c)). Then, the ultrasonic waves pass through the damage, and the measured signal \( s \) can be represented as

\[
s = h((x_a - \Delta x_D - \Delta x_d) - c(t - \Delta t_D - \Delta t_d)) \]

\[
= h\left(x_a + \frac{c}{c_d} - 1\right)\Delta x_d - ct \right)\]

\[
= G_f(x_c - ct) = G_f d_c = d_c \alpha_c,
\]

where the function \( h \) represents the ultrasonic waves transmitting through damage. \( \Delta t_d(=\Delta x_d/c_d) \) is the transmission time of the waves through the damage, \( \Delta x_d \) represents the width of the damage, and \( c_d (<c) \) is the wave speed within the damage. From equation (12), \( h \) can be represented by \( C_T \) and \( f \), which are the transmission coefficient and the direct incident waves, respectively. The basis \( d_c \) will have an amplitude of \( \alpha_c = C_T \). Note that the ultrasonic waves are delayed while transmitting through the damage because \( x_c(=x_a + \Delta x_d) \) is larger than \( x_a \).

An important observation in figure 4 is that the measured response in the spatial ultrasonic domain includes the basis \( d_a \), which corresponds to the intact incident waves, if no damage is observed between the excitation and sensing points (either no damage in the specimen or damage outside the direct wave propagation path). However, this basis is shifted if damage exists between them. Therefore, the damage presence within the direct wave propagation path can be easily identified by performing spatial ultrasonic transformation and verifying the existence of basis \( d_a \) that corresponds to the intact incident waves.

4. Numerical validation

4.1. Description of numerical simulation

The proposed technique is validated through a numerical simulation using a commercial finite element software program COMSOL Multiphysics. The simulated aluminum plate model has dimensions of 150 × 150 × 3 mm³, as displayed in figure 5. A 10 mm long, 0.1 mm wide and 1.5 mm deep notch is introduced on the opposite side of the scanned surface. A 35 × 35 mm² area around the notch is defined as an inspection region. The material properties of the aluminum plate model, which are necessary for simulating laser induced
ultrasonic wave generation, are given in table 1. Please refer to [41] for more details in simulating laser ultrasonic generation and measurement.

A spatial ultrasonic dictionary was constructed from an intact aluminum plate model. The bases in the spatial ultrasonic dictionary were generated by increasing the distance of the excitation point from the sensing point from 4 mm to 75 mm with 1 mm increment to create 72 bases. By spline interpolations between two adjacent bases, the dictionary was constructed from a total of 721 bases with a 0.1 mm spatial resolution. Each base was sampled for 25 μs with a 5.12 MHz sampling frequency. A bandpass filter with a low cutoff frequency of 550 kHz and a high cutoff frequency of 700 kHz was used to capture the response within the frequency range of interest.

For the binary search with fixed pitch-catch distance scanning, each scanning was performed with the same parameters as the ones used in the basis construction process. The spatial scanning resolution was 1 mm for the x and y directions, which divides the inspection region into 36 × 36 grids. The pitch-catch distance was fixed to 12 mm, leading to \( K = 12 \).

4.2. Spatial ultrasonic transformation

First, the simulated time response is transformed into the spatial ultrasonic domain to determine whether damage exists within the direct wave propagation path or not, as shown in figure 6.

Figure 7 compares the ultrasonic responses obtained from (a) an intact plate (figure 4(a)), (b) a damage plate where the damage is located outside the direct wave propagation path (figures 4(b) and 6(a)), and (c) a damage plate where the damage is located within the direct wave propagation path (figures 4(c) and 6(b)). In figure 7(b), the amplitude of the initial basis that corresponds to the incident waves (figure 7(a)) does not change and additional bases corresponding to the reflected waves appear. On the other hand, in figure 7(c), the location of the maximum peak amplitude is shifted away from the initial basis. By examining the amplitude of the basis that corresponds to the incident waves, the location of the damage with respect to the direct wave propagation path is determined, which enables a repeated binary search along a single inspection line, as described in the following subsection.

4.3. Damage visualization result

Figure 8 illustrates the outcome of the binary search with fixed pitch-catch distance scanning. The 35 mm by 35 mm square area represents the inspection region. Each inspection line is divided into three divisions \( \left( \frac{K}{3} = \frac{35}{36} \right) \) for damage region identification. Only 27 measurements are needed to identify the damage regions, as indicated by the dashed boxes in figure 8(a).

Figure 8(b) represents the identified left and right damage boundary points. Note that, because the size of the notch in each inspection line is less than the grid size, only single boundary point is identified within each inspection line. Additional 26 measurements are required to identify the damage boundary points.

The notch is visualized in figure 8(c) from the identified damage boundary points. The red color represents the damage points, where they are interpolated from the damage boundary points using cubic interpolation. When the inspection region of 35 mm by 35 mm is scanned with a 1 mm resolution, a total of 1296 \((36 \times 36)\) inspection points are generated. Among

![Figure 5. Overview of a numerical aluminum plate model: a 10 mm × 0.1 mm × 1.5 mm crack is introduced on the opposite side of the scanned surface.](image)

<table>
<thead>
<tr>
<th>Density ( \rho ) (kg m(^{-3}))</th>
<th>Young’s modulus ( E ) (GPa)</th>
<th>Poisson’s ratio ( \nu )</th>
<th>Coefficient of thermal expansion ( \alpha_t ) (K(^{-1}))</th>
<th>Thermal conductivity ( K ) (W/(m K(^{-1})))</th>
<th>Heat capacity at constant pressure ( C_p ) (J/(kg K(^{-1})))</th>
<th>Reflection coefficient ( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2700</td>
<td>68.9</td>
<td>0.33</td>
<td>2.34 × 10(^{-5})</td>
<td>170</td>
<td>900</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Material properties of aluminum used in this numerical simulation.
these inspection points, only 53 measurements (4.1%) are needed to visualize the notch. The presented numerical simulation validates that the proposed damage visualization technique can detect and visualize damage with a significantly reduced number of measurement points.

4.4. Comparison of scanning speed with the conventional full-field wave propagation imaging

Figure 9 shows the number of measurements $p$ required by the proposed technique (blue solid line, the measurement points necessary for the full-field wave propagation imaging (the black dashed line), and the reduction rate $R$ (red dotted line) for increasing $N$, predicted by equations (5) and (6). Note that the effectiveness of the proposed technique (reduction rate) increases as the inspection region increases or the spatial resolution is improved. Equation (6) predicts 91.8% reduction rate for the worst case when $N = 36$, while the actual value was 95.9% in this simulation example.

The number of averaging for each measurement location is also an important factor affecting the total scanning time. Figure 10 shows how the number of averaging defined in equation (16) decreases as the number of divisions in a single inspection line increases or as the pitch-catch scanning distance is shortened. When each inspection line is divided into three divisions in this simulation model, 54.8% less number of averaging is required to achieve the same level of SNR as that of the conventional full-field wave propagation imaging.
The attenuation coefficient $\alpha = 0.059 \text{ mm}^{-1}$ is numerically obtained from the simulation model.

Additional reduction of scanning time is feasible by decreasing the spatial scanning resolution or increasing the grid size. Figure 11 illustrates the effect of the spatial scanning resolution on the conventional wave propagation imaging and the proposed damage visualization. The ultrasonic wave propagation in the inspection region is visualized for the intact aluminum plate model and the damage aluminum plate model shown in figure 5, respectively. Here, the laser ultrasonic source is placed at the bottom-left corner of each inspection region. According to the Nyquist criterion, the grid size ($\Delta x$) should be smaller than 2 mm as the shortest ultrasonic wavelength of interest is 4 mm at 700 kHz in this example. When the grid size (1 mm) is smaller than this Nyquist criterion, the wave propagations are successfully constructed and the reflected waves from the notch are clearly visualized (figures 11(a) and (b)). However, when the grid
size (4 mm) becomes larger than the Nyquist criterion, the wave propagations are not successfully visualized and the notch existence is not properly observed (figures 11(d) and (e)). Figures 11(c) and (f) represent the damage visualization results using the proposed binary search with fixed pitch-catch distance scanning technique. The proposed damage visualization technique successfully detects the notch even when the grid size (4 mm) becomes larger than the one suggested by the Nyquist criterion.

Figure 12 compares the localization error (1) between the centroid locations of the actual notch and the notch visualized by the proposed technique (blue solid line with circles) and (2) between the centroid locations of the actual notch and the notch location obtained by the frequency-wavenumber analysis [15] of the conventional full-field wave propagation imaging (black dashed line with rectangles). The notch is considered to be unidentified if the notch is not visualized or the localization error is larger than 12 mm, 1/3 of the inspection region width. The full-field wave propagation imaging technique is suddenly unable to identify the notch as the scanning grid size becomes larger than the one suggested by the Nyquist criterion. On the other hand, the proposed technique visualizes the notch with a lower localization error even when the grid size becomes larger than the one suggested by the Nyquist criterion.

5. Experimental validation I: detection of a fatigue crack in an aluminum plate

5.1. Experimental setup

Figure 13 shows an overview of the laser ultrasonic scanning system used for the experimental validations. A diode pumped Q-switched Nd:YAG pulse laser (Quantel Centurion+) radiates 532 nm wavelength laser pulses. This device emits 12 ns width laser pulses up to 100 times per
second. Optical modules, which are covered by a black box, guide radiated pulse laser beams into the galvanometer (Scanlab hurrySCAN 20). This black box prevents an accidental reflection and scattering of high-power pulse laser beams outside the module. The laser beam was aimed at the desired points by controlling the galvanometer. The lens in

Figure 11. The effect of the scanning resolution on the conventional full-field wave propagation imaging and the proposed damage visualization. (a) and (b) show full-field wave propagation images for the intact model and the damage models with 1 mm grid size, respectively. (c) Represents the damage visualization result with the proposed technique with 1 mm grid size. (d) and (e) show full-field wave propagation images with 4 mm grid size, and (f) represent the damage visualization result with the proposed technique with the corresponding grid size (4 mm).

Figure 12. Comparison of the localization errors between the proposed technique (blue solid line) and the full-field wave propagation imaging (black dashed line).
front of the galvanometer focuses the laser beam so that its diameter on the specimen surface becomes 0.5 mm. The ultrasonic responses were measured by a commercial scanning LDV (Polytec PSV-400). The distance from the target specimen to the galvanometer and the LDV was 1 m and 1.1 m, respectively.

The first tested specimen is an aluminum plate with a fatigue crack. This plate has dimensions of $300 \times 120 \times 3 \text{ mm}^3$, as displayed in figure 14. A through-the-thickness fatigue crack with a length of 18 mm and a width of 10 $\mu\text{m}$ was introduced by repetitive tensile loadings with a universal testing machine. A $41 \times 20 \text{ mm}^2$ area around the crack was established as an inspection region.

A spatial ultrasonic dictionary was constructed from an intact aluminum plate. The bases in the spatial ultrasonic dictionary were generated in the same manner as the ones in the numerical simulation presented in section 4. The peak energy and power of the pulse laser were 3 mJ and 0.3 MW, respectively. Each basis was sampled for 37.5 $\mu\text{s}$ with a 2.56 MHz sampling frequency. A bandpass filter with a low cutoff frequency of 50 kHz and a high cutoff frequency of 450 kHz was used to capture the response within the frequency bandwidth of interest. Each basis was collected 100 times and averaged to improve their SNR.

For the binary search with fixed pitch-catch distance scanning, each scanning was performed with the same parameters as the ones used in the basis construction process except the number of averaging. Each measurement was averaged only 30 times thanks to the short fixed pitch-catch scanning distance. The spatial scanning resolution was 1 mm for the x and y directions, which divides the inspection region into $42 \times 21$ grids. The pitch-catch distance was fixed to 2 cm, leading to $K = 21$.

5.2. Damage visualization result

Figure 15 illustrates the outcome of the binary search with fixed pitch-catch distance scanning. The $41 \text{ mm} \times 20 \text{ mm}$ area represents the inspection region. Each inspection line is divided
into two divisions \( N = \frac{42}{21} \) for damage region identification. Only 18 measurements are needed to identify the damage regions, as indicated by the dashed boxes in figure 15(a).

Figure 15(b) represents the identified left and right damage boundary points. Note that, because the size of the notch in each inspection line is less than the grid size, only a single boundary point is identified within each inspection line. 56 additional measurements are required to identify the damage boundary points.

The crack is identified and visualized in figure 15(c) from the identified damage boundary points. The red color in figure 15(c) represents the damage points, where they are interpolated from the damage boundary points. When the 40 mm by 20 mm area is scanned with a 1 mm resolution, a total of 882 \((42 \times 21)\) inspection points are generated. Only 74 measurements \((8.4\%)\) along 882 inspection points are needed to quantify the crack. The corresponding scanning time was only 22 s. Note that this scanning time is obtained with (1) averaging 30 times for each scanning, (2) 100 Hz repetition rate of a pulse laser, and (3) 0.1 cm scanning resolution for a 2 cm square region. If (1) less averaging were acceptable, (2) a faster pulse laser were available, or (3) a lower scanning resolution were acceptable, the scanning time could be further reduced. Please note that the aforementioned parameters should be carefully designed to avoid (1) low SNR, (2) the reverberation issue, and (3) low damage visualization resolution.

Note that the proposed binary search with fixed pitch-catch scanning scheme provides further reduction in scanning time because the conventional full-field wave propagation imaging requires more time averaging of signals with its longer ultrasonic propagation distance. As discussed in sections 3.2.2 and 4.4, the proposed technique requires 35.6\% less number of averaging than full-field wave propagation imaging when the inspection line is divided into two divisions. Then, the reduction in scanning time with respect to the full-field wave imaging was 94.4\% \((392 \text{ s} = 842 \times 0.3 \text{ s} \div (100 - 35.6\%) \text{ to } 22 \text{ s})\). This reduced scanning time could be further shortened if a lower damage visualization resolution were acceptable, as discussed in section 3.2.3. The experiment presented in this section validates that the proposed damage visualization technique using binary search with fixed pitch-catch distance scanning can detect and visualize a fatigue crack with a significantly reduced scanning time.

6. Experimental validation II: detection of a delamination in a 10 kW wind turbine blade

6.1. Experimental setup

The other test specimen for experimental validation is a 10 kW wind turbine blade (figure 16). This specimen is manufactured by Human Composites Ltd, a Korean wind turbine blade manufacturer. This blade has dimensions of 3.5 m \( \times \) 0.45 m with the maximum thickness of 0.3 m, and the blade is composed of six plies of glass fiber reinforced plastic (GFRP), with a layup of \([0/\pm 45]\). The elastic modulus \( E_{12} \), shear modulus \( G_{12} \), and poisson ratio \( \nu_{12} \) are
24.65 GPa, 8.52 GPa and 0.476, respectively. A 15 mm diameter Teflon tape was inserted between the third and fourth plies during fabrication of the blade to simulate internal delamination. A 50 × 50 mm² region around the delamination is established as an inspection region. The delamination is located in the bottom-left corner of the inspection region.

A challenge in analyzing the ultrasonic waves within an anisotropic material is that the ultrasonic wave speeds and propagation characteristics vary with their propagation direction. To prevent this variance, all the inspection lines are oriented in one specific direction of the GFRP so that a dictionary only for this single GFRP layer direction is necessary.

Because no intact blade was available, a spatial ultrasonic dictionary was constructed from an intact part of the blade. The bases in the spatial ultrasonic dictionary were generated in the same manner as the numerical simulation presented in section 4. Each basis was collected with identical parameters with the aluminum plate experiment in section 5.

For the binary search with fixed pitch-catch distance scanning, all the scanning parameters were identical to those of the aluminum plate experiment in section 5 unless notified differently. The spatial scanning resolution was 2 mm for the x and y directions, which divided the inspection region into 26 × 26 grids. The pitch-catch distance was fixed to 26 mm, leading to \( K = 13 \).

### 6.2. Damage visualization result

Figure 17 illustrates the outcome of the binary search with fixed pitch-catch distance scanning. The 50 mm by 50 mm square area represents the inspection region. Each inspection line is divided into two divisions (\( N = \frac{26}{2} = 13 \)) for damage region identification. Only 18 measurements are needed to identify the damage regions, indicated by dashed boxes in figure 17(a).

Figure 17(b) represents the identified left and right damage boundary points. Thirty additional measurements are required to identify the damage boundary points. The delamination is visualized in figure 17(c) from the identified damage boundary points. The red color in figure 17(d) represents the damage points, where they are between the left and right damage boundary points. When the 50 mm by 50 mm area is scanned with a 1 mm resolution, a total of 676 (26 × 26) inspection points are generated. Only 48 measurements (7.1%) are needed to quantify the delamination, corresponding to 14 s of scanning time. This scanning time can be further reduced as aforementioned in section 5.2. The experiment presented in this section validates that the proposed damage visualization technique using the binary search with fixed pitch-catch distance scanning can detect and visualize delamination in anisotropic GFRP specimens.

### 7. Conclusion

This paper proposes a damage visualization technique based on accelerated laser ultrasonic scanning using the binary search with fixed pitch-catch distance scanning. The pitch-catch distance between the excitation point and the sensing point during scanning is fixed to maintain a high SNR for measured ultrasonic responses and to reduce the number of signal averaging. The uniqueness of the proposed damage visualization techniques can be summarized as follows:

1. The number of measurements that are required for damage visualization is significantly reduced from \( N \cdot M \) to \( 4 \log_2 N \cdot \log_2 M \) for the worst case scenario. \( N \) and \( M \) represent the number of equally spaced scanning grids that are required to obtain full-field wave propagation images of the target inspection region in the x and y directions, respectively.

2. The number of averaging that is necessary for maintaining a high SNR is dramatically reduced from \( n_t \) to \( n_t e^{-\alpha (\sqrt{N^2 + M^2} / 2 - K) \Delta x} \). \( n_t \), \( \alpha \), \( K \), \( \Delta x \) denotes the number averaging required to obtain full-field wave propagation images with a prescribed SNR, the attenuation coefficient of the specimen, the number of scanning grids corresponding to the fixed pitch-catch scanning distance, and the size of a single scanning grid, respectively.

3. A lower spatial scanning resolution is allowed for the proposed technique if a lower damage visualization resolution is accepted, while the conventional full-field wave propagation imaging always require a high spatial scanning resolution complying with Nyquist criterion.

The effectiveness of the proposed accelerated damage visualization technique is validated using a numerical
simulation and experimental tests performed on an aluminum plate with a crack and a 10 kW GFRP blade with a delamination. The tested damages are successfully visualized, and the number of measurements and scanning time are reduced by more than 90% compared with the conventional full-field wave propagation imaging techniques. For example, the number of measurement points and the scanning time necessary for the visualization of the crack in the tested aluminum plate were reduced by 91.6% (from 882 to 74 measurement points) and 94.4% (from 392 s to 22 s), respectively.

However, additional studies are needed before the proposed technique can be applied to more realistic conditions. First, only linear interactions between ultrasonic waves and damage are considered in this paper. Consideration of nonlinear interactions is required to detect nonlinear damage such as fatigue crack. Second, as the fixed pitch-catch distances scanning is sensitive to the surface conditions and special surface treatments are usually required, an improved sensing solution is needed. Third, the proposed technique may consider multiple damage as a single large one. Additional studies are necessary to distinguish multiple damages. Last, additional performance validations with realistic structures are also warranted. A follow-up study is also underway to investigate the effects of damage geometry and orientation on damage detectability.
Acknowledgments

This study is supported by a grant from Smart Civil Infrastructure Research Program (13SCIPA01) funded by Ministry of Land, Infrastructure and Transport (MOLIT) of Korea government and the Smart IT Convergence System Research Center as Global Frontier Project (CISS-2016M3A6A6054195).

References

[23] O’Dowd N M, Han D H, Kang L H and Flynn E B 2016 Exploring the performance limits of full-field acoustic wavenumber spectroscopy techniques for damage detection through numerical simulation Proc. 8th EWSHM
[33] Roderick R L and Truell R 1952 The measurement of ultrasonic attenuation in solids by the pulse technique and some results in steel J. Appl. Phys. 23 267–79