Accelerated noncontact laser ultrasonic scanning for damage detection using combined binary search and compressed sensing

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Abstract

Laser ultrasonic scanning is attractive for damage detection due 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 and compressed sensing, an accelerated laser scanning technique is developed to localize and visualize damage with reduced scanning points and scanning time. First, the approximate damage location is identified by examining the interactions between the ultrasonic waves and damage at the sparse scanning points that are selected by the binary search algorithm. Here, a time-domain laser ultrasonic response is transformed into a spatial ultrasonic domain using a basis pursuit approach so that the interactions between the ultrasonic waves and damage, such as reflections and transmissions, can be better identified in the spatial ultrasonic domain. Second, wavefield images around the damage are reconstructed from the previously selected scanning points using compressed sensing. The performance of the proposed accelerated laser scanning technique is validated using a numerical simulation performed on an aluminum plate with a notch and experiments performed on an aluminum plate with a crack and a carbon fiber-reinforced plastic plate with delamination. The number of scanning points that is necessary for damage localization and visualization is dramatically reduced from $N \cdot M$ to $2\log_2 N \cdot \log_2 M$. $N$ and $M$ represent the number of equally spaced scanning points in the x and y directions, respectively, which are required to obtain full-field wave propagation images of the target inspection region. For example, the number of scanning points in the composite plate experiment is reduced by 97.1% (from 2601 points to 75 points).

1. Introduction

Laser ultrasonic techniques are emerging as an attractive noncontact testing technique in the field of nondestructive testing (NDT) [1–8]. Ultrasonic waves can be generated and measured in a noncontact manner using a pulse laser and a laser Doppler vibrometer, respectively. Their generation and measurement locations are also freely controllable to the desired target points using mirrors. These techniques are very attractive for damage detection and localization due to their noncontact nature, long working distance and sensitivity to local damage.
Among various laser ultrasonic techniques, laser ultrasonic wave propagation imaging techniques visualize damage by constructing continuous images of full-field ultrasonic wave propagation in the target inspection region [9–14] with respect to time. Wave reflections, scattering, waveform and wave speed changes resulted from damage can be visually identified in the constructed wavefield images. This damage detection process can also be automated by extracting standing wave energy [12], wavenumber changes [13], or sudden changes in the ultrasonic wavefield images [14]. However, certain limitations of these techniques exist. 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 [15]. A special surface treatment is often necessary to minimize measurement noise and improve the signal-to-noise ratio. Second, a high-power pulse laser used for ultrasonic excitation may induce impairments, which are referred to as ablation, on the specimen surface and impose a safety concern, particularly for human eyes [16]. Therefore, the parameters associated with laser excitation should be carefully tailored, and users should wear special eye protection goggles. Third, laser scanning requires a prohibitively long scanning time to achieve a high spatial resolution and a good signal-to-noise ratio required for damage detection. For example, 40 min was required to scan a 5 cm × 5 cm square area from an aluminum plate with a spatial resolution of 1 mm, averaging 100 times and a pulse laser with a repetition rate of 100 Hz.

In this study, an accelerated laser scanning technique is developed so that damage can be located and quantified by using a reduced number of scanning points addressing the afore mentioned scanning time issue. First, sparse scanning points are adaptively selected using a binary search algorithm [17], and the approximate damage location is identified by examining the interactions between the ultrasonic waves and the damage at the selected scanning points. Here, a time-domain ultrasonic response from each selected scanning point is transformed into a spatial domain ultrasonic response using a basis pursuit approach so that the interactions between the ultrasonic waves and the damage can be better identified in the spatial ultrasonic domain. Second, the wavefield images around the damage are reconstructed from the selected scanning points using compressed sensing [18]. The number of scanning points that are needed for damage detection can be theoretically reduced from \(N \cdot M\) to \(2\log_2 N \cdot \log_2 M\). \(N\) and \(M\) represent the number of equally spaced scanning points in the \(x\) and \(y\) directions, respectively, which are required to obtain full-field wave propagation images of the target inspection region.

This paper is organized as follows. Section 2 provides a brief overview of the laser ultrasonic scanning system and a number of scanning strategies. In Section 3, an accelerated laser scanning technique is proposed using combined binary search and compressed sensing. The effectiveness of the proposed technique is validated using the numerical simulation described in Section 4 and experimental tests performed on an aluminum plate specimen with a crack in Section 5 and a carbon fiber-reinforced plastic (CFRP) plate with an impact-induced delamination in Section 6. This paper concludes with a brief summary and discussions in Section 7.

2. Laser ultrasonic scanning system and scanning strategies

Fig. 1 shows a schematic of the laser ultrasonic scanning system used in this study. This 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 infinitesimal area of a target specimen, a localized heating of the surface causes thermoelastic expansion of the material and generates ultrasonic waves [19]. An excessive temperature increase due to a high-power pulse laser beam may cause surface damage, which is referred to as ablation [20]. 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 ultrasonic response is measured by a laser Doppler vibrometer (LDV). When a laser beam is reflected from a vibrating surface, the reflected laser beam experiences a frequency shift. A LDV measures this frequency shift and relates it to the out-of-plane velocity of the target surface based on the Doppler effect [21]. The performance of the LDV highly depends on the intensity of the returned laser beam, which can be affected by the incident angle of the sensing laser beam and the light reflectivity of the target specimen [15]. A special surface treatment is often necessary to improve the reflectivity of the surface [22], and the incident angle is typically limited to ±20°. The position of the laser beam on the target specimen is 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.

For fully noncontact scanning, two different scanning strategies are represented in Fig. 2. The first strategy generates ultrasonic waves at a fixed point and measures the corresponding responses at predetermined points in the inspection region. This strategy is named the fixed excitation and scanning sensing (FE/SS) strategy. The second strategy works in reciprocal to the FE/SS strategy. Ultrasonic waves are sequentially generated at predetermined points and the corresponding responses are measured at a fixed sensing point. This strategy is named the fixed sensing and scanning excitation (FS/SE) strategy. Theoretically, FE/SS and FS/SE provide identical results based on the linear reciprocity of the ultrasonic waves [23]. However, the FS/SE strategy is preferred in practice because the intensity of the returned laser beam in the LDV, and consequently the quality of the LDV measurement, can be substantially affected by the incident angle of the laser beam [16]. For example, when the FE/SS strategy is used to scan a large surface, particularly a curved one, maintaining the intensity of the returned laser beam for consistency is challenging. On the other hand, because the thermoelastic expansion of the material produced by the excitation laser beam is not substantially affected by the incident angle, the FS/SE strategy can easily scan a curved surface.
3. Accelerated laser scanning using combined binary search and compressed sensing

3.1. Binary search for transition line detection

In this chapter, a binary search is adopted to reduce the number of excitation scanning points and to identify an approximate region of damage, which is referred to as the transition line. Specifically, the transition line is defined as a single side damage border that faces the sensing points. Fig. 3 provides an overview of the proposed binary search.

Fig. 1. Schematic of the laser ultrasonic scanning system used in this study.

Fig. 2. Two scanning strategies using the laser ultrasonic scanning system: (a) Fixed excitation and scanning sensing (FE/SS) and (b) fixed sensing and scanning excitation (FS/SE).
Step 1: Assume that we have an inspection region of size $N$ (width) $\times$ $M$ (height) with a predefined spatial resolution. Each point in this $N \times M$ grid is referred to as an inspection point, and the $m$th row of this region is referred to as the $m$th inspection line. The middle inspection line, $M/2$th row is selected and a sensing point is located to the left of this inspection line.

Step 2: Initially, the ultrasonic waves are generated at the center of the inspection line using a pulse laser and measured at the sensing point using a LDV. Then, the measured ultrasonic response is transformed into the spatial ultrasonic domain to verify whether the excitation point is ‘in front of the damage’ or ‘behind the damage’. Details on this checking procedure are provided in Section 3.2. If the excitation point is in front of the damage, the excitation point is marked in green. Then only the inspection points after the current excitation point to the very last (far right) inspection point in the given inspection line are considered for the next excitation point selection. If the excitation point is behind the damage, the excitation point is marked in yellow. In this case, the inspection points before the current excitation point to the very first (far left) inspection point are considered for the next excitation point selection. The next excitation point is moved to the center of the inspection points. This binary search is repeated until no considerable inspection point exists for the next excitation point selection.

Step 3: The closest ‘behind the damage’ point from the sensing point is defined as the transition point and is marked on the inspection region as a crossed yellow point. If no ‘behind the damage’ point in the inspection line exists, the corresponding inspection line is named as an intact inspection line. On the other hand, if any ‘behind the damage’ point in the inspection line exists, it is named as a damage inspection line.

Step 4: Steps 1 to 3 are repeated for the next inspection line. The next inspection line is selected using the binary search concept, and Steps 1 to 3 are repeated until the uppermost and lowermost transition points have been identified.

Step 5: The approximate damage location can be identified by connecting all transition points, and this connection of the transition points constitutes the transition line. Because the sensing points are located on the left side of the inspection region, the transition line corresponds to the left border of the damage.

This binary search process requires a fewer number of scanning points to find the transition line. Let $p_n$ be the number of scanning points that are required by the binary search for a single inspection line. Then, $p_n$ can be obtained as [17]

$$p_n = \log_2 N,$$  \hspace{1cm} (1)

where $N$ is the size of the inspection region in the widthwise direction, as defined in Step 1. $p_n$ is independent to whether the inspection line is intact or damaged. After $p_n$ scanning, the damage existence and the transition point in an inspection line can be identified.

This process is repeated for other inspection lines. The binary search algorithm is adopted to select the next inspection line. This algorithm is extended to the vertical direction by considering the intact inspection line and the damage inspection line as an ‘in front of the damage’ line and a ‘behind the damage’ line, respectively. To select the next inspection line and find...
the uppermost transition point, the inspection lines that are higher than the ‘behind the damage’ line or lower than the ‘in front of the damage’ line are considered for the next inspection line selection. To select the next inspection line to find the lowermost transition point, the opposite process is employed. The required number of inspection lines is presented as follows, where $M$ is the size of the inspection region in the heightwise direction, as defined in Step 1:

\[
\begin{align*}
p_m &= 2\log_2 M \text{ (damage)}, \\
p_m &= M \text{ (intact)}. \\
\end{align*}
\] (2)

Note that the logarithm term is multiplied by two because the uppermost and lowermost transition points are required by this approach. If there is no damage, every inspection line needs to be searched to ensure an intact condition. Then, the number of scanning points $p$ required by the proposed binary search is calculated as follows:

\[
\begin{align*}
p &= p_n \cdot p_m = 2\log_2 N \cdot \log_2 M \text{ (damage)}, \\
p &= p_n \cdot p_m = \log_2 N \cdot M \text{ (intact)}. \\
\end{align*}
\] (3)

Then, the reduction rate $R$ is defined as follows:

\[
\begin{align*}
R &= (1 - \frac{p_n \cdot p_m}{p_n \cdot p_m}) \times 100\% = \left(1 - \frac{2\log_2 N \cdot \log_2 M}{N \cdot M}\right) \times 100\% \text{ (damage)}, \\
R &= (1 - \frac{p_n \cdot p_m}{p_n \cdot p_m}) \times 100\% = \left(1 - \frac{\log_2 N}{N}\right) \times 100\% \text{ (intact)}. \\
\end{align*}
\] (4)

Assuming a 50 mm square inspection region with a 1 mm spatial resolution, a full-field wave propagation imaging requires 2500 scanning points, which is identical to the number of inspection points in this inspection region. The proposed binary search requires only 64 scanning points for a damage case achieving a 97.5% reduction in scanning points. The reduction rate decreases to 88% for the intact case. Fig. 4 shows the number of scanning points $p$ (blue solid line represents the proposed binary search, and the black dashed line represents the full-field wave propagation imaging) and the reduction rate $R$ (red dotted line) for increasing $N$. Note that the reduction rate increases as the inspection region increases or the spatial resolution is improved.

3.2. Identifying the location of the current excitation point with respect to damage using spatial ultrasonic transformation

The binary search algorithm in Section 3.1 is based on whether the current excitation point is ‘in front of the damage’ or ‘behind the damage’. This problem entails locating damage with respect to the sensing point and the current excitation point. Fig. 5 illustrates the limitation of the conventional ultrasonic approach in terms of locating damage with respect to the excitation and sensing points. Conventionally, damage existence is identified by subtracting the baseline data that corresponds to the pristine condition of a specimen from the measured signal in the time domain. Fig. 5(a) shows the baseline signal from an intact condition (blue solid line) and the measured signal from a damage condition (red dashed line) when the damage is located between the excitation point and the sensing point. In addition, the difference between the two signals is revealed in the bottom subfigure. In a similar manner, Fig. 5(b) shows the baseline and measured signals when the damage is introduced near but outside the direct path. Fig. 5(b) reveals that the measured signal significantly deviates from its pristine condition even when the damage is located outside the direct wave propagation path due to reflections from the damage. The effect of the damage outside the direct wave path may be alleviated by time truncation [24]. However, the selection of the proper truncation time point can be challenging due to the multi-mode and dispersive nature of Lamb waves.

To determine a damage location with respect to the excitation and sensing points, the measured time-domain ultrasonic signal $s$ ($T \times 1$ vector) is represented as a weighted linear combination of bases via the following transformation [25]

\[
\begin{align*}
s &= Dz, \\
D &= \{d_1, d_2, \ldots, d_L\}, \\
\end{align*}
\] (5)

where $z$ is a representation of $s$ in the transformed domain and has a dimension of $L \times 1$. $D$ is a $T \times L$ matrix, which is referred to as a dictionary and consists of $d_i$ bases ($i = 1, \ldots, L$). Each basis $d_i$ is a time-domain signal with the same dimensions as $s$.

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 that corresponds to a specific wave propagation distance from the fixed sensing points. For example, $d_i$ denotes the ultrasonic response generated at $x_i = x_1 + (i - 1)\Delta x$ distance from the sensing point. $x_1$ denotes the distance from the sensing point to the closest excitation point, and $\Delta x$ is the spacing between two excitation points.

\[
d_i = Ae^{-jk(x_i - ct)} = f(x_i - ct),
\] (6)

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 $D$.

As a large $L$ value is preferred to achieve a high resolution in the transformed domain, Eq. (5) typically represents an underdetermined system of equations ($L > T$), which creates non-unique solutions for $\alpha$. A unique $\alpha$ can be obtained via
the assumption that the actual solution has the sparsest representation, which produces the minimum number of nonzero entities in $\alpha$ [26]. Based on this assumption, Chen and Donoho proposed the basis pursuit approach to solve the underdetermined system in Eq. (5) [27]. The sparsest representation is obtained by solving the following problem with a given dictionary $D$. 

![Fig. 4. Comparison of the number of scanning points $p$ using the proposed binary search (blue solid line) and the full-field wave propagation imaging (black dashed line). The reduction rate $R$ (red dotted line) increases as the size of the inspection region increases. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image)

![Fig. 5. Comparison of ultrasonic responses (a) when a damage is located between the excitation point and sensing point and (b) outside the direct wave propagation path between the excitation point and sensing point. Blue solid line and red dashed line denote the measured signals from the intact condition and damage condition of the specimen, respectively. The bottom subfigures represent the difference between the intact signal and the damage signal.](image)
\[
\min \|x\|_1 \text{ s.t. } s = Dz, \tag{7}
\]
where \(\|x\|_1\) denotes the \(l_1\) norm of \(x\). 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, whereas other energy is reflected [28]. The incident \(u_i\), reflected \(u_r\), and transmitted \(u_t\) waves can be represented as
\[
u_i(x, t) = A_i e^{-jk_i(x-ct)}, \tag{8}
\]
\[
u_r(x, t) = A_r e^{jk_i(x+ct)} = C_R A_i e^{jk_i(x+ct)}, \tag{9}
\]
\[
u_t(x, t) = A_t e^{-jk_i(x-c\Delta t)} = C_t A_i e^{-jk_i(x-c\Delta t)}, \tag{10}
\]
where \(A_i, A_r, \text{ and } A_t\) represent the amplitudes of the incident waves, reflected waves, and transmitted waves, respectively, and \(k_d\) and \(c_d\) denote the wavenumber and wave speed, respectively, in the discontinuity. \(C_R\) and \(C_t\) are the reflection coefficient and transmission coefficient, respectively.

If no damage is introduced to the specimen after the dictionary is composed (Fig. 6(a)), the ultrasonic response \(s\) generated at \(x_s\) distance from the sensing point can be represented with only a single basis. This is only one nonzero element in \(x\), and a sparse representation of the time-domain signal is possible in the spatial ultrasonic domain. Then, \(s\) can be represented as
\[
s = f(x_s - ct) = d_s = d_s x_s, \tag{11}
\]
where \(x_s\) is the amplitude of the basis \(d_s\) in the transformed domain and its value is equal to one when no damage in the specimen exists.

Next, the time-domain responses obtained from a damage specimen are represented in the spatial ultrasonic domain. First, assume that the damage is located outside the direct wave propagation path (Fig. 6(b)). The excitation point is ‘in front of the damage’. Second, the measured signal \(s\) can be represented as the superposition of the direct incident waves and the damage reflected waves.
\[
s = f(x_s - ct) + g(x_s + \Delta x_D - ct) \quad (\Delta x_D = \Delta x_D/c) \quad \text{is the time-of-flight of the ultrasonic waves from the excitation point to the damage, where } \Delta x_D \text{ is the distance between the excitation point and the damage. The signal is represented with two bases: } d_s \text{ and } d_b. \text{ The first base corresponds to the incident waves with the ultrasonic travel distance } x_s \text{ and the second base corresponds to the reflected waves with travel distance } x_s = x_s + 2\Delta x_D. \quad \text{Its amplitude is equal to one when no damage.}
\]

The first term \(f\) represents the direct incident waves generated at \(x_s\) distance from the sensing point, and the second term \(g\) represents the reflection from the damage. The term \(\Delta x_D\) is included in \(g\) as the waves are reflected from the damage \(\Delta x_D\) after the original ultrasonic generation. \(\Delta t_D = \Delta x_D/c\) is the time-of-flight of the ultrasonic waves from the excitation point to the damage, where \(\Delta x_D\) is the distance between the excitation point and the damage. The signal is represented with two bases: \(d_s\) and \(d_b\). The first base corresponds to the incident waves with the ultrasonic travel distance \(x_s\) and the second base corresponds to the reflected waves with travel distance \(x_s = x_s + 2\Delta x_D\). \(x_b\) 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 the ultrasonic waves pass through the damage (Fig. 6(c)). Then, the excitation point is ‘behind the damage’, and the measured signal \(s\) can be represented as
\[
s = h(x_r - \Delta x_D - \Delta x_d) - c(t - \Delta t_D - \Delta t_d) \quad (\Delta t_D = \Delta x_D/c_d) \quad \text{is the transmission time of the waves through the damage, } \Delta x_D \text{ represents the width of the damage, and } c_d \text{ is the wave speed in the damage. From Eq. (10), } h \text{ can be represented by } C_t \text{ and } f, \text{ which are the transmission coefficient and the direct incident waves, respectively, without any damage transmission. The basis } d_c \text{ will have an amplitude of } x_c = C_t. \text{ Note that the ultrasonic waves are delayed while transmitting through the damage because } x_c \text{ is larger than } x_s.
\]

An important observation in Fig. 6 is that the measured response in the spatial ultrasonic domain includes the basis \(d_s\), which corresponds to the intact incident waves, if no damage is observed between the excitation point and sensing point (either no damage in the specimen or the excitation point is ‘in front of the damage’). However, this basis is shifted if the excitation point is ‘behind the damage’. Therefore, the damage presence within the direct wave propagation path can be
easily identified by performing spatial ultrasonic transformation and verifying the shift of the basis that corresponds to the intact incident waves.

3.3. Compressed sensing for damage quantification

Once the approximate damage region (transition line) is identified using the proposed binary search, the wavefield images around the transition line are solely reconstructed based on the previous scanning points without any additional scanning. Fig. 7 provides an overview of the proposed damage quantification technique based on compressed sensing.

Step 1: The imaging region is defined as the smallest rectangular region, including all scanning points in the damage inspection lines, as represented by a dashed box in Step 1 of Fig. 7.

Step 2: Within the imaging region, responses at unscanned inspection points are reconstructed from the scanning points using compressed sensing (CS) [18,29,30]. Here, what we need to obtain is a wavefield image signal $s_I$ (vector), which represents a spatial distribution of the ultrasonic waves in the imaging region at a specific time step. $s_I$ is the vectorization result of a wavefield image for the imaging region of size $N_I \times M_I$ (width $\times$ height). Note that this wavefield image signal represents a spatial information of wave propagation instead of a time-domain ultrasonic response. As shown in Eq.(5), the wavefield image signal can be represented as a weighted linear combination of bases.

$$s_I = \mathbf{D}_{CS} \alpha_I$$

Designing a dictionary is also an important task for Eq. (14). $\mathbf{D}_{CS}(N_I \times M_I \times T)$ matrix is a dictionary for this transformation, which consists of $\mathbf{d}_{CS}^i$ bases ($i = 1, \ldots, T$). Each basis $\mathbf{d}_{CS}^i$ has the same dimensions as $s_I$ and corresponds to the spatial wave distributions in the imaging region at each time step $t_i$ ($i = 1, \ldots, T$). The bases for $\mathbf{D}_{CS}$ is reconstructed from $\mathbf{D}$ ($T \times L$ matrix) in Eqs. (5) and (6) as

$$\mathbf{d}_{CS}^i = \mathbf{A}e^{j(\omega_0 - \omega_i)} = f(x_n - ct_i) = f(x_i - ct_i) = \mathbf{d}_{li},$$

where $x_n$ is the distance between the $n$th scanning point in the imaging region and the sensing point. The $n$th element of $\mathbf{d}_{CS}^i$ is obtained from the $l$th basis of $\mathbf{D}$, which corresponds to the ultrasonic response generated at $x_i = x_n$. $\mathbf{d}_{CS}^i$ represents the ultrasonic response of the $n$th scanning point in the imaging region at time step $t_i$. This is identical to $\mathbf{d}_{li}$, which is the ultrasonic response at time step $t_i$ generated at the distance $x_i = x_n$ from the sensing point.

As in Eq. (7), the following problem is solved to obtain $x_i$

$$\min ||x_i||_1 \text{ s.t. } \mathbf{s}_i = \mathbf{D}_{CS} \mathbf{z}_i = \mathbf{A} \mathbf{D}_{CS} \mathbf{z}_i,$$

where $\mathbf{s}_i$ ($P \times 1$ vector) is the scanned part of $\mathbf{s}_i$ and $P$ is the number of scanning points in the imaging region. $\mathbf{A}$ ($P \times N_I \times M_I$ matrix) is a measurement matrix that indicates the scanning point locations, e.g., yellow and green points in the imaging region in Fig. 6. Because $\mathbf{s}_i$, $\mathbf{A}$, $\mathbf{D}_{CS}$ are known, $\mathbf{z}_i$ is obtained using the basis pursuit approach. Then, $\mathbf{s}_i$ can be obtained from Eq. (14) with the designed $\mathbf{D}_{CS}$ and obtained $\mathbf{z}_i$. 

Fig. 6. Comparison of the transformed time-domain ultrasonic responses generated at (a) intact, (b) in front of the damage, and (c) behind the damage.
By repeating this process for every time step, the ultrasonic wave propagation data in the imaging regions are obtained. The estimated unscanned inspection points are represented as purple points in Step 2 of Fig. 6.

Step 3: Wavefield images are created for the imaging region by matricizing $s$ at each time step.

Step 4: The actual damage points are identified by extracting standing wave energy generated by wave-damage interactions [12]. Local standing waves are generated in the damage as the ultrasonic waves are trapped inside from their multiple reflections at the damage boundaries. Then, the damage is visualized and its size is quantified.

If there are multiple damages in the inspection region, the proposed binary search process (Section 3.1) cannot distinguish individual damage and it considers them all together as a large single image. But it is possible to distinguish them from the reconstructed wave propagation images and the proposed damage quantification technique.

4. Numerical validation

4.1. Description of numerical simulation

The proposed accelerated laser scanning technique is validated via a numerical simulation that is performed with the commercial finite element software program COMSOL Multiphysics.

The simulated aluminum plate model has dimensions of $15 \times 15 \times 0.3$ cm$^3$, as displayed in Fig. 8. A notch, with length, width and depth dimensions of 1 cm, 0.01 cm, and 0.15 cm, respectively, is introduced on the opposite side of the scanned surface. A square region of 4 cm around the notch is established as an inspection region. Detailed material properties for this aluminum plate model are given in Table 1.

To represent the phenomenon that occurs after the incident of a laser beam pulsed onto the plate, the model is divided into two parts: the thermal wave region and the ultrasonic wave region. First, thermoelasticity is used to model ultrasonic wave generations due to the thermal stress induced by a pulse laser. Second, an interaction between solid and acoustic is used for solving the ultrasonic wave propagation within a material. The entire model is meshed with triangular elements, and a multi-scale element length is used to reduce the computation burden. In this study, a multi-physics simulation in the time-domain analysis is considered. Please refer to [31] for details about the numerical modelling of ultrasonic wave propagation generated using a pulse laser.

A spatial ultrasonic dictionary was constructed from an intact aluminum plate model. Bases in the spatial ultrasonic dictionary were generated by moving the excitation point from a 0.4 cm distance to the sensing point to 7.5 cm with 0.1 cm resolution to create 72 bases. By spline interpolations between two adjacent bases, the dictionary was constructed from a total of 721 bases with a 0.01 cm spatial resolution. Each base was sampled for 25 $\mu$s with a 5.12 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 ultrasonic information in the interested frequency bandwidth in the measured signals.

For a binary search, each scanning is performed with identical parameters in the basis construction process. While the excitation laser beam scans the inspection region, the sensing laser beam vertically moves according to the vertical location.
of the current scanning point. The horizontal distance was fixed to 1 cm from the sensing points to the left edge of the inspection region. The spatial scanning resolution for a binary search was 0.2 cm for the $x$ and $y$ directions, which divides the inspection region into $21 \times 21$ grids.

4.2. Spatial ultrasonic transformation

First, the simulated time response is transformed into the spatial ultrasonic domain to determine whether the laser excitation point is positioned either ‘in front of’ or ‘behind’ the damage, as shown in Fig. 9.

Fig. 10 compares the ultrasonic responses obtained from intact (blue solid line) and damage (red dashed line) conditions of the plate in the proposed spatial ultrasonic domain. Fig. 10(a) compares the intact and damage conditions when the laser excitation point is placed in front of the damage. When the excitation is placed in front of the damage, the amplitude of the initial basis that corresponds to the incident waves does not change and only additional bases with non-zero amplitudes appear. When the excitation is positioned behind the damage (Fig. 10(b)), 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 position of the laser excitation point with respect to the damage is determined, which enables a repeated binary search along a single inspection line, as described in the following subchapter.

4.3. Transition line detection

To find the transition point in each inspection line, a basis pursuit (BP) index is defined. The BP index is the amplitude of the basis that corresponds to the incident initial waves. Fig. 11 maps the BP index values as the excitation point moves from a 10 mm distance from the sensing point to 50 mm. When there is no damage between the excitation point and the sensing points, the BP index values are similarly large for all scanning points. When a notch damage is observed, the BP index value significantly decreases as the excitation point passes through the damage location, that is, when the excitation point is in front of the damage, the BP index that corresponds to the excitation point is large. When the excitation point moves behind the damage, the BP index value becomes practically zero. In Fig. 11, all 21 scanning points in a single inspection line are scanned for illustration. In practice, only five ($\log_221$) scanning points are required to identify the transition point using the proposed binary search.

Fig. 12(a) illustrates the outcome of the binary search. The 40 mm by 40 mm square area represents the inspection region, whereas the sensing points had been located at a 10 mm distance from the left edge of the square area. When the scanning point is located behind the damage, the scanning point is colored in yellow. The scanning point in front of the damage is marked in green. The transition points are colored in yellow and marked with crosses. When the 40 mm by 40 mm area is scanned with a 2 mm resolution, a total of 441 ($21 \times 21$) inspection points are generated. Only 32 scanning points (7.3%) are needed to identify the transition line. The transition line in Fig. 12(b) is obtained by connecting all transition points in Fig. 12(a). This reduction rate of 92.7% is close to the theoretical reduction rate of 91.6% in Eq. (4).

Table 1

<table>
<thead>
<tr>
<th>Material properties of the aluminum in this numerical simulation.</th>
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<tr>
<td>Density $\rho$ (kg/m$^3$)</td>
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<tr>
<td>---------------------------</td>
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<tr>
<td>2700</td>
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Fig. 8. Schematic of an aluminum plate model for the numerical validation of the developed techniques.
Fig. 9. Determination of the location of the laser excitation point with respect to damage using the proposed spatial ultrasonic transformation: (a) The excitation point is in front of the damage, and (b) the excitation point is behind the damage.

Fig. 10. Comparison of ultrasonic responses measured from an intact plate (blue solid line) and a damage plate (red dashed line) in the spatial ultrasonic domain: (a) When the excitation point is in front of the damage (Fig. 9(a)), and (b) when the excitation point is behind the damage (Fig. 9(b)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 11. Variation of the basis pursuit (BP) index value as the excitation point moves from a 10 mm distance from the sensing point to 50 mm: (a) when there is no damage between the moving excitation point and the fixed sensing point, and (b) when there is a notch at 24 mm distance from the fixed sensing point.
4.4. Damage quantification

Next, compressed sensing is performed for detailed damage quantification. Ultrasonic wave propagation is visualized by estimating the responses in unmeasured points using compressed sensing. The imaging region is indicated with a dashed box in Fig. 13(a). Reconstructed wave propagation snapshots are visualized in Fig. 14(b) and compared with the original full-field wave propagation snapshots (Fig. 14(a)).

As represented in Fig. 14, the reconstructive wave propagation images reveal satisfactory agreement with the original full-field wave propagation images. Waves propagate from the left edge of the region towards the right, reflected from the notch, and propagate back to the left side. The actual damage quantification is achieved by applying a standing wave energy analysis [16]. By this analysis, the notch is identified and visualized in Fig. 13(b). The red color in Fig. 13(b) represents the damage points, where their damage-induced standing wave energy is greater than the threshold value obtained from the standing wave energy analysis. The numerical simulation that is presented in this chapter validates that the proposed damage detection technique using combined binary search and compressed sensing can detect and visualize damage with a significantly reduced number of scanning points.

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

5.1. Experimental setup

Fig. 15 shows an overview of the laser ultrasonic scanning system used in the experiments. A diode pumped Q-switched Nd:YAG pulse laser (Quantel Centurion+) radiates 532 nm wavelength laser pulses. The width of the laser pulse is 12 ns, and this device emits 3 mm diameter 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 front of the galvanometer focuses the laser beam diameter to 0.5 mm on the specimen surface. 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 $30 \times 12 \times 0.3$ cm$^3$, as displayed in Fig. 16. A through-the-thickness fatigue crack with a length of 1.8 and width of 10 μm was introduced by repetitive tensile loadings with a universal testing machine. A square region of 2 cm around the crack is established as an inspection region.

A spatial ultrasonic dictionary was constructed from an intact aluminum plate. Bases in the spatial ultrasonic dictionary were generated by moving the excitation point from a 1 cm distance to the sensing point to 7 cm with 0.1 cm resolution to create 61 measurements. By spline interpolations between the two adjacent bases, the dictionary was constructed from a total of 601 bases with a spatial resolution of 0.01 cm. The peak energy and power of the pulse laser was 3 mJ and 0.3 MW, respectively. Each basis was sampled for 37.5 μs with a 2.56 MHz sampling frequency. A bandpass filter with a

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1 For interpretation of color in Fig. 13, the reader is referred to the web version of this article.
A low cutoff frequency of 50 kHz and a high cutoff frequency of 450 kHz was used to capture ultrasonic information in the interested frequency bandwidth. Each basis collection was averaged 100 times to improve their signal-to-noise ratios.

For a binary search, each measurement was performed using identical parameters in the basis construction process. The sensing point was located at a distance of 1 cm from the left edge of the inspection region and vertically moved according to the vertical location of the current excitation scanning point. The spatial scanning resolution for a binary search is 0.1 cm for the $x$ and $y$ directions, which divides the inspection region into $21 \times 21$ grids.

### 5.2. Damage detection results

Fig. 17 illustrates the outcome of a binary search. The 20 mm $\times$ 20 mm square area represents the inspection region, whereas the sensing points have been located at a 10 mm distance from the left edge of the square area. When the 20 mm $\times$ 20 mm area is scanned with a 1 mm resolution, a total of 441 ($21 \times 21$) inspection points are generated. Only 37 scanning points (8.4%) are required to identify the transition line. The transition line in Fig. 17(b) is obtained by connecting all transition points in Fig. 17(a). This result identifies the left border of the crack with high accuracy. The discrepancies between the actual left border of the crack and the transitional line are less than the scanning resolution of 1 mm.
Fig. 15. Overview of the proposed laser ultrasonic scanning system.

Fig. 16. An aluminum plate with a fatigue crack. A crack with a height of 1.8 cm and width of 10 µm is introduced to the plate by repetitive tensile loadings.

Fig. 17. Binary search for a transition line detection: (a) layout of scanning points that were selected by the binary search and (b) the detected transition line.
To obtain the results shown in Fig. 17, 0.6 min of scanning time is required. Note that this scanning time is obtained with (1) averaging 100 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 was employed, (2) a faster pulse laser was available, or (3) a lower scanning resolution was acceptable, the scanning time could have been further reduced.

Next, compressed sensing is performed for detailed damage quantification. The imaging region is indicated with a dashed box in Fig. 18(a). Reconstructed wave propagation snapshots are visualized in Fig. 19(b) and compared with the original full-field wave propagation snapshots (Fig. 19(a)).

As represented in Fig. 19, the reconstructed wave propagation images show satisfactory agreement with the original full-field wave propagation images. Waves propagate from the left edge of the region towards the right edge of the region, reflected from the crack, and propagate back to the left side. From a standing wave analysis, the crack is identified and visualized in Fig. 18(b) using red points. This result visualizes the crack with a high accuracy. The experiment presented in this chapter validates that the proposed damage detection technique using combined binary search and compressed sensing can detect and visualize any damage with a significantly reduced number of scanning points, even for a fatigue crack.

6. Experimental validation II: Detection of an impact-induced delamination in a carbon fiber-reinforced plastic (CFRP) plate

6.1. Experimental setup

The other specimen for experimental validation is a carbon fiber-reinforced plastic (CFRP) plate. This plate has dimensions of 27.5 × 27.5 × 0.3 cm³, as displayed in Fig. 20. The plate is composed of IM7 graphite fibers with 977-3 resin material and 12 plies with a layup of [0/±45/0/±45]s. A 1 cm diameter delamination was introduced at the center of the plate by an impact. A square region of 5 cm around the delamination is established as an inspection region. The delamination is located in the top-left corner of the inspection region.

A challenge of the ultrasonic wave analysis of an anisotropic material is that the ultrasonic wave speeds and propagation characteristics vary with their propagation direction. To prevent this variance, the inspection lines are oriented in the same direction with each other. A dictionary only for this single direction is sufficient to apply the proposed accelerated laser scanning technique to anisotropic specimens.

Because no intact CFRP plate is available, a spatial ultrasonic dictionary was constructed from an intact part of the plate. Bases in the spatial ultrasonic dictionary were generated by moving the excitation point from a 1 cm distance to the sensing point to 10 cm with 0.1 cm resolution to create 91 measurements. Using spline interpolations between the two adjacent bases, the dictionary was constructed from a total of 901 bases with a 0.01 cm spatial resolution. The peak energy and power of the pulse laser was 3 mJ and 0.3 MW, respectively. Each basis was sampled for 37.5 µs 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 employed to capture ultrasonic information in the interested frequency bandwidth. Each basis collection was averaged 100 times to improve their signal-to-noise ratios.

For a binary search, each measurement was performed with identical parameters in the basis construction process. The sensing point was located 1 cm distance from the left edge of the inspection region and vertically moved according to the vertical location of the current excitation scanning point. The spatial scanning resolution for a binary search is 0.1 cm for both x and y directions, which divides the inspection region into 51 × 51 grids.

6.2. Damage detection results

Fig. 21 illustrates the outcome of a binary search. The 50 mm × 50 mm square area represents the inspection region, whereas the sensing points had been located at a 10 mm distance from the left edge of the square area. When the 50 mm × 50 mm area is scanned with a 1 mm resolution, a total of 2601 (51 × 51) inspection points are generated. Only 75 scanning points (2.9%) are needed to identify the transition line, which corresponds to 1.3 min of scanning time. This scanning time can be reduced as mentioned in Section 5.2. The transition line in Fig. 21(b) is obtained by connecting all transition points in Fig. 21(a).

Next, compressed sensing is performed for detailed damage quantification. The imaging region is indicated with a dashed box in Fig. 22(a). Reconstructed wave propagation snapshots are visualized in Fig. 23(b) and compared with the original full-field wave propagation snapshots (Fig. 23(a)). As represented in Fig. 23, the reconstructed wave propagation images show satisfactory agreement with the original full-field wave propagation images. Waves propagate from the left edge of the region toward the right and interact inside the delamination. In the standing wave analysis, the delamination is identified and visualized in Fig. 22(b) with red points. The visualized delamination is comparable to the conventional laser ultrasonic imaging results, as shown in Fig. 24. The experiment in this chapter validates that the proposed damage detection technique using combined binary search and compressed sensing can detect and visualize damage, even for anisotropic specimens.
Fig. 18. Damage quantification via compressed sensing. (a) The imaging region is represented as a dashed box and (b) the corresponding crack quantification result is presented.

Fig. 19. Comparison of the original full-field and the reconstructed wave propagation snapshots that correspond to the dashed box in Fig. 18(a): (a) Original full-field wave propagation images and (b) reconstructed wave propagation images.
Fig. 20. A CFRP plate with a delamination. A delamination with a 1 cm diameter is introduced to the plate with an impact.

Fig. 21. Binary search for a transition line detection: (a) layout of the scanning points selected by the binary search and (b) the detected transition line.

Fig. 22. Damage quantification through the compressed sensing. (a) The imaging region is represented as a dashed box and (b) the corresponding delamination quantification result is presented.
7. Conclusion

This paper proposes an accelerated laser ultrasonic scanning technique for damage detection by combining a binary search and compressed sensing. First, the approximate damage location is identified by examining the interactions between the ultrasonic waves and damage at the sparse scanning points selected by a binary search algorithm. A time-domain laser ultrasonic response is transformed into a spatial ultrasonic domain using a basis pursuit approach so that the interactions between the ultrasonic waves and damage, such as reflections and transmissions, can be better identified in the spatial ultrasonic domain. Then, the wavefield images around the damage are reconstructed from the previously selected scanning points using compressed sensing. The number of scanning points that are necessary for damage localization and visualization are significantly reduced from \( N \cdot M \) to \( 2 \log_2 N \cdot \log_2 M \), where \( N \) and \( M \) represent the number of the scanning points in the \( x \) direction and \( y \) direction, respectively, which are required to obtain full-field wave propagation images of the target inspection area.

The effectiveness of the proposed accelerated laser scanning technique is validated using a numerical simulation and experimental tests performed on an aluminum plate with a crack and a carbon fiber reinforced plastic (CFRP) plate with a delamination. The tested damage is detected and quantified with a high spatial accuracy, and the number of scanning points and scanning time are reduced by more than 90% compared with the number of scanning points of conventional full-field wave propagation imaging techniques. For example, the detection of the delamination in the CFRP plate results in a 97.1% reduction in the number of scanning points (2601–75 points) and scanning time (43–1.3 min).

However, additional studies are needed before the proposed accelerated laser scanning technique can be applied to more realistic conditions. First, only linear interactions between the ultrasonic waves and damage are considered in this paper. Consideration of nonlinear interactions is required to detect nonlinear damages, including smaller fatigue cracks. Second, as a LDV usually requires surface treatments for high sensitivity, an improved sensing solution is needed. Last, additional
performance validations with realistic structures are also warranted. A follow-up study is underway to investigate the effects of damage geometry and orientation on damage detectability.

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References