Laser Ultrasonic Scanning using Binary Search

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Abstract
Laser ultrasonic imaging is attractive for damage localization because of its noncontact nature, sensitiveness to local damages, and high spatial resolution. However, its field application is limited as the scanning with high spatial resolution demands a long scanning time. Inspired by a binary search algorithm, an accelerated scanning technique is developed so that damage can be located and visualized with a reduced number of laser ultrasonic measurements. First, ultrasonic waves are generated at the center of a single line in an inspection region using a pulsed laser, and measured at a fixed sensing point using a laser Doppler vibrometer (LDV). Second, the measured ultrasonic response is analyzed using a spatial ultrasonic transformation technique to check whether the corresponding ultrasonic waves have passed through the damage or not. If the waves crossed the damage, the damage should be located between the excitation and the sensing point. If not, the damage should be located outside the propagation path, allowing us to rule out the half of the inspection region as possible damage locations. Third, the center of the remained inspection region is selected as the next excitation point. These steps are repeated until there is no remained binary inspection region. Fourth, the first to the third steps are repeated with a next line in the manner of binary search. Then, the boundary between the areas affected by the damage and the intact area is determined as the damage location. The number of measurement points required for damage localization and visualization are dramatically reduced from $N\cdot M$ to $\log_2 N \cdot \log_2 M$, where $N$ and $M$ represents the size of inspection region in $x$ and $y$ direction, respectively. The performance of the proposed accelerated scanning technique is evaluated through a numerical simulation and an experiment performed on a cracked aluminum plate.

Keywords: Damage Localization, Laser ultrasonics, Basis pursuit, Binary search

1. INTRODUCTION

In these days, there is an increasing concern on structural safety as there have been a number of catastrophic failures of civil, mechanical and aerospace structures which caused numerous economic loss and fatalities. Damage detection is important for not only those structures but also industrial products to increase their reliability and reduce corresponding expenses. Especially, there is a large demand for effective noncontact damage detection techniques as they can detect and localize damages without any sensor installation.

Laser ultrasonic imaging is attractive for damage localization because of its noncontact nature, sensitiveness to local damages, and high spatial resolution [3-7]. This technique visualizes ultrasonic wave propagation in a scanned area, and extracts damage-wave interactions for automated damage diagnosis. However, its field application is limited as the scanning with high spatial resolution demands a long scanning time. For example, according to the experimental results of the authors’ group, an inspection time of 40 minutes is required
to scan a 10 cm × 10 cm square region with 2 mm spatial resolution. Compressed sensing is
one of the rising solutions for this problem [8-9]. It estimates unmeasured ultrasonic responses
from measured points, enabling reconstruction of a full wavefield from a limited number of
laser scanning. The compression ratio, between the reduced number of measurements and the
originally required number of measurements, can be up to 90% while achieving 0.9 coherence
with the original wavefield [10]. However, its performance is maximized with a narrowband
excitation, and usually requires contact transducers for it.

In this study, a novel damage detection technique is proposed so that damage can be located
and visualized with a reduced number of laser ultrasonic measurements. The proposed
technique searches the damage location from optimized measurement points, instead of
reconstructed ultrasonic wavefield. The optimization process of measurement points is inspired
by a binary search algorithm [11]. The proposed technique reduces the required number of
measurements from $N \cdot M$ to $2 \log_2 N \cdot \log_2 M$, where $N$ and $M$ represent the size of inspection
region in x and y direction, respectively.

This paper is organized as follows. Section 2 proposes an accelerated damage detection
technique using binary search. In Sections 3 and 4, the performance of the proposed technique
is validated numerically and experimentally using an aluminium plate model with a crack and
an aluminium plate with a fatigue crack, respectively. Finally, this paper concludes with a brief
summary and discussion in Section 5.

2. ACCELERATED DAMAGE DETECTION TECHNIQUE

2.1 Damage detection using spatial ultrasonic transformation

A time domain ultrasonic signal $s$ can be represented in other domains, such as frequency
domain. This process is called a transformation.

$$s = D\alpha$$

(1)

$$D = \{d_1, d_2, ..., d_L\}$$

Here, $\alpha$ is a vector of length $L$ and called as a representation in a transform domain. $D$ is known
as a dictionary, and consisted of $L$ atoms or basis, $d_i$. In other words, $s$ can be represented as a
linear combination of atoms through a given transformation. But it is very challenging to obtain
$\alpha$ if Equation (1) is an undetermined problem.

Chen and Donoho proposed a basis pursuit approach to solve this problem [12]. They
assumed that the representation is sparse so that the signal can be represented with a small
number of atoms. Then the optimal representation can be obtained by solving the following
problem where $\|\alpha\|_1$ is defined as the L1 norm of $\alpha$ [13].

$$\min \|\alpha\|_1 \quad s.t. \quad s = D\alpha$$

(2)

By selecting an appropriate dictionary, the signal can be represented sparsely and its
representation can be obtained by basis pursuit.

A spatial ultrasonic dictionary is created in this study to effectively transform ultrasonic
responses. For a given structure, ultrasonic responses are generated at different distances from
a fixed sensing point. Each collected response is assigned as an atom of the dictionary. Here,
each atom $d_i$ corresponds to a ultrasonic response traveled a distance $x_i = x_0 + i\Delta x$ from its
generation point to the fixed sensing point at $x = 0$.

This approach assures sparse representations naturally as the dictionary itself is a set of
ultrasonic signals from the structure. If there is no damage or change in the structure after the
dictionary created, the measured ultrasonic response \( s \) generated at \( x_d \) can be represented with a single basis corresponding to its ultrasonic generation coordinate \( x_d \). If there is a damage outside of the direct path between an excitation and a sensing point, \( s \) can be represented with a basis corresponding to \( x_d \) and the other basis corresponding to \( x_p \), the distance traveled by the damage reflected waves. However, if the ultrasonic waves pass through the damage, the measured response is delayed and changed during damage transmission and not represented with the basis corresponding to \( x_d \) anymore.

Then, the damage existence between the excitation and the sensing points can be identified by checking if the basis corresponding to \( x_d \) exists after spatial ultrasonic transformation of \( s \). As this basis peak is shifted only if ultrasonic waves propagate through a damage, this is a sensitive feature in damage detection. Conventional baseline based damage techniques have tracked the time-of-flight of the measured ultrasonic responses or measured residual responses by subtracting a reference response from the measured response. Extracting these features is highly susceptible to measurement noise, and the measured responses are usually contaminated by damage reflected responses even for intact paths. This makes the proposed technique very attractive.

### 2.2 Accelerated damage detection using binary search

In Figure 1, an overview of the proposed damage detection technique is provided, which works in following steps.

**Step 1:** Assume that we have an inspection region of size \( N \times M \) with a predefined spatial resolution. Then the \( m \)th row of this region is called as the \( m \)th inspection line. A spatial ultrasonic dictionary \( D \) is collected in prior for the inspection region. The middle inspection line, \( \lfloor M/2+1 \rfloor \)th row, is selected and a fixed sensing point is located on a line extending this inspection line.

**Step 2:** Ultrasonic waves are generated at the center of the inspection line using a pulsed laser, and measured at the fixed sensing point using a laser Doppler vibrometer (LDV). Then, the measured ultrasonic response is analyzed using a spatial ultrasonic transformation to check whether the corresponding ultrasonic waves have passed through the damage or not. If the waves crossed the damage, the damage should be located between the excitation and the sensing point. If not, the damage should be located outside the propagation path, allowing us to rule out the half of the inspection line as possible damage locations. The center of the remained inspection line is selected as the next excitation point, and these steps are repeated until there is no remained binary inspection line. The required number of measurements \( p_n \) for a single inspection line is:

\[
P_n = \log_2 N
\]

and this is independent of whether a damage exists in the inspection line or not. After \( p_n \) measurements, the damage existence on this inspection line and its boundary location can be identified.

**Step 3:** Binary search results from Step 2 are assigned onto the map of the inspection region. Red points imply the damage existence on them or their right side, while the green points imply the intact condition or the damage existence on their left side. The boundary between the areas affected by the damage and the intact area, represented as a crossed red point, is determined as the damage location.
Step 4: Step 2 and 3 are repeated for a next inspection line. Here, the next line is not selected sequentially but in the manner of binary search to find the upper and lower boundary of the damage. Then the required number of inspection line is presented as follows.

\[ p_m = 2 \log_2 M \text{ (damaged)} \]
\[ p_m = M \text{ (intact)} \]  

(4)

Note that the logarithm term is multiplied by 2, as this approach needs to find both upper and lower boundary. If there is no damage, all the inspection lines need to be searched to assure the intact condition. Then the total number \( p \) of required measurements and its ratio \( R \) to the number of original scanning points is:

\[ p = p_n \cdot p_m = 2 \log_2 N \cdot \log_2 M \text{ (damaged)} \]
\[ p = p_n \cdot p_m = \log_2 N \cdot M \text{ (intact)} \]  

(5)
\[ R = \frac{p_n \cdot p_m}{N \cdot M} = \frac{2 \log_2 N \cdot \log_2 M}{N \cdot M} \] (damaged)

\[ R = \frac{p_n \cdot p_m}{N \cdot M} = \frac{\log_2 N}{N} \] (intact)

Let us assume the inspection region is a 50 mm square with 1 mm spatial resolution, where \( N=M=50 \). Then 2500 points are required for conventional laser ultrasonic imaging schemes. But only \( p=72 \) measurements are needed with the proposed techniques, which is only 2.9% compared to its original required data. This increases to 12% for intact case, but still requires fewer number of measurements. The performance of this technique dramatically increases as the inspection region is larger or the spatial resolution is denser, as the number of measurements is proportional to the square of logarithms.

Step 5: Search results from Step 4 are assigned onto the map of the inspection region. The damage location can be roughly identified from a reduced number of measurements.

Step 6: By interpolating the crossed red points, the damage location is visualized in the inspection region.

3. NUMERICAL VALIDATION OF THE DEVELOPED TECHNIQUE

3.1 Model description

The proposed technique is validated through simulations with a numerical model first. The numerical validations are performed with a commercial finite element software COMSOL Multiphysics. This modeled aluminum plate has a dimension of 15 \( \times \) 15 \( \times \) 0.3 cm\(^3\) as displayed in the left of Figure 2. A 1 cm long, 0.01 cm wide and 0.15 cm deep crack is introduced on its surface. A square region of 4 cm around the crack is determined as an inspection region. The crack is located on the right side of the inspection region, as shown in the right of Figure 2.

Detailed material properties for this aluminum plate model is given in Table 1. For more details about the model and numerical simulation process, please refer to the following reference [14].

A spatial ultrasonic dictionary is obtained from an intact aluminum plate model. Ultrasonic waves are generated by changing the distance from a fixed sensing point, from 0.4 cm to 7.5 cm with 0.1 cm resolution, achieving 72 measurements. Through spline interpolations of 0.01 cm resolution between these measurements, 721 bases with 0.01 cm spatial resolution are collected and the dictionary is constructed from them. Each basis is collected 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 is used to remove noise components in the measured signals.
Sensing points are fixed at 1 cm from the right edge of the inspection region. The spatial scanning resolution in binary search measurements is 0.2 cm for both x and y direction, dividing the inspection region into 21×21 grids.

<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))</th>
<th>Heat capacity at constant pressure $C_p$ (J/(kg·K))</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>

Table 1. Material properties of aluminum used in this numerical simulation

### 3.2 Damage detection result

![Spatial maps of basis pursuit index (BP index) for (a) an intact and (b) a damaged inspection line.](image)

Figure 3. Spatial maps of basis pursuit index (BP index) for (a) an intact and (b) a damaged inspection line.

First, the damage detection using spatial ultrasonic transformation is performed for every spatial points in a single inspection line to visualize its performance. Figure 3 maps basis pursuit index (BP index), the sum of basis amplitudes in a half of scanning spatial resolution from the ideal basis location. For an intact inspection line, which does not pass through the crack, every points have positive BP index. This indicates that the basis peak corresponding to the incident waves is not shifted at every spatial point. On the other hand, for another inspection line passing through the crack, BP index dramatically drops to zero from the crack location. This is due to the basis peak shifted during the ultrasonic wave transmission through the crack. This validates that the proposed damage detection process can detect damage existence in the ultrasonic propagation path with a very high spatial sensitivity. Please note that only five ($\log_2 21$) points are required to detect the damage boundary for a single inspection line. Only for this example, every points are measured to discuss about the performance of the damage detection using spatial ultrasonic transformation.
Then the proposed searching technique is applied to the inspection region. The measurement points for binary search is shown in Figure 4 (a). The square area is corresponding to the inspection region in Figure 2. Red points imply the damage existence on them or their right side, while the green points imply the intact condition or the damage existence on their left side. The damage boundary locations are presented as crossed red points. The white points, which no color is assigned, are indicating no measurement is performed on them. Then the damage detection result is presented in Figure 4 (b) by interpolating the red crossed points in Figure 4 (a). The search result perfectly identifies the crack location both in x and y direction. This result is obtained with a reduced number of laser ultrasonic measurements. Measurements are performed at only 32 points in this region, while 441 (21×21) points are required for conventional laser ultrasonic scanning with 0.2 cm scanning resolution. This reduces 92.7% of required data.

4. EXPERIMENTAL VALIDATION OF THE DEVELOPED TECHNIQUE

4.1 Experimental setup

The proposed technique is also validated experimentally on an aluminum plate with a fatigue crack. This plate has a dimension of 30 × 12 × 0.3 cm³ as displayed in Figure 5. A 1.8 cm long and 10 μm wide crack is introduced by repetitive tensile loadings with a universal testing machine. A square region of 2 cm around the notch is determined as the inspection region. The crack is located at the center of the inspection region.

A spatial ultrasonic dictionary is obtained from another intact aluminum plate. Ultrasonic waves are generated by changing distance from a fixed sensing point, from 1 cm to 7 cm with 0.1 cm resolution, resulting 61 measurements. Through spline interpolations of 0.01 cm resolution between these measurements, 601 bases with 0.01 cm spatial resolution are collected and the dictionary is constructed. The peak energy and power of the pulse laser is 3 mJ and 0.3 MW respectively. Each basis is collected 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 is used to remove noise components from the measured signals. 200 times of averaging are performed for each measurement to improve its reliability. Sensing points are fixed at 1 cm
from the right edge of the inspection region. The spatial scanning resolution in binary search measurements is 0.1 cm for both directions, dividing the inspection region into 21×21 grids. 100 times of averaging are done for each measurement.

Figure 5. An aluminum plate with a fatigue crack. A crack with 1.8 cm height and 10 μm width is introduced to the plate by repetitive tensile loadings.

4.2 Damage detection result

The damage detection using spatial ultrasonic transformation is performed for every spatial points in a single inspection line to visualize its performance. Figure 6 maps BP index for an intact and a damaged inspection line. For an intact inspection line, which does not pass through the crack, every points have positive BP index. On the other hand, for another inspection line passing through the crack, BP index dramatically drops to zero from the notch location. This validates that the proposed damage detection process can detect damage existence in the ultrasonic propagation path with a very high spatial sensitivity. Again, please note that only five (\( \log_2 21 \)) points are required to detect the damage boundary for a single inspection line.

Figure 6. Spatial maps of basis pursuit index (BP index) for (a) an intact and (b) a damaged inspection line.
Figure 7. Binary search of damage boundary. (a) Measured points and (b) corresponding crack detection result is presented.

Then the proposed searching technique is applied to the inspection region. The measurement points for binary search is shown in Figure 7 (a). The square area is corresponding to the inspection region in Figure 5. Red points imply the damage existence on them or their right side, while the green points imply the intact condition or the damage existence on their left side. The damage boundary locations are presented as crossed red points. The white points, which no color is assigned, are indicating no measurement is performed on them. Then the damage detection result is presented in Figure 7 (b) by interpolating the red crossed points in Figure 7 (a). The search result perfectly identifies the crack location both in x and y direction. This result is obtained with a reduced number of laser ultrasonic measurements.

Measurements are performed at only 37 points in this region, while 441 points are required for conventional laser ultrasonic scanning with 0.1 cm scanning resolution, corresponding to a reduced inspection time of 0.5 minutes from 7.4 minutes. This reduces 91.6% of required data and measurement time. Note that this measurement time is calculated with an assumption of (1) 100 averaging for each measurement; (2) pulse laser repetition rate of 100 Hz; and (3) 0.1 cm scanning resolution for 5 cm square region. If lower number of averaging is used, a faster pulse laser is available, or lower scanning resolution is acceptable, the measurement time can be further reduced.

5. CONCLUSION

Laser ultrasonic techniques are gaining popularity in the nondestructive testing field with their noncontact nature and high spatial resolution. However, their field applications are limited as they require a huge amount of inspection time to achieve their high spatial resolution in damage detection. This research aims to accelerate laser based nondestructive testing with a proposed novel search technique. The proposed technique searches the damage location from optimized measurement points, and optimization of measurement points is inspired by a binary search algorithm. The proposed technique reduces the required number of measurements from $N \cdot M$ to $2\log_2 N \cdot \log_2 M$, where $N$ and $M$ represent the size of inspection region in x and y direction,
respectively. The feasibility of this technique is validated using an aluminum plate with a crack, both numerically and experimentally.

However, as the proposed technique provides only damage boundary location, it is hard to quantify the damage. It would not be a significant problem to detect narrow damages such as cracks and notches, but it is challenging to apply this technique to wide damages e.g. delaminations. The possibility of damage quantification using reduced number of measurements is being explored by the authors’ group.

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