DAMAGE DETECTION IN A LARGE COMPOSITE PANEL OF FIVE STIFFENERS USING LAMB WAVE SIGNALS

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ABSTRACT

The propagation characteristics of Lamb waves activated and collected by an active piezoelectric (PZT) sensor network in a CF/EP composite panel of five stiffeners were investigated. In particular, wave attenuation in terms of propagation distance and wave energy loss induced by reinforced stiffeners were evaluated. The interaction between Lamb wave modes and a through-thickness hole of 11.9 mm diameter was subsequently examined. Given the complexity of the captured wave signals, an inverse algorithm based on correlation between wave signals in the benchmark and damaged structures was developed. Different combinations of actuator-sensor paths were used to estimate the location of damage. The diagnostic results demonstrate that the proposed approach has a good capability for defining location of damage using the probability of occurrence of damage.

KEY WORDS

Sensor networks, Composite structures, Lamb waves, Wave attenuation, Damage identification

1 INTRODUCTION

Damage detection techniques based on Lamb wave propagation, using the concept of structural health monitoring (SHM), have been the subject of research since the 1980s [1-3]. In comparison with Lamb waves propagating in isotropic objects, wave propagation in composite structures presents additional complexity for effective damage identification. The inherent material anisotropy and the multi-layered construction lead to the significant dependence of wave modes on laminate layup configurations, direction of wave propagation, frequency, and interface conditions [4]. In addition, complex geometry configurations, e.g. with multiple reinforced stiffeners in structures, will also affect the propagation characteristics of Lamb waves, in particular, wave attenuation and dispersion. These phenomena become more complex with the presence of a defect, which further interferes with wave propagation and complicates received signals. Many forward and inverse algorithms have therefore been developed for effective damage detection with the aid of advanced signal processing and identification approaches [5].

In this study, the propagation characteristics of Lamb waves activated and collected by an active piezoelectric (PZT) sensor network in a CF/EP composite panel of five reinforced stiffeners were investigated. Wave attenuation in terms of propagation distance was evaluated, as well as the influence of reinforced stiffeners. Subsequently the interaction between Lamb wave modes and a through-thickness hole was examined. An inverse algorithm was developed with different combinations of actuator-sensor paths to establish the probability of the occurrence of damage, with the aim of identifying the location of the damage.

2 WAVE CHARACTERISTICS IN A COMPOSITE PANEL OF MULTIPLE STIFFENERS

2.1 Experiment setup

A carbon fiber composite panel of a layup [0°/±45°/90/0]s, was studied experimentally. The panel had five reinforced stiffeners co-cured on the panel surface, a circular hole at the center of the panel, and a certain number of small holes distributed along four boundaries, illustrated in Figure 1(a). 18 PZT discs (PI® PIC151) with the properties shown in Table 1, denoted as S1 to S18, were surface-attached along three lines on the panel surface, shown in Figure 1(b). The dimensions of the structure and the positions of PZT discs are summarized in Table 2. The sensors were classified into three groups, namely line I, line II and line III, which were deployed to investigate the properties of Lamb waves along different propagation routes. In detail, line I (sensors S1 to S6) was used to investigate wave characteristics across the stiffeners and the central hole, line II (sensors S7 to S12) was used to examine the effect of the stiffeners on wave propagation, and line III...
(sensors S13 to S18) provided the baseline information on wave characteristics where Lamb waves propagated in a flat route without stiffeners.

A 5-cycle Hanning-windowed toneburst at a central frequency of 0.3 MHz was actuated by an Agilent® E1441 arbitrary waveform generator and then amplified by a piezo system amplifier (EPA-104) to impose an electric field on S1, S7 and S13 as actuators, respectively, with a peak-to-peak voltage of 45 V. After being conditioned [6], Lamb wave signals in the respective sensor lines were captured by an Agilent® E-1437A digitizer at a sampling frequency of 20.48 MHz.

Table 1. Mechanical properties of piezoelectric discs

<table>
<thead>
<tr>
<th>Geometry (mm)</th>
<th>Diameter: 6.9, Thickness: 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $\rho_p$ (g/cm$^3$)</td>
<td>7.80</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu_p$</td>
<td>0.34</td>
</tr>
<tr>
<td>Charge constant $d_31$ (m/V)</td>
<td>$-210 \times 10^{-12}$</td>
</tr>
<tr>
<td>Charge constant $d_{33}$ (m/V)</td>
<td>$500 \times 10^{-12}$</td>
</tr>
<tr>
<td>Young’s modulus $E_p$ (GPa)</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2. Geometry of composite panel and PZT discs

<table>
<thead>
<tr>
<th>Composite panel</th>
<th>Length: 900 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>560 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>1.6 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stiffener</th>
<th>Thickness</th>
<th>Height</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central hole</td>
<td>2 mm</td>
<td>26 mm</td>
<td>670 mm</td>
</tr>
</tbody>
</table>

| Distance between stiffeners in the Y direction | 80 mm |
| Distance from stiffeners to boundaries B and D | 115 mm |
| Distance from stiffeners to boundaries A and C | 120 mm |

| Distance between PZT discs in the Y direction | 80 mm |
| Distance between sensor lines I and II | 170 mm |
| Distance between sensor lines II and III | 215 mm |

2.2 Characteristics of Lamb wave modes

Wave attenuation, defined as the reduction in signal amplitude with propagation distance, is one of the decisive features in the effectiveness of Lamb wave-based damage identification [7]. The mechanisms causing wave attenuation are mostly wave dispersion/scattering and energy divergence, also known as beam spreading, in which the amplitude of wave signals is inversely proportional to the square root of the distance from the actuator [8, 9].

The first packets of wave signals acquired at different sensors were extracted to compare the wave attenuation under different propagation conditions. Figure 2(a) demonstrates the obvious amplitude decrease of wave signals captured at sensors S14 to S18 when S13 acted as an actuator, when Lamb waves propagated in a flat route (line III).

In comparing the wave signals at S2, S8 and S14 with the same scale when S1, S7 and S13 respectively acted as actuators, more wave attenuation was observed when Lamb waves propagated through the stiffener, shown in Figure 2(b). It is appreciated that the stiffener separated Lamb waves into two parts, i.e. the transmitted waves propagating in the composite panel and the components propagating along the stiffener [10]. The first wave packets in the captured signals at S2 and S8 are therefore the superposition of the transmitted waves and the components reflected from the top of the stiffener with a time delay, which complicates and elongates the waveform, but does not affect the arrival time of the first wave packet, indicated in Figure 2(b). The different bonding conditions of sensors S2 and S8 during installation [11] may also contribute to the discrepancy in the captured waveforms.

A Hilbert transform [9] was applied to calculate the peak amplitudes of wave signals captured by each sensor. After the peak amplitudes of the first wave packets were normalized by the value of the signal captured at S14, the amplitude reductions along different propagation routes are compared in Figure 3. It is noticed that the
peak amplitudes of wave signals at S2 (line I) and S8 (line II) are about 59% and 64% of that at S14 (line III), respectively, after Lamb waves passed through one stiffener. More severe decreases in amplitude were observed when Lamb waves propagated through more stiffeners, and waveforms eventually became barely visible after normalization, especially for line I where the central through-thickness hole lay in the path of wave propagation.

3 DAMAGE DETECTION IN THE COMPOSITE PANEL

3.1 Interaction between Lamb waves and hole damage

A through-thickness hole of 11.9 mm diameter was introduced by drilling between sensors S9 and S15, at a distance of 55 mm from the center of sensor S9 (Figure 1(b)). Wave signals from all combinations of actuators and sensors were collected for both the benchmark and damaged structures, for a comprehensive analysis of the interaction between Lamb waves and the hole damage. Representative signals with and without damage are compared in Figures 4(a)-(d). It is observed that the amplitude of transmitted waves for S9-S15 decreases significantly after the introduction of the hole damage in comparison with the benchmark signals, whereas signals for S8-S14 show only a marginal difference. Similarly, the differences in wave signals for S3-S9 are also significant before and after the introduction of the hole damage, whereas the differences for S2-S8 are negligible.
The analysis described indicates that the damage should be located somewhere close to the path of S3-S15 because of the significant changes in relevant wave signals. Algorithms based on the time-of-flight (ToF) of specific wave modes can be applied subsequently to locate the damage. However, such explicit analyses of damage location are not straightforward in practical application, since the sensor network is initially blind to the existence of damage. The identification of unknown damage from scattered waves, where the damage may be oblique to specific actuator-sensor paths, is known as an inverse problem [12]. In most cases, the useful information in wave signals from individual actuator-sensor paths is vulnerable to contamination by multiple factors, e.g. wave dispersion and reflections from boundaries (including those from stiffeners in this study). As a result, locating the exact ToF of wave components scattered by damage, in particular by minute damage, is generally a matter of rule of thumb for complex signals, with potential for error. Inspired by the dissimilar intensities of signal changes in different actuator-sensor paths, an inverse algorithm based on signal correlation was developed in this study, by means of which the probability of the occurrence of damage in the composite structure could be determined.

### 3.2 Inverse algorithm based on signal correlation

The correlation of linear relationship between two signals can be calibrated by a cross-correlation coefficient, which varies from -1 to 1 for the two extreme conditions of perfect negative and perfect positive correlations, whereas there is no linear relationship if the value is equal to 0 [13]. It is appreciated that in comparison with the benchmark signals, signals from actuator-sensor paths that are close to or lie exactly across the damage (for example, S9-S15) are significantly affected by the presence of damage, whereas signals from actuator-sensor paths that are distant from the damage would remain intact (e.g., S8-S14). As a result, the cross-correlation coefficient between affected and benchmark signals is deemed to be lower than that between unaffected and benchmark signals.

The probability of the occurrence of damage at a certain point in the composite structure can thus be determined by the cross-correlation coefficient, which represents the severity of changes in signals for individual actuator-sensor paths, and the position of the point in relation to these paths [14]. The robustness of damage identification would be significantly improved with the aid of an active sensor network in which multiple sensors are applied to cross-examine the inspected area. Assuming that N paths of actuators-sensors are involved for constructing the probability of the occurrence of damage, the probability of damage \( P(x, y) \) at position \( (x, y) \) can be expressed as [14]

\[
P(x, y) = \frac{\sum (1 - \rho_k) R(x, y, x_{\text{act}}, y_{\text{act}}, x_{\text{sen}}, y_{\text{sen}}) + \beta}{\beta - 1}
\]

where

\[
r(x, y, x_{\text{act}}, y_{\text{act}}, x_{\text{sen}}, y_{\text{sen}}) = \frac{\sqrt{(x-x_{\text{act}})^2 + (y-y_{\text{act}})^2} + \sqrt{(x-x_{\text{sen}})^2 + (y-y_{\text{sen}})^2}}{\sqrt{(x-x_{\text{act}})^2 + (y-y_{\text{act}})^2} + \sqrt{(x-x_{\text{sen}})^2 + (y-y_{\text{sen}})^2}}
\]

is the ratio of the sum of distances from point \((x, y)\) to actuator \((x_{\text{act}}, y_{\text{act}})\) and sensor \((x_{\text{sen}}, y_{\text{sen}})\) to the distance between the corresponding actuator and sensor for the \(k^{th}\) path of actuator-sensor. \(\rho_k\) is the cross-correlation coefficient defined as [14]

\[
\rho_k = \frac{\text{cov}(S_{\text{act}}, S_{\text{sen}})}{\sigma_{\text{act}} \sigma_{\text{sen}}}
\]

where \(S_{\text{act}}\) and \(S_{\text{sen}}\) are signals collected from the damaged and benchmark structures, respectively, for the \(k^{th}\) path of actuator-sensor. \(\text{cov}\) and \(\sigma\) are the corresponding covariance and standard deviation [14]. \(\beta\) is a scaling parameter controlling the area influenced by the \(k^{th}\) path of actuator-sensor, and in this study it was set to 1.07 [14]. Equation (1) indicates that the lower the values of coefficient \(\rho_k\) and ratio \(R\), the higher the probability of damage existing at the point \((x, y)\) of the structure. For data fusion to establish the probability of the occurrence of damage in the inspected area, each actuator-sensor path makes different contributions to a specific point, weighted by the relative distances from the point to all actuator-sensor paths.
Such an algorithm based on correlation requires only two sets of wave signals over a certain period of time, one at the beginning and the other at the end, regardless of any previous structural status. The proposed approach is thus promising for practical application in periodical assessment, where damage identification can be accomplished by comparing the current condition with the continuously updated immediate-past status as the benchmark. On the basis of such a principle, the complexity of structural geometry, such as the central and distributed holes in the composite panel, would not affect the capability of the proposed approach for damage detection, as those influences are implicitly included in the benchmark signals.

4 RESULTS

In the coordinate system shown in Figure 5(a), three combinations of actuator-sensor paths are established as Figures 5(b)-(c), where C1, C2 and C3 represent the interrogation between any two of sensor lines I, II and III, each owning 72 paths, respectively, for damage identification. Diagnostic scenarios were configured accordingly in terms of different combinations of C1, C2 and C3. Following Equation (2), the cross-correlation coefficients between the signals in the benchmark and damaged structures were calculated for each actuator-sensor path indicated in Figures 5(b)-(c). After the inspected area enclosed by the sensor network was meshed by a grid of $1 \times 1$ mm$^2$, the probability of the occurrence of damage at each grid in the area could be estimated based on Equation (1).

The probability of the occurrence of damage in scenario 1 using interrogations of C1 and C2 with 144 actuator-sensor paths is shown in Figure 6(a), where the darkest circle implies the area of greatest probability of damage occurrence, with a threshold of 95%. The location with the maximum value of probability of the occurrence of damage can be recognized as the central location of the damage, which is compared with the actual position of the hole center in Figure 6(a) and Table 3, in a coordinate system where the center of sensor S6 is the origin. Scenario 1 presents a preliminary estimation of the location of the damage. That estimation, however, entails a degree of error, symbolized by the distance between the estimated and actual central locations of the hole.
Figure 6 (b) illustrates the predicted result of scenario 2 using the information of C3 with 72 actuator-sensor paths only, showing a larger error in terms of hole position. In contrast, scenario 3, which appraises all the information of C1, C2 and C3 with 216 actuator-sensor paths in total, demonstrates improved accuracy in identifying the position of the damage, shown in Figure 6(c). In comparison with the diagnostic results of scenarios 1 and 2, it can be appreciated that the more the sensitive actuator-sensor paths (i.e. those are close to or across the damage), the better the accuracy of damage identification. The predicted central locations of the hole from scenarios 2 and 3 are also compared with the actual position of the hole center in Table 3.

![Figure 6(a) - Probability of the occurrence of hole with different combinations of actuator-sensor paths (a) scenario 1; (b) scenario 2; (c) scenario 3](image)

<table>
<thead>
<tr>
<th>Predicted position</th>
<th>Error (Relative distance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>(261 mm, 215 mm) 43.83 mm</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>(189 mm, 189 mm) 62.43 mm</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>(241 mm, 218 mm) 27.20 mm</td>
</tr>
</tbody>
</table>

On the other hand, the proposed algorithm assumes that the points along the \( k \rho \) path of actuator-sensor naturally show a higher probability of the occurrence of damage because these points have the same value of correlation coefficient \( \rho \) but the lowest value of ratio \( R_k \), compared with other points with \( R > 1 \) which are distant from the \( k \rho \) path. As a result, the points where actuators and sensors are located, as the particular points of intersections of relevant actuator-sensor paths, are vulnerable to showing a higher probability of the occurrence of damage in data fusion, probably yielding an incorrect prediction of the position of damage. Such a situation generally occurs when the engaged sensors are allocated within the inspected area, for instance, sensors S7-S12 in scenarios 1 and 3. As observed in Figures 6(a) and (c), the areas coincident with the locations of these sensors also demonstrate local higher probability of the presence of damage. These points should therefore be treated as pseudo-indicators of damage and ignored.

**CONCLUSION**

The propagation characteristics of Lamb waves in a CF/EP composite panel of five reinforced stiffeners were investigated, using an active piezoelectric sensor network. Both wave attenuation in terms of propagation distance and the influence of reinforced stiffeners were studied. Lamb wave scattering caused by the existence of a through-thickness hole was subsequently examined in experiments. An inverse algorithm based on the correlation between wave signals in the benchmark and
damaged structures was developed to estimate the position of the hole. The capacity of different combinations of actuator-sensor paths of the sensor network in identifying the location of the hole was evaluated.

It is concluded that Lamb waves show more complex propagation characteristics in composite structures. The existence of reinforced stiffeners further complicates the properties of Lamb wave modes and significantly suppresses the effective wave propagation distance with extra energy loss. Diagnostic results demonstrate that the proposed inverse approach has good capability for defining the location of damage using the probability of the occurrence of damage, obviating the need to extract local information such as ToF from complex signal segments.

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References