Instantaneous Crack Detection under Changing Operational and Environmental Variations

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ABSTRACT

A new methodology of guided wave based nondestructive testing (NDT) is developed to detect crack damage in a thin metal structure without using prior baseline data or a predetermined decision boundary. In conventional guided wave based techniques, damage is often identified by comparing the “current” data obtained from a potentially damaged condition of a structure with the “past” baseline data collected at the pristine condition of the structure. However, it has been reported that this type of pattern comparison with the baseline data can lead to increased false alarms due to its susceptibility to varying operational and environmental conditions of the structure. To develop a more robust damage diagnosis technique, a new concept of NDT is conceived so that cracks can be detected even when the system being monitored is subjected to changing operational and environmental conditions. The proposed NDT technique utilizes the polarization characteristics of the piezoelectric wafers attached on both sides of the thin metal structure. Crack formation creates Lamb wave mode conversion due to a sudden change in the thickness of the structure. Then, the proposed technique instantly detects the appearance of the crack by extracting this mode conversion from the measured Lamb waves, and the threshold value from damage classification is also obtained only from the current data set. Numerical and experimental results are presented to demonstrate the applicability of the proposed technique to instantaneous crack detection.

Keywords: Lamb Wave, Detection, Nondestructive Testing, Mode Conversion, Piezoelectric Polarization

1. INTRODUCTION

There has been an increasing demand in using Structural Health Monitoring (SHM) and Nondestructive Testing (NDT) techniques for continuous monitoring of aging aircraft, civil infrastructure and mechanical systems that have driven maintenance costs to unprecedented levels. For SHM/NDT, guided waves have received a great deal of attention and have been a topic of considerable interest, because they can propagate over considerable distances with little attenuation. Conventional guided wave studies have focused on schemes where baseline signals are measured so that changes from the baseline can be detected. However, there are significant technical challenges to realizing this pattern comparison. For instance, structural defects typically take place long after the initial baseline are collected, and other operational and environmental variations of the system can produce significant changes in the measured response, masking any potential signal changes due to structural defects.

As an alternative that can overcome the drawbacks of the conventional NDT methods, a new concept of NDT technique, which does not rely on previously obtained baseline data, is proposed for crack detection. In a thin elastic medium such as an aluminum plate, the formation of a crack causes the conversion of the propagation waves to other modes. In this paper, a technique that can isolate this mode conversion is developed using the poling directions of piezoelectric materials such as Lead Zirconate Titanate (PZT). The uniqueness of the proposed crack damage detection technique is that this mode conversion due to a crack is instantly identified without using prior baseline data. By removing the dependency on the prior baseline data, the proposed damage detection system becomes less vulnerable to operational and environmental variations that might occur throughout the life span of the structures being monitored.

This paper is organized as follows. First, the polarization process of piezoelectric materials is briefly described. Then, the effect of a PZT polarization direction on Lamb wave measurement is investigated, and the proposed reference-free

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diagnosis technique is developed based on the PZT poling directions. Furthermore, a thresholding technique is proposed to determine the existence of crack damage even at the presence of variations in PZT size, bonding condition and alignment. Finally, experimental tests as well as numerical simulations are executed to investigate the applicability of the proposed NDT technique to crack detection.

2. THEORETICAL DEVELOPMENT

2.1 Piezoelectric material and its polarization characteristics

Piezoelectric materials are natural or artificially polarized ceramics which have piezoelectricity [1]. These materials develop an electrical charge or voltage when a mechanical pressure is applied, which is the simplest description of piezoelectricity. Conversely, piezoelectric materials produce deformation (strain) when exposed to an applied electric field. Due to this unique nature of the piezoelectric materials, they are commonly used as both sensors and actuators in many applications [2]. For instance, wafer-type piezoelectric materials such as PZT are commonly used for exciting and measuring guided waves for SHM and NDT applications [3]. In some natural ceramic materials such as quartz, crystal cells, which behave similarly to electric dipoles, are oriented along the crystal axes. However, artificially polarized materials should be poled to have piezoelectricity due to the random orientation of the dipoles at the initial state [1]. In order to force piezoelectricity to the materials, a thermal treatment is commonly utilized. In the first stage, a crystalline material with randomly oriented dipoles is slightly warmed up below its Curie temperature [Fig. 1 (a)]. After strong electric field $E$ is applied to the crystalline material, the dipoles in the material align along the field lines [Fig. 1 (b)]. Finally, the material is cooled down, and the electric field is removed [Fig. 1 (c)]. The polarization of the material is permanently maintained as long as the poled material stays below its Curie temperature. The overall behavior of a piezoelectric material as well as its electrical characteristics is governed by the poling direction of the material [2]. In the next section, the influence of the poling direction on Lamb waves is discussed.

![Fig. 1. A poling process of an artificially polarized material [1]](image)

2.2 The effect of PZT poling directionality on Lamb wave propagation

In this section, it is investigated how the phase of a Lamb wave mode changes depending on (1) the poling directions of exciting and sensing PZT wafer transducers and (2) whether a wafer transducer is attached either on the top or bottom surface of a plate. For illustration, it is assumed four identical PZT wafer transducers, labeled as “A”, “B”, “C,” and “D”, are attached to a plate as shown in Fig. 2 (a). The arrows indicate positive poling directions of PZT transducers. PZTs A and D are placed exactly at the same position but on the other side of the plate. PZTs B and C are positioned in a similar fashion. Furthermore, it is assumed that a narrow-band tone burst is applied as an input signal, and the driving frequency is chosen such that only the fundamental symmetric ($S_0$) and anti-symmetric ($A_0$) modes are generated. In this paper, the term of “positive bending” is used when the positively polarized side of the PZT is subjected to tensile strain. On the other hand, the PZT is subjected to negative bending when the negatively polarized side of the PZT is subjected to tensile strain. The positive bending produces a “positive” output voltage while the negative bending results in a “negative” output voltage value.

When PZT A is excited, the $S_0$ and $A_0$ modes are generated and measured at PZTs B and C [4]. In an ideal condition, the amplitude and arrival time of the $S_0$ mode measured at PZTs B and C should be identical. In addition, both PZTs B and C should be subjected to positive bending because of the symmetric nature of the $S_0$ mode (See the figure on the left hand side of Fig. 2 (b)). Because both PZTs B and C are subject to the positive bending, the phase of the $S_0$ mode
measured at these PZTs are identical as well as the amplitude and arrival time (See the \( S_0 \) mode in Fig. 4 (a)). As far as the \( A_0 \) mode is concerned, PZT B is subjected to the negative bending although PZT C still undergoes the positive bending (See the figure on the right in Fig. 2 (b)). Therefore, the \( A_0 \) modes measured at PZTs B and C are out-of-phase (See the \( A_0 \) mode in Fig. 4 (a)). However, when the poling direction of the PZT C is switched [Fig. 3 (a)], PZTs B and C will produce out-of-phase \( S_0 \) modes and in-phase \( A_0 \) modes [Fig. 3 (b) and Fig. 4 (b)].

This idea of using the PZT poling directionality in Lamb wave propagation is not a completely new idea. However, the majority of the past work has focused on selective generation of \( S_0 \) and \( A_0 \) modes [5]. For instance, by exciting PZTs A and D shown in Fig. 2 (a) in-phase, only the \( S_0 \) mode can be excited. In this study, the polarization characteristic of the PZT is utilized not only for selective generations of Lamb wave modes but also for selective measurements.

Sign notations for \( S_0 \) and \( A_0 \) modes are graphically defined in Fig. 5. As shown in Fig. 5 (a), \( S_0 \) and \( A_0 \) modes are defined to be positive when they cause the shape of the specimen’s top surface to be convex. On the other hand, \( S_0 \) and \( A_0 \) modes are called negative when the deformed shape of the top surface becomes concave. For example, positive \( S_0 \) and \( A_0 \) modes are generated when PZT A in Fig. 2 (a) is excited. On the other hand, PZT D in Fig. 2 (a) generates positive \( S_0 \) and negative \( A_0 \) modes. When the \( S_0 \) and \( A_0 \) modes arrive at a sensing PZT, the sign of an output voltage will depend on the poling direction of the sensing PZT. In Fig. 4 (a) and (b), it is shown that signal AC becomes out-of-phase due to the poling direction change of the sensing PZT. In the following section, this idea of using PZT poling directionality is further advanced so that the mode conversion due to crack formation can be extracted from the measured Lamb wave signals.

![Diagram](image1.png)

(a) Test configuration I with colocated PZTs with the opposite poling directions
(b) The \( S_0 \) mode produces the same bending for PZTs B and C while the \( A_0 \) mode results in the opposite bending.

Fig. 2. The effect of the PZT poling directions on the phases of the \( S_0 \) and \( A_0 \) modes (Configuration I)

![Diagram](image2.png)

(a) Test configuration II with all PZTs with the same poling directions
(b) The \( S_0 \) mode produces the opposite bending for PZTs B and C while the \( A_0 \) mode results in the same bending.

Fig. 3. The effect of the PZT poling directions on the phases of the \( S_0 \) and \( A_0 \) modes (Configuration II)

![Diagram](image3.png)

(a) \( S_0 \) and \( A_0 \) modes measured from configuration I in Fig. 2 (a): \( S_0 \) modes in-phase & \( A_0 \) modes out-of-phase
(b) \( S_0 \) and \( A_0 \) modes measured from configuration II in Fig. 3 (a): \( S_0 \) modes out-of-phase & \( A_0 \) modes in-phase

Fig. 4. A schematic comparison of the \( S_0 \) and \( A_0 \) modes measured from Configurations I and II shown in Fig. 2 (a) and Fig. 3 (a), respectively: AB (a dash line) and AC (a solid line) denote the response signals measured at PZTs B and C when a tone burst input is applied at PZT A.
2.3 Detection of crack induced mode conversion using a PZT poling direction

In this subsection, the PZT polarization characteristic is further advanced so that the mode conversion due to crack formation can be detected without using any prior baseline data. First, the effect of a crack on Lamb wave modes is described. If Lamb waves propagating along a thin plate encounter a discontinuity, some portion of the waves are reflected at the discontinuity point and others are transmitted through it. When a S0 mode arrives at the notch as shown in Fig. 6, it is separated into S0 and A0 modes (denoted as S0/S0 and A0/S0, respectively). In a similar manner, an A0 mode is also divided into S0 and A0 modes (S0/A0 and A0/A0). This phenomenon is called mode conversion [6].

In Fig. 7, it is shown how the signs of Lamb wave modes change as they transmit through a crack. From numerical simulations and experiments, it has been shown that the sign of a single (non-converted) mode is not affected by crack formation. That is, a positive S0 mode always produces a positive S0/S0 mode, and a negative A0 mode generates a negative A0/A0 mode, respectively. On the other hand, the sign of newly generated modes (A0/S0 and S0/A0) can be altered depending on the characteristics of a discontinuity that the launching Lamb mode is passing through. Although the sign of these converted modes cannot be determined undoubtedly, certain relationships among these converted modes can be revealed. For instance, if a positive S0 mode creates a positive A0/S0 mode, a positive A0 mode also produces a positive S0/A0 mode. That is, the signs of the A0/S0 and S0/A0 modes should be always identical. This is based on the reciprocity of signals AB and BA. Here, signal AB denotes the response signal measured at PZT B when the excitation is applied at PZT A. In order for signals AB and BA to be identical, the shape, amplitude and phase of the A0/S0 mode in signal AB should be identical to those of the S0/A0 mode in signal BA. In addition, the sign of the A0/S0 mode created from a positive S0 mode should be always opposite to that of the A0/S0 mode generated from a negative S0 mode.

In Fig. 8, the process of mode conversion is illustrated including the predefined sign concept of Lamb wave mode change. When the plate is in a pristine condition and four identical PZTs are instrumented as shown in Fig. 8 (a), it can be shown that signal AB becomes identical to signal CD [Fig. 8 (b)]. For instance, PZT A generates positive S0 and A0 modes and PZT C creates a negative S0 mode and a positive A0 mode [Fig. 5, Fig. 8 (b)]. Even though PZT B and PZT D experience opposite bending due to difference in S0 modes, both PZTs will produce identical responses because their poling directions are opposite. Similarly, responses due to A0 modes measured at both PZTs will be identical. However, signal AB is no longer identical to signal CD when there is a crack between PZTs A and B (or PZTs C and D) [Fig. 8 (c) and (d)]. As for signal AB, the S0/A0 mode arrives at PZT B earlier than the A0/S0 mode when the notch is located closer to PZT A than PZT B (assuming that the S0 mode travels faster than the A0 mode). Therefore, a S0 mode is followed by S0/A0, A0/S0, and A0 modes in signal AB. Based on the sign concept in Fig. 7, both S0/A0 and A0/S0 modes are positive so that the signs of all modes are the same in signal AB. On the other hand, a S0 mode is followed by A0/S0, S0/A0, and A0 modes in signal CD because the S0/A0 mode arrives at PZT D later than the A0/S0 mode. In this case, a negative A0/S0 mode and a positive S0/A0 mode are created because of a negative S0 mode and a positive A0 mode, respectively [Fig. 7]. Note that signal CD has two S0 modes, S0/A0 and S0/S0, and their signs are opposite. Also, two A0 modes in signal CD, A0/S0 and A0, have opposite signs as well. In Fig. 8 (d), signals AB and CD are drawn considering not only the arrival time of each mode but also the poling directions of the PZTs.

Note that, while the S0 and A0 modes in Fig. 8 (d) are in-phase, the S0/A0 and A0/S0 modes in signals AB and CD are fully out-of-phase. Therefore, the additional modes generated by a notch can be extracted simply by subtracting the signal AB from the signal CD as shown in Fig. 8 (d). Because this approach relies only on comparison of two signals obtained at the current state of the system rather than comparison with previously recorded reference data, it is expected that this approach reduce false alarms of defect due to changing operational and environmental variations of the system.
Fig. 6. A schematic diagram of mode conversion and reflection due to a discontinuity on a plate

(a) Mode conversion of a positive $S_0$ mode

(b) Mode conversion of a positive $A_0$ mode

(c) Mode conversion of a negative $S_0$ mode

(d) Mode conversion of a negative $A_0$ mode

Fig. 7. The mode conversion process of $S_0$ and $A_0$ modes due to crack formation

(a) An intact plate with the PZT configuration II shown in Fig. 3 (a)

(b) Comparison of signals AB and CD without a notch: the $S_0$ & $A_0$ modes are identical

(c) A damaged plate with the PZT configuration II shown in Fig. 3 (a)

(d) Comparison of signals AB and CD with a notch: the $S_0$ & $A_0$ modes are identical, but the $S_0/A_0$ & $A_0/S_0$ modes are out-of-phase

Fig. 8. Extraction of the additional Lamb wave modes generated by a notch using the poling directionality of the PZT transducers
($A_0/S_0$ mode denotes an $A_0$ mode converted from a $S_0$ mode when it passes through a crack. $S_0/A_0$ is defined similarly.)
3. NUMERICAL SIMULATION

The idea of using a PZT poling direction for crack detection was first validated by numerical simulation. Using COMSOL Multiphysics software (www.comsol.com), Lamb wave propagation in a two dimensional aluminum beam was simulated using the combination of plain strain, piezo plain strain, and electrostatics modules in COMSOL software. The length of the beam was 70 cm, and its thickness was 6 mm. Four identical PZTs with a size of 10 mm × 10 mm × 0.508 mm were attached to the beam model as shown in Fig. 9. Note that PZTs A and D were collocated but on the other side of the beam with the same poling direction. PZTs B and C were placed in a similar fashion. The parameter values used in the numerical simulation are listed in Table 1. A narrowband tone-burst signal at 150 kHz frequency was used as an input signal. In the simulation, Rayleigh damping coefficients were set to $10^{-4}$ for a mass damping coefficient and 0 for a stiffness damping coefficient, respectively. The simulation results were obtained from a time dependent solver, and a time step was set to 0.25 μs, which is equivalent to 4 M samples/sec. To control the error in each integration step, relative tolerance and absolute tolerance for the solution were chosen to be $10^{-3}$ and $10^{-10}$, respectively. The maximum backward differentiation formula (BDF) order for setting the degree of the interpolating polynomials in the time-stepping method was set to order 2. Finally, the model was meshed using a mapped mesh option, and the size of each mesh was limited to 1 mm × 1 mm [8].

Fig. 10 illustrates that signals AB and CD were almost identical and this well corresponds to the theoretical expectation. Once a notch of 3 mm depth and 1 mm width was introduced 100 mm away from PZT D toward PZT C, the signal AB became different from the signal CD as a result of the mode conversion induced by the crack [Fig. 11 (a)]. The mode conversion due to cracking was extracted simply by subtracting the signal CD from the signal AB [Fig. 11 (b)]. This numerical simulation is further substantiated in the following experimental study.

![Fig. 9. Dimension of an aluminum plate used in numerical simulation](image)

![Fig. 10. Simulated Lamb wave signals without notch](image)

**Table 1. Parameters used in numerical simulation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exciting frequency</td>
<td>150 kHz</td>
</tr>
<tr>
<td>$\alpha$ (Mass damping coeff.)</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$\beta$ (Stiffness damping coeff.)</td>
<td>0</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>4 Ms/s</td>
</tr>
<tr>
<td>Relative tolerance</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Absolute tolerance</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Maximum BDF order</td>
<td>2</td>
</tr>
<tr>
<td>Mesh size (mapped mesh)</td>
<td>1 mm × 1 mm max</td>
</tr>
</tbody>
</table>

(a) Signals AB and CD without a notch

(b) Difference between signals AB and CD
4. EXPERIMENTAL RESULTS

4.1 Description of experimental setup

To further examine the proposed reference-free NDT technique, experimental tests have been conducted on an aluminum plate. The overall test configuration of the experiment and the test specimen are shown in Fig. 12. The data acquisition system was composed of an arbitrary waveform generator (AWG), a high-speed signal digitizer (DIG), a low noise preamplifier (LNP) and a multiplexer. The dimension of the plate was 122 cm × 122 cm × 0.6 cm, and four PSI-5A4E type PZT wafer transducers (1.0 cm × 1.0 cm × 0.0508 cm) were mounted in the middle of the plate. PZTs A and D were collocated and attached on the other side of the plate, and PZTs B and C were mounted in a similar fashion. The PZTs were attached so that their poling directions were identical to the configuration shown in Fig. 3 (a). PZTs A and B (or PZTs C and D) were 0.52 m apart each other. In this experiment, the PZT transducers were attached to either the top or the bottom surface of the plate with commercial cyanoacrylate adhesive.

Using the 14-bit AWG, a tone-burst signal with a ±10 peak-to-peak voltage and a driving frequency of 150 kHz was generated and applied. First, PZT A in Fig. 12 (b) was excited by this input waveform. Then, PZT A generated elastic waves and the response was measured at PZT B. When the waves arrived at PZT B, the voltage output from PZT B was amplified by the LNP with a gain of twenty and measured by the DIG. The sampling rate and resolution of the DIG were 20 MS/sec and 16 bits, respectively. In order to increase signal-to-noise ratio, the forwarding signals were measured twenty times and averaged. After the forwarding signal from PZT A to PZT B (signal AB) was measured, the same process was repeated by exciting PZT C and measuring response at PZT D (signal CD). The entire experimental process without averaging signals took less than 15 Seconds. Detailed test results are described in 4.2.
4.2 Crack detection without relying on baseline data

From the numerical simulation described in Section 3, it is shown that signals AB and CD are indistinguishable when there is no crack [Fig. 10]. This is based on the assumption that all PZT transducers are identical and PZTs A and D or (PZTs B and C) are perfectly collocated. In practice, these assumptions cannot be fully satisfied because of variations in PZT size, alignment and bonding condition [7]. In Fig. 13 (a), Lamb wave signals experimentally obtained from the pristine condition of the specimen described in Section 4.1 are shown. As expected, differences between signals AB and CD were observed even in the absence of crack due to imperfections in PZT alignment, size and bonding condition [Fig. 13 (b)]. These initial differences in the absence of the crack are called residual differences hereafter.

Next, a 3 mm (depth) × 1 mm (width) × 60 mm (length) notch was introduced between PZTs A and B (or PZTs C and D). The notch was located 150 mm away from PZT A toward PZT B. As a consequence, two additional modes due to mode conversion appeared between the existing S0 and A0 modes as shown in Fig. 14 (a). Comparison of Fig. 13 (b) and Fig. 14 (b) clearly demonstrates the appearance of additional modes due to crack formation.

As mentioned previously, imperfection in PZTs may generate residual differences and lead to positive false alarms. A damage detection scheme is developed here based on the premise that mode conversion produces signal differences between signals AB and CD that is bigger than the residual differences due to PZT imperfection. The proposed technique takes advantage of not only signals AB and CD but also signals AC and BD to extract mode conversion in the presence of variations of the PZT size, alignment and bonding. In Fig. 15 (a), these four signals are schematically shown emphasizing the relative phase of individual Lamb mode among these signals. Fig. 15 (a) is drawn based on the sign definition presented in 2.3 assuming a notch is closer to PZT A.

From Fig. 15 (a) and (b), it can be shown that signal AB is a simple superposition of signals S0, MC1, MC2 and A0 in Fig. 15 (b). On the other hand, the S0 and MC1 modes in signal AC are out-of-phase compared to these modes in signal AB. Therefore, signal AC can be obtained by flipping signals S0 and MC1 and summing up signals S0, MC1, MC2 and A0 all together. Signals BD and CD are related to signals S0, MC1, MC2 and A0 in the similar manners. The relationship between the signals that can be measured (signals AB, AC, BD and CD) and the individual Lamb modes (S0, MC1, MC2 and A0) are shown below:

\[
\begin{bmatrix}
\text{Signal AB} \\ 
\text{Signal AC} \\ 
\text{Signal BD} \\ 
\text{Signal CD}
\end{bmatrix} = \begin{bmatrix}
1 & 1 & 1 \\
-1 & -1 & 1 \\
-1 & 1 & -1 \\
1 & -1 & -1 \\
\end{bmatrix}
\begin{bmatrix}
\text{Signal } S_0 \\ 
\text{Signal } MC_1 \\ 
\text{Signal } MC_2 \\ 
\text{Signal } A_0
\end{bmatrix}
\]  

(1)

where signal S0 indicates a time signal that contains only the S0 mode but whose length is identical to that of signal AB, AC, BD or CD. Signal MC1, signal MC2 and signal A0 are denoted in a similar fashion. MC1 and MC2 represent the first and second arrivals of Lamb wave modes created by mode conversion, respectively. Note that MC1 and MC2 can represent either S0/A0 or A0/S0 depending on the relative position of crack and the actuating and sensing PZTs used for the signal measurement. For instance, MC1 denotes a S0/A0 mode in signal AB when a notch is closer to PZT A than PZT B. This is because the S0/A0 mode arrives at PZT B earlier than the A0/S0 mode. Similarly, signal MC1 in signal BD represents an A0/S0 mode. While Eq. (1) shows how different combinations of individual Lamb modes constitute each measurable signals, Eq. (2) below shows how each individual mode can be extracted from signals AB, AC, BD and CD. For instance, signal S0 can be obtained by adding signals AB and CD and subtracting signals AC and BD. Similarly, signal MC1 is isolated by adding signals AB and BD and subtracting signals AC and CD. In practice, there will be some measurement errors in the measured signals AB, AC, BD and CD, and each decomposed Lamb mode signal will be also expressed as a superposition of the exact mode with error signals.

\[
\begin{bmatrix}
\text{Signal } S_0 \\ 
\text{Signal } MC_1 \\ 
\text{Signal } MC_2 \\ 
\text{Signal } A_0
\end{bmatrix} + \begin{bmatrix}
e_{AB} \\ 
e_{MC1} \\ 
e_{MC2} \\ 
e_{A0}
\end{bmatrix} = \begin{bmatrix}
1 & -1 & -1 & 1 \\
1 & -1 & 1 & -1 \\
4 & 1 & 1 & -1 \\
1 & 1 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
\text{Signal } AB + e_{AB} \\ 
\text{Signal } AC + e_{AC} \\ 
\text{Signal } BD + e_{BD} \\ 
\text{Signal } CD + e_{CD}
\end{bmatrix}
\]  

(2)

where eAB is an error signal in the measured signal AB that is superimposed to the exact signal AB, and eAC, eBD, and eCD are defined similarly. eS, eMC1, eMC2 and eA0 represent error signals in each decomposed Lamb mode signal. From Eq. (2),
the relationship between the measurement errors (\(e_{AB}, e_{AC}, e_{BD}\) and \(e_{CD}\)) and the estimation errors in the individual Lamb modes (\(e_S, e_{MC1}, e_{MC2}\) and \(e_A\)) can be obtained as follows:

\[
\begin{bmatrix}
    e_S \\
    e_{MC1} \\
    e_{MC2} \\
    e_A
\end{bmatrix} =
\begin{bmatrix}
    1 & -1 & -1 & 1 \\
    1 & 1 & 1 & 1 \\
    1 & 1 & 1 & 1 \\
    4 & 1 & 1 & -1
\end{bmatrix}
\begin{bmatrix}
    e_{AB} \\
    e_{AC} \\
    e_{BD} \\
    e_{CD}
\end{bmatrix}
\]

(3)

According to Eq. (2), the measured signals can be separated into individual Lamb mode signals, signals \(S_0, MC_1, MC_2\) and \(A_0\). Note that only signals \(MC_1\) and \(MC_2\) contain responses created by damage. The damage identification scheme proposed in this paper starts from the decomposition process of measured signals. Next, the error signals \(e_S\) and \(e_A\) due to measurement errors in signals \(S_0\) and \(A_0\) are estimated. After the threshold values for damage classification are determined from \(e_S\) and \(e_A\), the existence of damage is determined by comparing the magnitudes of signals \(MC_1\) and \(MC_2\) with the threshold values. If the responses beyond the threshold values are found, it is concluded that the mode conversion is detected.

1) Decomposition of signals \(S, MC_1, MC_2\) and \(A\)

First, each Lamb mode signals are estimated from signals \(AB, AC, BD\) and \(CD\) obtained from the unknown condition of the specimen. Fig. 16 displays individual Lamb mode signals decomposed using Eq. (2). At this step, it is assumed that it is unknown whether damage exists or not, but, if it does, it is located closer to PZT A. In Fig. 16 (a), the estimated signal \(S_0\) is shown as a superposition of the exact signal \(S_0\) and the error signal, \(e_S\). Similarly, signal \(A_0\) shown in Fig. 16 (b) illustrates that the error signal \(e_A\) is superimposed to the exact signal \(A_0\). Signals \(MC_1\) and \(MC_2\) are also drawn Fig. 16 (c) and (d). Ideally, signals \(MC_1\) and \(MC_2\) are to be zero signals in the absence of damage. However, due to sensor imperfection, additional modes appeared in signals \(MC_1\) and \(MC_2\). Because the existence of damage is assumed to be unknown, these additional modes in signals \(MC_1\) and \(MC_2\) are regarded as responses induced by damage.

2) Estimation of error signals

Next, the error signals \(e_S\) and \(e_A\) are estimated. The estimated signal \(S_0\) is composed of the exact signal \(S_0\) and \(e_S\). Furthermore, it can be shown that a certain part of the estimated signal \(S_0\) contains only \(e_S\). Therefore, \(e_S\) is estimated from a portion of the estimated signal \(S_0\) where the \(S_0\) mode does not exist. To accomplish this, the estimated signal \(S_0\) is divided into two regions, \(S_0\) and \(A_0\) regions, as shown in Fig. 16 (a). Here, the boundary between two regions lies exactly in the middle of the \(S_0\) and \(A_0\) modes. Because the \(S_0\) mode always exists in the \(S_0\) region, the response in the \(A_0\) region is attributed only to \(e_S\). Therefore, the maximum magnitude of \(e_S\) is estimated from the \(A_0\) region as shown in Fig. 16 (a). In a similar manner, the maximum magnitudes of \(e_A\) is estimated from the \(S_0\) region of the estimated signals \(A_0\) as depicted in Fig. 16 (b).

3) Damage diagnosis

From the estimated maximum and minimum values of \(e_S\) and \(e_A\), the upper and lower threshold values for damage diagnosis are established as shown in Fig. 17 (a). It is assumed that, if the magnitudes of \(MC_1\) and \(MC_2\) modes exceed the maximum level of \(e_S\) and \(e_A\), the mode conversion beyond the measured noise is induced by the notch. Note that these threshold values for damage classification are strictly obtained from signals \(AB, AC, BD\) and \(CD\) of the system's current state. That is, the dependence on the prior baseline data is relaxed during both feature extraction and damage diagnosis. In Fig. 17 (a), the proposed diagnosis scheme is applied to the signals obtained from the pristine condition of the specimen. Fig. 17 (a) illustrates that both \(MC_1\) and \(MC_2\) modes in the \(S_0\) and \(A_0\) regions did not exceed the threshold values determined from \(e_S\) and \(e_A\). Therefore, it can be concluded that no mode conversion beyond measurement error is detected for the undamaged condition.

Next, the proposed scheme was applied to the signals measured from the 3 mm notch case. Four decomposed signals using Eq. (2) are drawn in Fig. 16 along with the signals obtained from undamaged case for comparison. Fig. 16 (a) and (b) show that the occurrence of damage changed signals \(S_0\) and \(A_0\) very little. Furthermore, it is revealed that the magnitude and shape of \(e_S\) and \(e_A\) did not change much because they are not related to mode conversion. On the other hand, the appearance of mode conversion is clearly observed in signals \(MC_1\) and \(MC_2\) [Fig. 16 (c) and (d)]. After threshold values are determined from \(e_S, e_{MC1}, e_{MC2}\) and \(e_A\), it is tested whether the \(MC_1\) mode in the \(S_0\) region of signal...
MC₁ and the MC₂ mode in the A₀ region of signal MC₂ exceed the thresholds. Fig. 17 (b) shows that both MC₁ and MC₂ modes in signals MC₁ and MC₂ exceeded the threshold values determined from the damaged condition of the structure.

4) Damage localization

Now, the notch location can be estimated by measuring the arrival time of the MC₁ mode in signal MC₁. From the S₀ and A₀ modes in Fig. 16, the velocities of the S₀ (V₅) and A₀ modes (V₆) were estimated to be 5.113 m/ms and 3.090 m/ms (theoretically, V₅ = 5.088 m/ms and V₆ = 3.055 m/ms), respectively. Because the location of the notch was assumed to be closer to PZT A than PZT B, the distance from A to the notch can be estimated using Eq. (4).

\[
\text{The arrival time of the MC₁ mode} = \frac{s}{V_a} + \frac{\text{Distance between PZT A and PZT B} - s}{V_s} 
\]

where \( s \) denotes the distance of the notch from PZT A. From the estimated arrival time of the MC₁ mode (0.1206 ms) and Eq. (4), \( s \) is estimated to be 14.76 cm. This estimated distance was close to the actual distance (15 cm from PZT A, 1.6 % difference).

5) When a notch is closer to PZT B than PZT A

So far, it has been assumed that a notch is located closer to PZT A than PZT B if it exists. In reality, the location of the notch is unknown in advance. When the notch is formed closer to PZT B, it can be shown that (1) the estimated signals S₀ and A₀ are not affected by the location of the notch, but (2) the MC₁ and MC₂ modes in signals MC₁ and MC₂ are switched. That is, the MC₂ mode appears in the estimated signal MC₁ instead of the estimated signal MC₂. (Note that the definition of the MC₂ mode is the second arrival of the converted mode, and it appears in the A₀ region of signal MC₁.)

From these observations, it is found that Eq. (2) can be used regardless of the location of the notch. In fact, it can be used to decide whether the notch is closer to PZT A or B. For example, if a mode found in signal MC₁ is located in the S₀ region, the notch is located closer to PZT A. Conversely, if the mode is found in the A₀ region of signal MC₁ instead of the S₀ region, it confirms that the notch is closer to PZT B. Therefore, once the existence of the mode conversion is determined, the location of the defect can be also determined by checking the location of the mode in signal MC₁.

In this subsection, it is shown that the existence and the location of a notch can be determined from instantly measured signals without relying on baseline data. The application of the proposed technique to other types of damage such as corrosion is now being investigated.
(a) Signals AB and CD with a 3 mm notch

(b) Difference between signals AB and CD

Fig. 14. Comparison of signals AB and CD with a 3 mm depth notch

(a) Diagram of Lamb wave signals (Notch closer to PZT A)

(b) Decomposed signals using Eq. (2)

Fig. 15. Diagram of Lamb wave signals and decomposed signals (When a notch is closer to PZT A)

(a) Decomposed signal $S_0$

(b) Decomposed signal $A_0$

(c) Decomposed signal $MC_1$

(d) Decomposed signal $MC_2$

Fig. 16. Decomposed Lamb wave signals from experimental data using Eq. (2)
Fig. 17. Damage identification using the proposed threshold technique

5. CONCLUSION

A new concept of nondestructive testing is developed in this study so that crack in a thin metal structure can be instantaneously detected without referencing to previously stored baseline data. This reference-free technique for crack detection is developed based on the Lamb wave theory and PZT polarization characteristics. Crack formation in a thin plate converts Lamb waves reflected and refracted from the crack to other modes. The appearance of this mode conversion is extracted by strategically placed PZT wafer transducers considering the poling directions of individual PZTs. Numerical simulations and experimental tests conducted in this study substantiate the effectiveness of the proposed reference-free technique for crack detection. In this subsection, it is shown that the existence and the location of a crack can be determined from instantly measured signals without relying on baseline data. Because this reference-free technique does not rely on previously obtained baseline data for crack detection, it is expected that this approach minimize false alarms of damage due to changing operational and environmental variations experienced by in-service structures. This robustness of the proposed technique against undesirable variations in the system, such as temperature and external loading, makes it attractive for onboard monitoring. Further investigation is underway to extend the proposed concept to more complex structures and corrosion detection.

6. ACKNOWLEDGEMENT

This work was supported by the National Science Foundation under grants CMS-0529208, the Pennsylvania Infrastructure Technology Alliance (PITA), a partnership of Carnegie Mellon University, Lehigh University and the Commonwealth of Pennsylvania Department of Community and Economic Development, and Smart Infra-Structure Technology Center (SISTeC) at Korea Advanced Institute of Science and Technology.

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