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Instantaneous reference-free crack detection based on polarization characteristics of piezoelectric materials

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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 dataset. Numerical and experimental results are presented to demonstrate the applicability of the proposed technique to instantaneous crack detection.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

There has been 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 is 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 [1].

As an alternative that can overcome the drawbacks of conventional NDT methods, a new NDT technique concept, which does not rely on previously obtained baseline data,



(a) A crystalline material is heated (b) The applied electric field aligns (c) The polarization is permanently the dipoles along the field lines maintained after cooling

Figure 1. The poling process of an artificially polarized material (adapted from [5]).



(a) Test configuration I with collocated PZTs with the opposite poling directions
 (b) The S₀ mode produces the same bending for PZTs B and C while the A₀ mode results in the opposite bending.

Figure 2. The effect of the PZT poling directions on the phases of the S₀ and A₀ modes (configuration I).

is proposed for crack detection. In a thin elastic medium such as an aluminum plate with a uniform thickness, the formation of a crack causes the conversion of the propagating 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 dependence 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. Another reference-free concept based on time reversal acoustics is also investigated by the authors [2–4].

This paper is organized as follows. First, the polarization process of piezoelectric materials is briefly described. Then, the effect of the PZT polarization direction on Lamb wave generation and measurement is investigated, and the proposed reference-free diagnosis technique is developed based on the PZT poling directions. Furthermore, a thresholding technique is proposed to determine the existence of crack damage even in 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 [5]. 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 piezoelectric materials, they are commonly used as both sensors and actuators in many applications [6]. For instance, wafer-type piezoelectric materials such as PZT are commonly used for exciting and measuring guided waves for SHM and NDT applications [7]. 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 [5]. In order to introduce piezoelectricity into the materials, a thermal treatment is commonly utilized. In the first stage, a crystalline material with randomly oriented dipoles is warmed up slightly below its Curie temperature (figure 1(a)). After a strong electric field E is applied to the crystalline material, the dipoles in the material align along the field lines (figure 1(b)). Finally, the material is cooled down and the electric field is removed (figure 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 [6]. In the next subsection, the influence of the poling direction on Lamb waves is discussed.

2.2. The effect of PZT poling directionality on Lamb wave propagation

In this subsection, 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 figure 2(a). The arrows indicate positive



(a) Test configuration II with all PZTs with the same (b) The S_0 mode produces the opposite bending for PZTs poling directions



B and C while the A₀ mode results in the same bending.





figure 2 (a): S₀ modes in-phase & A₀ modes out-ofphase

(a) S_0 and A_0 modes measured from configuration I in (b) S_0 and A_0 modes measured from configuration II in figure 3 (a): S₀ modes out-of-phase & A₀ modes in-

Figure 4. A schematic comparison of the S_0 and A_0 modes measured from configurations I and II shown in figures 2(a) and 3(a), respectively: AB (a dashed line) and AC (a solid line) denote the response signals measured at PZTs B and C when a toneburst input is applied at PZT A.

phase

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 narrowband toneburst signal is applied as an input and the driving frequency is chosen such that only the fundamental symmetric (S_0) and antisymmetric (A_0) modes are generated. In this paper, the term '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 [8]. In an ideal condition, the amplitude and arrival time of the S₀ modes measured at PZTs B and C should be identical. In addition, both PZTs B and C would be subjected to positive bending because of the symmetric nature of the S₀ mode (see the figure on the left-hand side of figure 2(b)). Because both PZTs B and C are subject to positive bending, the phase as well as the amplitude and arrival time of the S₀ mode measured at these PZTs are identical (see the S_0 mode in figure 4(a)). As far as the A₀ mode is concerned, PZT C is subjected to negative bending although PZT B still undergoes positive bending (see the figure on the right in figure 2(b)). Therefore, the A₀ modes measured at PZTs B and C are out-of-phase (see the A₀ mode in figure 4(a)). However, when the poling direction of PZT C is switched (figure 3(a)), PZTs B and C will produce out-of-phase S_0 modes and in-phase A_0 modes (figures 3(b) and 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 [9–12]. For instance, by exciting PZTs A and D shown in figure 2(a) in-phase, only the S₀ mode can



Figure 5. A schematic diagram of mode conversion and reflection due to a discontinuity on a plate.

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. In the following subsection, 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.

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 with a uniform thickness encounter a discontinuity such as a sudden thickness variation of the plate, some portion of the waves are reflected at the discontinuity point and others are transmitted through it. When a S_0 mode arrives at the discontinuity as shown in figure 5, the transmitted wave is separated into S₀ and A₀ modes (denoted as S_0/S_0 and A_0/S_0 , respectively). In a similar manner, an A_0 mode is also divided into S_0 and A_0 modes (S_0/A_0 and A_0/A_0). Similarly, the reflected waves are split into S_0 and A_0 modes. This phenomenon is called mode conversion [13]. This





Figure 7. Relative phase information of the S_0 and A_0 modes during the mode conversion process due to crack formation.

mode conversion has been investigated by many researchers to determine the amplitudes of displacement fields in the case of crack formation using a modal decomposition method as well as a boundary element method (BEM) [14, 15]. In this study, instead of focusing on the amplitude of each mode in displacement fields, the sign changes of Lamb wave modes are closely investigated.

In order to fully investigate the sign changes of Lamb wave modes due to mode conversion, sign notations are defined first. In figure 6, sign notations for the S_0 and A_0 modes are defined schematically. As shown in figure 6(a), the S₀ and A₀ modes are defined to be positive when they cause the deformed shape of the specimen's top surface to be convex. On the other hand, the S_0 and A_0 modes are called negative when the deformed shape of the top surface becomes concave (figure 6(b)). In figure 7, it is shown how the signs of Lamb wave modes are determined 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 S_0 mode always produces a positive S_0/S_0 mode and a negative A_0 mode generates a negative A_0/A_0 mode, respectively.

On the other hand, the signs of newly generated modes $(A_0/S_0 \text{ and } S_0/A_0)$ can be altered depending on the characteristics of a discontinuity that the launching Lamb mode is passing through. Although the signs of these converted modes cannot be determined without knowing the detailed characteristics of the discontinuity, certain relationships among these converted modes can be revealed. For instance, if a positive S_0 mode creates a positive A_0/S_0 mode, a positive A_0 mode also produces a positive S_0/A_0 mode. That is, the signs of the A_0/S_0 and S_0/A_0 modes should always be identical. This is based on the reciprocity of signals AB and BA [16]. 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 S_0/A_0 mode in signal BA. In addition, the sign of the A_0/S_0 mode created from a positive S_0 mode should always be opposite to that of the A_0/S_0 mode generated from a negative S₀ mode. In figures 8(a) and (b), the phases of the S₀ and A₀

of the A_0/S_0 mode in signal AB should be identical to those

modes in signals AB and CD are compared when the specimen is in an intact condition. As for signal AB, when PZT A generates positive S₀ and A₀ modes, both modes produce positive bending in PZT B as shown in the upper part of figure 8(a). On the other hand, PZT C in signal CD creates a negative S_0 mode and a positive A_0 mode because the poling direction of PZT C is opposite to PZT A, as shown in the lower part of figure 8(a). However, because the poling directions of PZT B and D are also opposite to each other, the negative S₀ mode will produce positive bending in PZT B and the positive A₀ mode produces positive bending as well. As a consequence, the phases of the S_0 and A_0 modes measured at PZT D are always identical to those measured at PZT B. Therefore, when the plate is in a pristine condition and four identical PZTs are instrumented as shown in figure 8(a), it is concluded that signal AB becomes identical to signal CD as shown in figure 8(b).

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) as shown in figures 8(c) and (d). As for signal AB, the S_0/A_0 mode arrives at PZT B earlier than the A_0/S_0 mode when the notch is located closer to PZT A than PZT B (assuming that the S_0 mode travels faster than the A_0 mode). Therefore, the S_0 mode is followed by the S_0/A_0 , A_0/S_0 and A_0 modes in signal AB. Based on the sign convention in figure 7, both the S_0/A_0 and A_0/S_0 modes are positive so that the signs of all modes are the same in signal AB. On the other hand, the S_0 mode is followed by A_0/S_0 , S_0/A_0 and A_0 modes in signal CD because the S_0/A_0 mode arrives at PZT D later than the A_0/S_0 mode. In this case, a negative A_0/S_0 mode and a positive S_0/A_0 mode are created because of a negative S_0 mode and a positive A_0



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





(b) Comparison of signals AB and CD without a notch: the S₀ & A₀ modes are identical



- (c) A damaged plate with the PZT configuration II shown in figure 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

Figure 8. Extraction of the additional Lamb wave modes generated by a notch by comparing signals AB and CD. (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.)

mode, respectively (figure 7). Note that signal CD has two S_0 modes, S_0/A_0 and S_0 , and their signs are opposite. Also, two A_0 modes in signal CD, A_0/S_0 and A_0 , have opposite signs as well.

In figure 8(d), signals AB and CD are drawn considering not only the arrival times of each modes but also their relative signs (or phases). Note that, while the S_0 and A_0 modes in figure 8(d) are in-phase, the S_0/A_0 and A_0/S_0 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 signal AB from signal CD as shown in figure 8(d). In addition to signals AB and CD, it can be readily shown that the S₀ and A₀ modes in signals AC and BD are identical while the S_0/A_0 and A_0/S_0 modes are fully out-of-phase. Because this approach relies only on the comparison of two instantaneous signals obtained at the current state of the system rather than comparison with previously recorded reference data, it is expected that this approach may reduce false alarms of defects due to changing operational and environmental conditions of the system. For instance, the comparison of signals AB and CD is always valid regardless of the temperature and loading conditions of the system being monitored. The robustness of the proposed technique under varying temperatures was successfully demonstrated through experimental tests [17], and the effect of external loading on the measured Lamb waves was investigated through a field test of the Buffalo Creak Bridge in Pennsylvania, USA [18]. Note that the difference between signals AB and CD will increase even when the crack is not along the direct path between the exciting and sensing PZTs.

2.4. Damage classification using instantaneously measured Lamb wave signals

So far, it is theoretically shown that signals AB and CD are indistinguishable when there is no crack, as shown in figure 8. 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 [19]. This imperfection in PZTs may generate initial differences in signals AB and CD even in the absence of cracks and lead to positive false alarms.

Here, a damage detection scheme is developed based on the premise that mode conversion produces signal differences between signals AB and CD that are bigger than the initial 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. The uniqueness of the proposed damage classification scheme is that threshold values for damage classification are obtained using only signals instantaneously measured from the current state of the system without relying on predetermined threshold values.

In figure 9, signal AB is schematically drawn based on the sign definition presented in section 2.3 assuming a notch is closer to PZT A. From figure 9, it can be shown that signal AB is a simple superposition of signals S_0 , MC₁, MC₂ and A₀. Signal S₀ indicates a time signal that contains only the S₀ mode but its length is identical to that of signal AB. Signal MC₁, signal MC₂ and signal A₀ are defined in a similar fashion. MC₁ and MC₂ represent the first and second arrivals of Lamb



Figure 9. Decomposition of signal AB into individual Lamb wave mode signals (when a notch is closer to PZT A).

wave modes created by mode conversion, respectively. Note that MC_1 and MC_2 could be either S_0/A_0 or A_0/S_0 modes, depending on the relative position of crack and the actuating and sensing PZTs used for the signal measurement. For instance, MC_1 denotes a S_0/A_0 mode in signal AB when a notch is closer to PZT A than PZT B. This is because the S_0/A_0 mode arrives at PZT B earlier than the A_0/S_0 mode. Similarly, signal MC_2 in signal AB represents the A_0/S_0 mode.

Similar to signal AB, signals AC, BD and CD can also be expressed as combinations of individual Lamb wave signals (figure 10). In figure 10, these four signals are schematically shown emphasizing the relative phases of individual Lamb modes among these signals. For instance, 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 similar manners. Based on these observations, the relationship between the signals that can be measured (signals AB, AC, BD and CD) and the individual Lamb signals (signals S₀, MC₁, MC₂ and A₀) can be obtained as follows:

Because of measurement errors and variations in PZT size, alignment and bonding condition, error terms are added in equation (1). Here, e_{AB} is an error signal in the measured signal AB that is superimposed onto the exact signal AB, and e_{AC} , e_{BD} and e_{CD} are defined similarly. e_S , e_{MC1} , e_{MC2} and e_A represent error signals in each decomposed Lamb mode signal. While equation (1) illustrates how different combinations of individual Lamb mode signals constitute each measurable signal, equation (2) below shows how each individual mode signal can be extracted from the measured signals AB, AC, BD and CD. For instance, signal S₀ can be extracted by adding signals AB and CD and subtracting signals AC and BD.



Figure 10. Comparison of relative phase information among signals AB, AC, BD and CD (when a notch is closer to PZT A).

Similarly, signal MC_1 can be isolated by adding signals AB and BD and subtracting signals AC and CD:

According to equation (2), the measured signals can be separated into individual Lamb mode signals S_0 , MC_1 , MC_2 and A_0 . Note that only signals MC_1 and MC_2 contain Lamb modes created by damage (MC_1 and MC_2 , respectively). Ideally, signals MC_1 and MC_2 should be zeros in the absence of damage. In practice, however, due to e_{MC1} and MC_2 , signals MC_1 and MC_2 may not be zeros even without damage. Since e_{MC1} and e_{MC2} cannot be extracted from signals MC_1 and MC_2 using equation (2) only, it is challenging to determine whether additional modes in these signals are due to mode conversion or PZT imperfections. To tackle this issue, a new damage classifier is developed to determine if the non-zero responses in signals MC_1 and MC_2 are due to mode conversion or simply due to initial errors.

The damage identification scheme proposed in this study starts from the decomposition of individual Lamb mode signals from measured signals using equation (2). Next, the maximum absolute amplitude of the error components, $e_{\rm S}$ and $e_{\rm A}$, in signals S₀ and A₀ are estimated. Because the arrival time of the S₀ mode in signal S₀ is known, the non-zero response of signal S_0 outside the S_0 mode is mainly attributed to e_S . Therefore, the maximum amplitude of $e_{\rm S}$ can be estimated from the rest of signal S_0 where the S_0 mode does not exist. The maximum absolute amplitude of e_A can also be estimated from signal A₀ in a similar fashion. Then, the threshold value for damage classification is set to be the maximum absolute amplitude of $e_{\rm S}$ and $e_{\rm A}$. Finally, the existence of damage is determined by comparing the amplitudes of signals MC₁ and MC₂ with respect to the threshold value. In this way, a crack can be detected if the crack produces signal differences between signals AB and CD that are bigger than the initial differences due to PZT imperfection and measurement errors. Note again that no predetermined threshold values are required during this



Figure 11. Dimension of an aluminum plate used in numerical simulation.

damage classification procedure because the threshold value is obtained from instantaneously measured signals AB, AC, BD and CD. The applicability of the proposed thresholding technique is experimentally investigated in section 4.2.

3. Numerical simulation

The idea of using a PZT poling direction for crack detection was first validated by numerical simulation. Using COMSOL 3.3a 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 the COMSOL software. The length of the beam was 70 cm and its thickness was 6 mm. Four identical PZTs with 10 mm length and 0.508 thickness were attached to the beam model as shown in figure 11. 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 toneburst signal at 150 kHz frequency was used as an input signal. The effect of the PZT size and the driving frequency on the relative amplitudes of A_0 and S_0 modes are previously investigated [12]. In this study, the driving frequency was selected so that the amplitudes of the A_0 and S_0 modes could be relatively the same. 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 using a time-dependent solver, and a time step was set to 0.25 μ s, which is equivalent to 4 MS s^{-1} . To control the error in each integration step, relative tolerance and absolute tolerance for the solution were chosen to be 10^{-4} and 10^{-10} , respectively. The maximum backward differentiation formula (BDF) order

 Table 1. Parameters used in numerical simulation.

 Parameters
 Values

 Exciting frequency
 150 kHz

Exciting frequency	150 kHz
α (mass damping coefficient)	10^{-4}
β (stiffness damping coefficient)	0
Sampling rate	4 MS s^{-1}
Relative tolerance	10^{-4}
Absolute tolerance	10^{-10}
Maximum BDF order	2
Mesh size (mapped mesh)	$1 \text{ mm} \times 1 \text{ mm}$ maximum

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 $1 \text{ mm} \times 1 \text{ mm}$ [20].

Figure 12(a) illustrates that signals AB and CD were almost identical and this matches well with theory. In addition to signals AB and CD, signals AC and BD are also identical without damage as shown in figure 12(b). Once a notch of 3 mm depth and 1 mm width was introduced 100 mm away from PZT A toward PZT B, signal AB (AC) became different from signal CD (BD) as a result of the mode conversion induced by the crack, as illustrated in figure 13. After signals AB, AC, BD and CD are obtained, the decomposition process described in equation (2) was conducted and shown in figure 14. Because the effect of PZT imperfection was neglected in modeling, individual Lamb wave modes (S₀, A₀, MC_1 and MC_2 modes) were clearly extracted. In figure 14(a), only the S_0 mode was shown without the MC₁ or MC₂ modes. Also, the effect of mode conversion did not appear in figure 14(b) while the A₀ mode was clearly decomposed. On the other hand, figures 14(c) and (d) show that the additional modes due to mode conversion were isolated from the S₀ and A_0 modes. In the following experimental results, the outcome of this numerical simulation is further substantiated and the effect of the PZT imperfection is investigated.

4. Experimental results

4.1. Description of the experimental set-up

To further examine the proposed reference-free NDT technique, experimental tests have been conducted on an aluminum plate. The overall test configuration and the test specimen are shown in figure 15. The data acquisition system was composed of an arbitrary waveform generator (AWG),



Figure 12. Comparison of signals AB and CD (or signals AC and BD) when there is no notch.



Figure 13. Comparison of signals AB and CD (or signals AC and BD) with a notch of 3 mm depth and 1 mm width.



Figure 14. Decomposition of individual Lamb mode signals S_0 , MC_1 , MC_2 and A_0 from measured signals AB, AC, BD and CD using equation (2) (damaged case).



(a) A data acquisition system

(b) A square aluminum plate

Figure 15. Testing configuration for detecting a crack on an aluminum plate.

a high-speed signal digitizer (DIG), a low noise preamplifier (LNP) and a multiplexer. The dimension of the plate was 122 cm \times 122 cm \times 0.6 cm and four PSI-5A4E type PZT wafer transducers (1.0 cm \times 1.0 cm \times 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 figure 3(a). PZTs A and B (or PZTs C and D) were 0.52 m apart from 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 toneburst signal with a ± 10 peak-to-peak voltage and a driving frequency of 150 kHz was



Figure 16. Comparison of signals AB and CD without a notch.



Figure 17. Comparison of signals AB and CD with a 3 mm deep notch.

generated and applied. First, PZT A in figure 15(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 20 and measured by the DIG. The sampling rate and resolution of the DIG were 20 MS s⁻¹ and 16 bits, respectively. In order to improve the signal-tonoise ratio, the forwarding signals were measured 20 times and averaged in the time domain. After the forwarding signals from PZT A to PZT B (signal AB) were measured, the same process was repeated by measuring signals AC, BD and CD. The entire experimental process without averaging took less than 10 s. Detailed test results are described in section 4.2.

4.2. Extraction of reference-free damage features

In this section, damage-sensitive features are instantaneously extracted simply by subtracting two time signals measured from the current state of the system. In figure 16, signals AB and CD are instantaneously measured from the pristine condition of the specimen and shown. As expected, an initial difference between signals AB and CD was observed even in the absence of a crack due to imperfections in PZT alignment, size and bonding condition. 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 figure 17(a). Comparison of figures 16(b) and 17(b) clearly demonstrates the appearance of the additional modes due to crack formation.

It can also be shown that a similar comparison between signals AC and BD can be made: signals AC and BD and their difference are shown in figures 18 and 19, respectively. Similar to the difference between signals AB and CD, signals AC and BD showed an initial difference without a notch (figure 18(b)) and a large increase of the difference due to mode conversion (figure 19(b)). However, it is not clear in practice how large the signal difference should be before it leads to warning of damage. To tackle this issue, the applicability of the instantaneous thresholding technique proposed in section 2.4 is tested hereafter.

4.3. Reference-free damage diagnosis

The proposed reference-free NDT technique utilizes only four instantly measured Lamb wave signals, signals AB, AC, BD and CD for damage classification. After these four signals are decomposed into individual Lamb mode signals, signals S_0 , MC_1 , MC_2 and A_0 , a threshold value is determined from error components, e_S and e_A , in signals S_0 and A_0 . Finally, the existence of damage is indicated when the magnitude of signal MC_1 or signal MC_2 exceeds the threshold value. Detailed descriptions of the proposed technique are provided below.

4.3.1. Decomposition of signals S_0 , MC_1 , MC_2 and A_0 from measured signals AB, AC, BD and CD. First, each Lamb mode signal is estimated from signals AB, AC, BD and CD measured from an unknown condition of the specimen. Figure 20 displays individual Lamb mode signals decomposed using equation (2). At this stage, it is assumed that the existence of damage is unknown, but, if it does, it is located closer to PZT A. In figure 20(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 figure 20(b) illustrates that the error signal e_A is superimposed onto the exact signal A_0 . Signals MC_1 and MC_2 are also drawn in



Figure 18. Comparison of signals AC and BD without a notch.



Figure 19. Comparison of signals AC and BD with a 3 mm deep notch.



Figure 20. Decomposition of individual Lamb mode signals S_0 , MC_1 , MC_2 and A_0 from measured signals AB, AC, BD and CD using equation (2).

figures 20(c) and (d). Ideally, signals MC_1 and MC_2 should be zero for the entire length of the signals in the absence of damage. However, due to PZT imperfections, additional modes appeared in signals MC_1 and MC_2 .

4.3.2. Estimation of error components e_S and e_A . Once the individual Lamb mode signals are decomposed, the threshold for damage classification is set to be the maximum absolute amplitude of error components, e_S and e_A , in signals S_0 and A_0 . Here, it is shown how the magnitude of e_S and e_A can be

estimated from signals S_0 and A_0 . For illustration purposes, figures 9 and 10 are modified in figure 21 by including error components in the measured and decomposed signals. The estimated signal S_0 is composed of the exact signal S_0 and e_S as shown in figure 21. Furthermore, it can be shown that the S_0 mode exists only in a certain portion of the estimated signal S_0 while e_S is present for the entire length of the estimated signal S_0 . Therefore, the maximum absolute amplitude of e_S can be estimated from a portion of the estimated signal S_0 where the S_0 mode does not exist. To accomplish this, the estimated





(a) Comparison of relative phase information among signals AB, AC, BD, and CD with error signals (When a notch is closer to PZT A)

(b) Decomposed Lamb mode signals using equation (2) (When a notch is closer to PZT A)

Figure 21. Comparison of relative phases among measured signals and decomposition to individual Lamb mode signals (when a notch is closer to PZT A).



Figure 22. Autonomous damage identification using instantaneously obtained threshold values instead of predetermined decision boundaries. (Max(abs(es,ea)) denotes maximum absolute value of e_s and e_A .)

signal S_0 is divided into two regions, S_0 and A_0 regions, as shown in figures 20 and 21. Here, the boundary between two regions is placed exactly in the middle of the S_0 and A_0 modes. Because the S_0 mode always exists only in the S_0 region, the response in the A_0 region is attributed only to e_S . Therefore, the maximum absolute amplitude of e_S is estimated from the A_0 region as shown in figure 20(a). In a similar manner, the maximum absolute amplitude of e_A is estimated from the S_0 region of the estimated signals A_0 as depicted in figure 20(b).

4.3.3. Damage classification. From the estimated maximum absolute amplitude of e_S and e_A , the upper and lower limits for damage diagnosis are established as shown in figure 22(a). It is assumed that, if the amplitudes of MC₁ and MC₂ modes exceed one of the threshold values, the mode conversion beyond PZT imperfections or measurement noises is induced by the notch. Note that these threshold values for damage classification are strictly estimated from signals AB, AC, BD and CD instantaneously measured from the system's current state. That is, the dependence on the prior baseline data is eliminated during the damage classification process.

In figure 22(a), the proposed diagnosis scheme is applied to the signals obtained from the pristine condition of the specimen. Figure 22(a) illustrates that both MC₁ and MC₂ modes in the S₀ and A₀ regions did not exceed the threshold values determined from e_S and e_A . Therefore, it can be concluded that these signals are obtained from the undamaged condition of the test article.

Next, the proposed scheme was applied to the signals measured from the 3 mm notch case. Four decomposed signals using equation (2) are drawn in figure 20 along with the signals obtained from the undamaged case for comparison. Figures 20(a) and (b) showed that the occurrence of damage changed signals S₀ and A₀ very little. Furthermore, it is revealed that the amplitudes and shape of $e_{\rm S}$ and $e_{\rm A}$ did not change much because they were not related to mode conversion. On the other hand, the appearance of mode conversion is clearly observed in signals MC1 and MC2 (figures 20(c) and (d)). After the threshold values are determined from the maximum absolute amplitude of e_S and e_A , it is tested whether the MC₁ mode in the S₀ region of signal MC₁ and the MC₂ mode in the A_0 region of signal MC₂ exceed the thresholds. Figure 22(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. Therefore, these signals are classified to be damaged.

4.4. Damage localization

Next, the notch location is estimated by measuring the arrival time of the MC₁ mode in signal MC₁. From the S₀ and A₀ modes in figure 20, the group velocities of the S₀ (V_S) and A₀ modes (V_A) were estimated to be 5.113 m ms⁻¹ and 3.090 m ms⁻¹ (theoretically, $V_S = 5.088$ m ms⁻¹ and $V_A = 3.055$ m ms⁻¹), respectively. Because the location of the notch was assumed to be closer to PZT A than PZT B, the distance from PZT A to the notch can be estimated using equation (3):

The arrival time of the MC₁ mode =
$$\frac{s}{V_A}$$

+ $\frac{\text{Distance between PZT A and PZT B} - s}{V_S}$ (3)

where *s* denotes the distance of the notch from PZT A. From the estimated arrival time of the MC₁ mode (0.1206 ms) and equation (3), *s* is estimated to be 14.76 cm. This estimated distance was close to the actual distance (15 cm from PZT A, 1.6% error). Similarly, the location of the notch can be estimated using the arrival time of the MC₂ mode. In this case, the estimated distance from PZA was 15.45 cm and this corresponded to a 3% error.

4.5. 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 closer to PZT B, the following equation should be used to relate the measured signals and the individual Lamb modes instead of equation (1):

$$\begin{bmatrix} \text{Signal AB} + e_{\text{AB}} \\ \text{Signal AC} + e_{\text{AC}} \\ \text{Signal BD} + e_{\text{BD}} \\ \text{Signal CD} + e_{\text{CD}} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & \underline{1} & -\underline{1} & 1 \\ -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} \text{Signal S}_0 + e_{\text{S}} \\ \text{Signal MC}_1 + e_{\text{MC1}} \\ \text{Signal MC}_2 + e_{\text{MC2}} \\ \text{Signal A}_0 + e_{\text{A}} \end{bmatrix}.$$
(4)

Accordingly, equation (2) should be also changed to

$$\begin{bmatrix} \text{Signal } S_0 + e_{\text{S}} \\ \text{Signal } \text{MC}_1 + e_{\text{MC1}} \\ \text{Signal } \text{MC}_2 + e_{\text{MC2}} \\ \text{Signal } A_0 + e_{\text{A}} \end{bmatrix} = \frac{1}{4} \begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & \underline{1} & -\underline{1} & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \\ \times \begin{bmatrix} \text{Signal } \text{AB} + e_{\text{AB}} \\ \text{Signal } \text{AC} + e_{\text{AC}} \\ \text{Signal } \text{BD} + e_{\text{BD}} \\ \text{Signal } \text{CD} + e_{\text{CD}} \end{bmatrix}.$$
(5)

To assist comparison between equations (1) and (4) (or equations (2) and (5)), underlines are drawn in equations (4) and (5) indicating specific changes compared to equations (1) and (2). The comparison between equations (2) and (5) reveals that signals S_0 and A_0 are not affected by the location of the notch. Also, it is shown that signal MC₁ in equation (2) corresponds to signal MC₂ in equation (5). Therefore, when the notch is formed closer to PZT B, 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 A_0 region of signal MC₁.) From these observations, it is found that equation (2) can be still 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 MC ₂ mode is found in the A_0 region of signal MC₁ instead of the S₀ region, it confirms that the notch is closer to PZT B. Therefore, once the existence of mode conversion is determined, the location of the defect can also be determined by checking the location of the mode in signal MC₁.

5. Conclusion

A new concept of nondestructive testing is developed in this study so that cracks in a specimen with a uniform thickness 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. In the presence of a crack, some portions of Lamb waves reflected and refracted from the crack are converted to other modes. First, the appearance of this mode conversion is extracted by strategically placed PZT wafer transducers considering the poling directions of individual PZTs. Then, an autonomous damage classifier is developed so that the threshold value for classification could be estimated from instantaneously measured signals rather than pre-determined thresholds. In this way, the entire process of damage diagnosis including feature extraction and damage diagnosis is completed without direct dependence on prior baseline data. Numerical simulations and experimental tests are conducted to substantiate the effectiveness of the proposed reference-free technique for crack detection. Because this reference-free technique does not rely on previously obtained baseline data for crack detection, it is expected that this approach will 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 online continuous monitoring. Further investigation is underway to extend the proposed concept to more complex structures and corrosion detection. The intent of the present approach is not to disregard useful prior knowledge or information gained but to relax explicit dependence on baseline data so that the proposed methodology can be made more attractive for field applications. By incorporating the proposed approach into the conventional NDT techniques, it is envisioned that more reliable damage diagnosis can be achieved.

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