Title***: Reference-free Structural Health Monitoring for Detecting Delamination in Composite Plates***

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ABSTRACT

This paper presents a new methodology that allows detection of delamination in a single wave propagation path without using prior baseline data or a predetermined decision boundary. This study shows that, if delamination exists along a wave propagation path, the first arrival anti-symmetric mode (A_0) is followed by another A_0 mode reflected off from the "inside" delamination. Unlike other conventional techniques, the proposed technique takes advantage of this A_0 mode reflected off from the inside delamination to instantly detect the existence of delamination. First, Lamb wave signals are measured in a pitch-catch mode using a dual PZT composed of concentric ring and disk PZTs for excitation and two circular PZTs for sensing. Here, the dual PZT actuator is used to extract only the A_0 mode at any desired driving frequency. Then, the response time signals are measured by the two circular PZTs, and the damage sensitive feature, which is the A_0 mode reflected off from the delamination, is extracted. Because the proposed technique does not require baseline signals during the entire delamination detection process, it has been demonstrated that robust delamination detection can be achieved even under varying temperature conditions.

INTRODUCTION

Structural health monitoring (SHM) is a process to evaluate the health and performance of structures using real-time data obtained from sensors. Currently, non-destructive testing (NDT) is performed to detect damages during ground inspections, and there are ongoing efforts to develop online SHM, which can perform automated damage diagnosis during the normal operation of aircraft. These automated systems will need to be robust in the presence of airplane-to-airplane variations and ever-changing environmental conditions. Development of so called "baseline free" damage detection algorithms is therefore a key element of development of fieldable SHM solutions.

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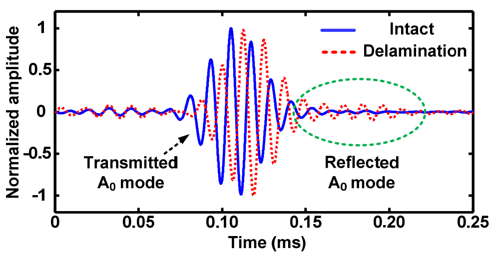
One of such efforts is the development of an online SHM system based on Lamb wave propagation characteristics in composite structures [1-4]. These conventional techniques often have focused on schemes where baseline signals are measured from a pristine condition of the structure so that changes from the baseline data can be detected and related to defects. However, large signal changes under varying environmental conditions like temperature mask the small signal changes due to damage, making damage detection challenging.

To address this issue, the authors's group have been developing a suite of reference-free damage detection techniques so that damage can be detected without using any direct comparison with previously obtained baseline data even at the presence of temperature variation [4,8-9]. The uniqueness of this study lies in utilization of a new damage-sensitive feature for the reference-free damage detection technique: The A_0 mode reflected off from the "inside" delamination is extracted and used to identify the existence of delamination. Because the appearance of the A_0 mode reflection is instantaneously extracted without using any past reference data, robust delamination detection is achieved even under varying temperature conditions.

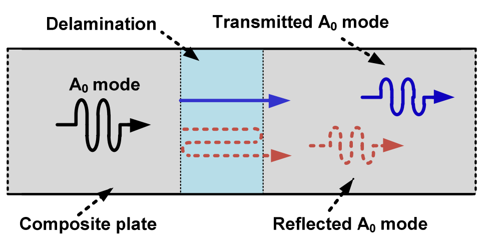
DELAMINATION SENSITIVE FEATURES

First, the effect of delamination on Lamb wave propagation is experimentally and numerically investigated for the development of a robust delamination detection technique. The findings are summarized as below:

(1) Figure 1(a) shows that the A_0 mode slows down when it passes through a delamination area. Furthermore, a proportional relationship between the severity of delamination and the time delay of the A_0 mode is observed.
(2) As delamination increases, the amplitude of the A_0 mode is initially amplified and followed by attenuation with a further increase of delamination. A similar initial amplification of the A_0 mode is also reported by others [2].
(3) A numerical simulation also reveals that the A_0 mode is more significantly delayed and attenuated by delamination than the S_0 mode. This is because delamination primarily decreases interlaminar shear strength, and the A_0 mode is dominantly affected by the shear modulus of the specimen.



(a) Comparison of A_0 modes under intact and delamination conditions



(b) Schematic diagram of transmitted and reflected A_0 modes due to a delamination on a composite plate

Figure 1. The effect of delamination on Lamb wave propagation

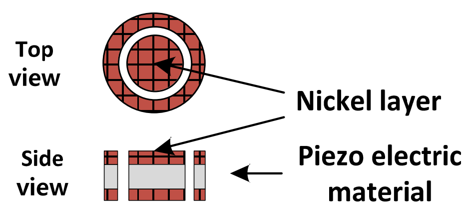
(4) The waveform of the A_0 and S_0 modes are hardly distorted by delamination because the frequency content of the propagating waves is little affected by delamination.
(5) Mode conversion occurs due to delamination, but the converted modes rapidly attenuate, making it difficult to reliably measure the converted modes. Furthermore, a numerical simulation shows that the amplitudes of the converted modes due to delamination are typically less than 1% of the amplitudes of the A_0 and S_0 modes.
(6) Figure 1(b) shows that when the A_0 mode interacts with delamination, some portion of the A_0 mode is transmitted through it and other is transmitted after bounced back and forth from the entrance and exit boundaries of the delamination. Thus, two A_0 mode wave packets (transmitted and reflected waves) are observed in the presence of a delamination as shown in Figure 1(a).
(7) The arrival time difference between the transmitted and reflected A_0 modes is invariant of the wave propagation distance and only controlled by the delamination length.

In this study, the last two observations listed above are particularly taken advantage of for the development of the proposed delamination detection technique, which is described below.

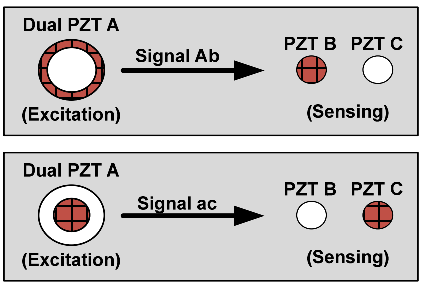
REFRERNECE-FREE DELAMINATION DETECTION TECHNIQUE

Sensor design and layout

The schematic drawing of a dual PZT, which is used for the A_0 mode extraction, is shown in Figure 2(a). The dual PZT is composed of concentric disk and outer ring PZTs, and these disk and ring PZTs can be selectively activated for actuation [4, 7]. Figure 2(b) shows the PZT transducer layout and notations of signals used in this study. “Signal Ab” denotes a response measured by the sensing circular PZT B, when the outer ring of the dual PZT A is actuated. Similarly, “Signal ac” is the response of the sensing PZT C corresponding to the excitation of the disk of the dual PZT A. Other signals are defined similarly. The darker (red) areas of the dual PZT and circular PZTs represent the PZT component activated either for excitation or sensing.



(a) A schematic drawing of the dual PZT



(b) Notations of signals

Figure 2. A schematic drawing of the dual PZT and examples of signals obtained by the excitation dual PZT and two sensing PZTs: The darker (red) areas of the dual PZT and circular PZTs represent the PZT components activated either for excitation or sensing.

A_0 mode extraction

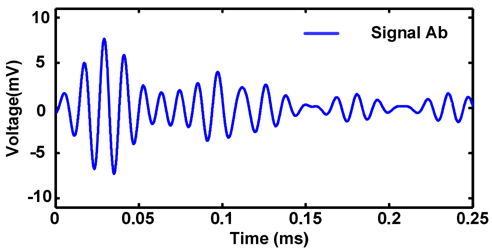
The proposed mode extraction technique isolates the A_0 modes from measured time signals by scaling these signals, which are obtained from the same path but with two different actuator PZT sizes. The measurement of such signals from the same path with different excitation PZT sizes is made possible using the prescribed dual PZT. A brief description of the A_0 mode extraction technique is provided below along with Figure 3 using a path between PZTs A and B in Figure 6(a). More details can be found in [5]. The procedure can be summarized as follows:

(1) In a pitch-catch mode, Signals Ab and ab are measured at the PZT B when the ring and disk parts of the dual PZT A are used for excitation as shown in Figures 3(a) and (b).

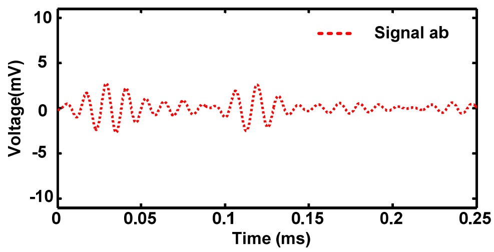
(2) In Figure 3(c), Signal ab is scaled so that the S_0 modes in both signals have the same amplitude. S_c is the amplitude ratio of the S_0 mode in Signal Ab to that in Signal ab.

(3) By subtracting scaled Signal ab from Signal Ab, all the S_0 modes are removed and only A_0 modes remains as shown in Figure 3(d).

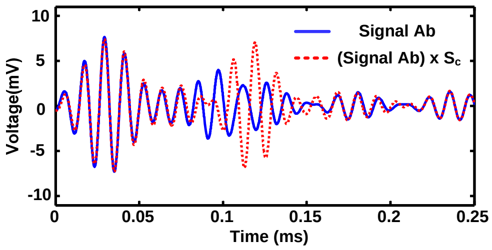
The A_0 mode in a path between the dual PZT A and PZTC can be extracted in a similar way.



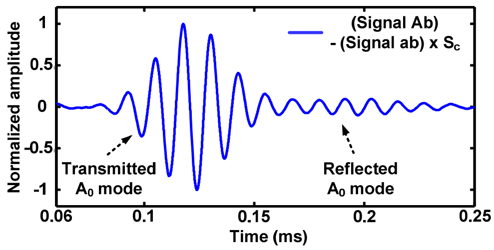
(a) Signal Ab



(b) Signal ab

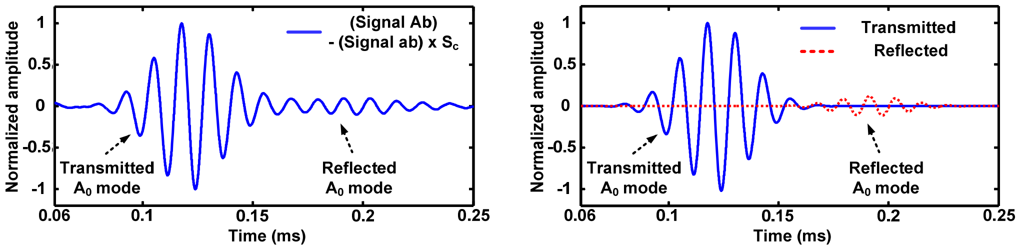


(c) Subtraction of Signal Ab from scaled Signal ab



(d) Extraction of the A_0 mode

Figure 3. Illustration of the A_0 mode extraction using the proposed mode extraction technique: Signal Ab and Signal ab are measured from a delamination condition. S_c is the amplitude ratio of the S_0 mode in Signal Ab to that in Signal ab.



(a) Extracted A_0 mode (b) Decomposed A_0 modes

Figure 4. Illustration of the A_0 mode decomposition using the matching pursuit algorithm

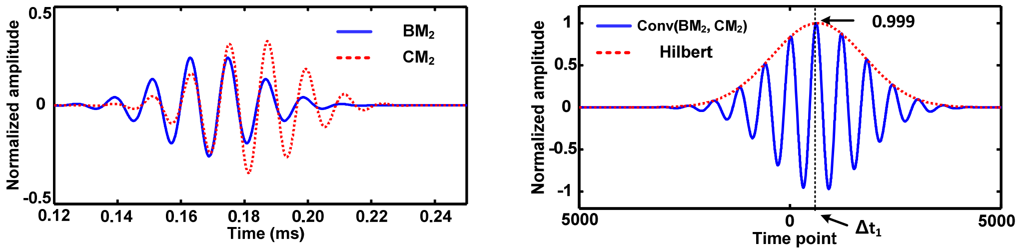
Mode separation using matching pursuit algorithm

A matching pursuit technique is employed in this study to decompose the extracted A_0 mode into the transmitted and reflected modes [6]. The matching pursuit technique is a signal processing technique that iteratively decomposes a target time signal into a linear combination of basic functions. At first iteration, parameters of the first basis function, such as arrival time, scale, amplitude, are optimized so that the target signal can be best projected on to the first basis function. Next, the residual signal, which is the remaining component of the target signal after projected onto the first basis function, is now projected onto the second basis function. Finally, these steps are repeated until all wave components of interest are identified and decomposed. In this study, this technique allows two dominant waveforms, the transmitted and reflected A_0 modes, to be extracted and decomposed from the previously obtained time signal only with A_0 modes.

The matching pursuit technique is illustrated in Figure 4 using Signals Ab and ab obtained from a delamination condition. The transmitted and reflected A_0 modes are well separated as indicated in Figure 4(b). Although the appearance of the reflected A_0 mode indicates the existence of delamination, a more rigorous damage identification procedure, such as the one described below, is necessary for complete reference-free diagnosis.

Reference-free damage classifier

The proposed damage classifier identifies the existence of delamination by comparing the reflected A_0 modes, BM_2 and CM_2. Here, BM_2 and CM_2 are the reflected A_0 modes obtained from PZTs B and C in the PZT layout shown in Figure 2 (b) and Δt_1 is arrival time difference between BM_1 and CM_1, which are the transmitted A_0 modes. In particular, it relies on the previous observation that *the arrival time difference between the transmitted and reflected A_0 modes is invariant of the wave propagation distance and only controlled by the delamination length.* This can be translated to the fact that the arrival time difference between BM_1 and CM_1, Δt_1, is equal to the time difference between BM_2 and CM_2, Δt_2, if delamination exists. The damage classification procedure can be summarized as follows.



(a) Comparison of reflected A_0 modes obtained from PZTs B and C

(b) Hilbert transform of convolution of BM_2 and CM_2

Figure 5. Example of the proposed damage classification: The DI is estimated from the Hilbert transform of the convolution of BM_2 and CM_2 at time Δt_1: BM_2 and CM_2 are the reflected A_0 modes obtained from PZTs B and C in the PZT layout shown in Figure 2 (b) and Δt_1 is arrival time difference between BM_1 and CM_1, which are the transmitted A_0 modes.

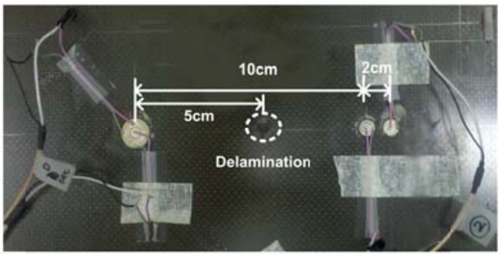
(1) Compute Δt_1 using arrival times of BM_1 and CM_1 estimated from matching pursuit technique
(2) Estimate the closeness of BM_2 and CM_2 as a function of the time delay. This similarity is check by computing the Hilbert transform, H_2, of the convolution of BM_2 and CM_2 as a function of the time delay.
(3) Define the damage index (DI) as the H_2 value when the time difference between BM_2 and CM_2 is Δt_1.
(4) Alarm delamination if the DI exceeds a predetermined threshold value. If Δt_2 is similar to Δt_1, the DI goes to 1.

DELAMINATION DETECTION IN A COMPOSITE SPECIMEN

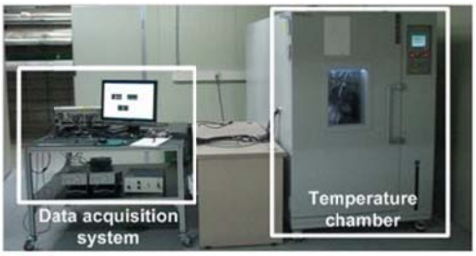
Description of the experimental set-up

To validate the proposed delamination detection technique, a multi-layer carbon fiber composite plate shown in Figure 6(a) is tested. The material properties and prepreg lay-up information of the specimen are unknown to the authors. The dimensions of the specimen are 1512 mm × 762 mm × 5 mm, and a dual PZT and two circular PZTs are installed on the inside surface of the specimen. The spacings between a dual PZT A and PZTs B and C are 10cm and 12 cm, respectively. A dual PZT is composed of inner circular and outer ring PZTs, and the radius of the circular PZT, and the radii of the inner and outer rings of the exterior ring PZT are 2 mm, 3 mm and 4 mm, respectively and its thickness was 0.5 mm. The radius and thickness of the circular PZT B and C is 5mm and 0.5 mm..

The data acquisition system and temperature chamber used in this study are shown in Figure 6(b). The data acquisition system consists of an arbitrary waveform generator (AWG), a high speed signal digitizer (DIG), a low noise preamplifier (LNP), a high power amplifier and eight multiplexers. A toneburst signal with a 10 peak-to-peak voltage is generated using the 14-bit AWG. The response signals are measured twenty times and averaged in the time domain to improve the signal-to-noise ratio. A testing frequency is performed at 80 kHz, which is selected to be below the cutoff frequencies of the A_1 and S_1 modes. For intact and delamination conditions, temperature chamber experiments are conducted at -10, 20 and 50 ^{o}C, respectively.



(a) A composite plate with PZTs



(b) Data acquisition system and temperature chamber

Figure 6. Testing configuration for detecting a delamination on a composite plate

A conventional drop-weight impact tester with a 10 mm radius steel ball tip is used to introduce low velocity impact damage. Two consecutive impacts are applied to a single point, exerting 24.5J energy each time. In this manner, delamination is formed at 5cm from a dual PZT A.

Test results

The effects of delamination on Lamb wave modes are investigated in Figure 1. The extracted A_0 mode used in Figure 1 are obtained from Signals Ab and ab. By comparing the A_0 modes measured from the undamaged and delamination conditions, it is observed that the A_0 mode slows down when it passes through a delamination area. Additionally, the A_0 mode reflected from delamination edges is observed at the back of the transmitted A_0 mode.

As a result of experimental works, a delamination is successfully detected even under three different temperatures (-10, 20 and 50^{o}C). For the intact case, no false-positive alarm was produced.

CONCLUSION

In this study, a new reference-free delamination technique is developed so that delamination in a composite plate can be detected by identifying additional A_0 mode generated by the formation of delamination from pitch-catch Lamb wave signals. The effectiveness of the proposed technique is validated using test data obtained from multi-layer carbon reinforced polymer composite plates. An impact induced delamination is successfully identified while no false-positive alarms are produced from the intact conditions even under temperature variation.

ACKNOWLEDGEMENT

This work is supported by the Boeing Company and the National Research Foundation of Korea (NRF) under the Ministry of Education, Science & Technology (2010-0017456 and 2010-0020423).

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