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Instantaneous delamination detection in a composite plate using a dual piezoelectric transducer network

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ABSTRACT

This study proposes a new damage detection technique so that delamination in composite plates can be detected by comparing pitch-catch Lamb wave signals obtained from a piezoelectric transducer (PZT) network without using their own baseline signals obtained from the pristine condition. The proposed technique is based on the premise that the fundamental anti-symmetric (A_0) mode slows down when it passes through a delamination area while the speed of the fundamental symmetric mode is little affected by delamination. First, the A_0 mode in each path is isolated using a mode extraction technique. This mode extraction technique is able to isolate the A_0 mode without frequency or transducer size tuning using dual PZTs composed of concentric ring and circular PZTs. Once the A_0 modes are extracted from all paths in the transducer network, the relative time delay of the A_0 mode in each path with respect to the other paths is defined as a delamination sensitive feature. Then, an instantaneous outlier analysis is developed and performed on the damage sensitive feature to identify the path(s) affected by the delaminated region(s). Because the relative time delays of the A_0 modes are instantaneously compared, robust delamination detection is achieved even under varying temperature conditions.

1. Introduction

Structural health monitoring (SHM) is a process to evaluate and assure the safety and performance of structures using data obtained from sensors. There is an increasing interest for SHM of composite aircraft as composite materials are widely used for aircraft structures. Composite materials have many advantages over metals such as lightweight and higher strength. However, composite materials are susceptible to damages such as delamination and disbond due to abrupt impact or accumulated fatigue loading. Such defects often occur beneath the surface of composite aircraft, and they are hardly visible or detectable by the naked eyes. Currently, non-destructive testing (NDT) is performed to detect such 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.

One of such efforts is the development of an online SHM system based on Lamb wave propagation characteristics in composite structures [1–9]. In a pulse-echo mode, delamination is detected by examining waves reflected and/or scattered from the delamination [10–12]. In a pitch-catch mode, transmitted waves instead of reflected waves are analyzed for delamination detection. Similar to the pulse-echo mode, signal attenuations and time delays are commonly used features [13–17]. Furthermore, phase array transducers can be used to visualize the defect location and size. An input with a proper time delay is applied to each transducer constituting the phase array, and the phase array transducers allow steering of the principal wave propagation direction and/or focusing of propagating wave energy at desired points [18,19].

These conventional techniques often operate under the assumptions that (1) baseline signals are available from the pristine condition of the system being monitored, (2) changes from the baseline signals can be detected and related to defects, and (3) a decision boundary for damage diagnosis can also be established using the available baseline signals. However, the application of these techniques to online SHM becomes challenging, because the baseline signals are subjected to continuous changes due to continuously varying temperature and external loading conditions.

To overcome this problem, damage detection techniques which are insensitive to environmental variations have been developed by relaxing the dependency on the prior baseline signals [20–23]. The majority of work has focused on the detection of crack or corrosion damages in metallic structures. Based on polarization characteristics of piezoelectric materials, crack formation is instantaneously detected by extracting the mode conversion induced by the crack

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[20]. In a damage visualization technique based on phase array transducers, incident waves and additional waves backscattered from a crack are visualized and filtered to identify and locate the crack without using baseline data [21]. However, because mode conversion created by delamination is often insignificant and waves backscattered from delamination rapidly die out, the performances of the aforementioned techniques for delamination detection are less effective.

In this study, a new delamination detection technique is proposed so that delamination can be detected without using any direct comparison with previously obtained baseline data even at the presence of temperature variation. The development of the proposed technique is based on the premise that the fundamental anti-symmetric (A_0) mode slows down when it passes through a delamination area while the speed of the fundamental symmetric (S_0) mode is little affected by delamination. Based on this assumption, the existence of delamination can be detected by comparing the time delay of the A_0 mode in each path with respect to the other paths in the transducer network rather than with the previously obtained baseline data. For the extraction of the A_0 mode in each path, a mode extraction technique using dual PZTs, which are composed of ring and circular PZTs, is proposed. Once the relative time delays of the A_0 modes are computed from all the paths in the transducer network, an instantaneous outlier analysis is conducted so that the path(s) crossing the delamination area can be automatically identified using only current data. The effectiveness of the proposed technique is experimentally validated under varying temperature conditions using a simple composite plate and a composite specimen with stiffeners. The uniquenesses of this study lie in that (1) robust delamination diagnosis can be achieved even under varying temperature, (2) multiple delaminations can be detected, and (3) the proposed technique can be also applied to complex structures.

This paper is organized as follows. In Section 2, the effects of delamination and temperature on Lamb wave modes are investigated. In Sections 3 and 4, the mode extraction and delamination detection algorithm are proposed, respectively. The applicability of the proposed technique to delamination detection in simple and complex composite structures is investigated in Sections 5 and 6, and followed by the conclusion in Section 7.

2. The effects of delamination and temperature on Lamb wave modes

In this section, the effects of delamination and temperature on Lamb wave propagation are compared to justify the development of the proposed damage detection technique under temperature variation. Here, only a brief summary of the numerical and experimental studies conducted is presented. Note that the pitch-catch Lamb wave signals presented in Fig. 1 are obtained from the composite plate presented in Section 5, and the experimental details are provided in Section 5. The findings are summarized as below.

(1) Fig. 1a shows that the A_0 mode slows down when it passes through a delamination area while the speed of the S_0 mode does not change much at delamination. 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 slightly amplified initially and followed by attenuation with a further increase of delamination. A similar initial amplification of the A_0 mode is also reported by others [15].
(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.
(4) Mode conversion occurs due to delamination, but the converted modes rapidly attenuate, making it difficult to reliably measure the converted modes. The numerical simulation shows that the amplitude of the converted modes due to delamination is typically less than 1% of the amplitudes of the A_0 and S_0 modes.
(5) The waveforms 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.

Next, the effect of temperature is investigated. Similar to the effect of delamination, the amplitude and arrival time of the A_0 mode are affected by temperature variation. More specifically, Fig. 1b shows that, as temperature increases, the A_0 mode amplitude decreases and the arrival time of the A_0 mode is delayed. However, the S_0 mode characteristics are rarely affected by temperature. Note that, the second wave packet in the Fig. 1 is, in fact, the superposition of the first arrival A_0 mode and the S_0 modes reflected from structural boundaries. Because the S_0 mode characteristics are not much affected by either delamination or temperature variation, it can be assumed that the variation of the second wave packet is mainly due to the influence of the temperature and delamination on the first arrival A_0 mode not on the reflected S_0 modes.

These observations reveal the challenge of applying the conventional damage detection techniques to in-flight aircraft. Because of the similarity of the delamination and temperature effects on Lamb wave modes, it is difficult to infer the damage state of aircraft simply by comparing the current data with the baseline data under varying temperature conditions. To address this issue, a reference-free technique, which does not rely on previously obtained baseline data, is developed for robust delamination detection in

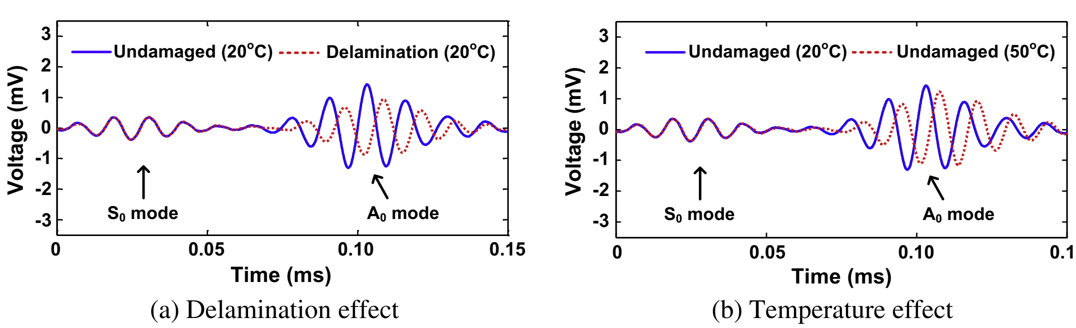

Fig. 1. The investigation of the effects of delamination and temperature on Lamb wave propagation based on experimental data obtained from the composite specimen test: Both described in Section 5: delamination and temperature mainly cause time delay and attenuation of the A_0 mode.