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Detection of delamination in composite laminates using Lamb wave based nonlinear method

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ABSTRACT

In this study, a Lamb wave based nonlinear method is used to detect delamination in a composite laminate. For this purpose, an artificial delamination is created in a composite laminate using a thin Teflon sheet. The research includes an experimental study as well as finite element simulation. Two higher harmonics are observed in the Lamb wave response as a result of contact nonlinearity at the delamination. A spectral damage index is extracted from the spectral information of the fundamental and higher harmonics. It is found to be invariant to the sensor location and its values show decreasing trend with increase in the delamination width. Further, a new hybrid method is introduced, wherein the spectral and temporal data are used together in order to locate a delamination.

1. Introduction

Thin walled structures are omnipresent in the aerospace applications. These structures typically involve use of laminated composite materials. These materials are susceptible to delaminations which are induced during manufacturing or by external impact. For structural safety and reliability, it is important to detect the delaminations before they reach their threshold limit of causing catastrophic failure. Ultrasonic testing using guided waves, typically Lamb waves, is an effective method for detecting such delaminations in the thin walled structures as Lamb waves can scan moderately large area even in the materials with high attenuation ratio [1].

Lamb wave based methods can be broadly classified into two groups, linear and nonlinear, based on the characteristics of wave-damage interaction [2]. In the linear methods, the presence of damage is indicated by parameters like attenuation, transmission, and reflection coefficients [2]. Lamb wave based linear methods have been used in plenty for detection of delamination in the composite laminates [3–13]. However, detection of small delaminations using these methods is seen to be difficult, whereas, Lamb wave based nonlinear methods are said to be sensitive to the delaminations of small size [2]. In the case of Lamb wave based nonlinear methods, the presence of damage is shown by higher harmonics, sub-harmonics, shift of resonance frequency, and mixed frequency response [2]. There are basically two types of nonlinearities, classical and non-classical, introduced by the wave-damage interaction [14]. The classical nonlinearity is associated with the damages such as distributed micro-cracks in the material continuum during fatigue damage progression. Such damages make the material more complaint and in turn makes the Hooke's law nonlinear by introducing higher order elastic terms into it [14]. Whereas, the non-classical nonlinearity is introduced by the wave-damage interaction through various mechanisms such as stress–strain hysteresis, contact nonlinearity, rough surfaces contact, Luxemburg–Gorky effect, etc. [14]. Each mechanism is responsible for producing different nonlinear effects as mentioned above. In the present case, contact nonlinearity is emphasized as it is predominant in the case of delamination. This mechanism typically produces higher harmonics in Lamb waves excited at relatively lower frequencies.

The classical nonlinear mechanism is shown to produce higher harmonics in Lamb waves in [15–19]. Deng and Yang [15] and Bermes et al. [16] used this method for material characterization purpose, whereas, Deng and Pei [17] and Pruell et al. [18,19] used it for the detection of damages such as accumulated fatigue damage and plasticity driven material damage. The contact nonlinearity, a non-classical mechanism, has been used with Lamb waves by the authors for the detection and sizing of a breathing crack in an aluminium plate [20] and for showing up the presence of higher harmonics in a pristine aluminium plate because of the disbonding of

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the piezoelectric wafer (PW) actuator [21]. As far as delamination is concerned, it appears that only Shkerdin and Glorieux [22] and Sarens et al. [23] have studied their effect on the nonlinear behaviour of Lamb waves. Shkerdin and Glorieux [22] modelled the nonlinear interaction between high frequency Lamb waves and bilayer containing a delamination, using a quasi-stationary approach. Sarens et al. [23] carried out full-field dynamic shearography and laser Doppler vibrometry to investigate delamination-induced effects on the vibration of a harmonically excited composite laminate. Though, Sarens et al. [23] have claimed Lamb wave excitation at a sinusoidal frequency of 20 kHz, only local vibration responses confined to the delamination area are given. To the best of the authors' knowledge, the Lamb wave based nonlinear method involving higher harmonics generation as a result of the contact nonlinearity, has not yet been applied for estimating the size of a delamination using any damage index or locating a delamination in composite laminates.

In the present work, experimental and finite element (FE) simulation studies are carried out in order to detect, size, and locate a delamination in composite laminates using Lamb wave based nonlinear method. This method typically involves the detection and measurement of higher harmonics generated in the response due to the contact nonlinearity at a delamination. The composite laminates used in the present study are made from E-glass/epoxy materials. The specimens required for the experiments are prepared in the authors' laboratory. Lamb wave actuation and reception is carried out using PW transducers. These transducers have several advantages such as compactness, portability, and can work over a wide frequency range. The task of sizing the delamination is achieved using a spectral damage index (SDI) [20] extracted from the spectral information of the fundamental and higher harmonics. Authors have extended use of the experimental setup and FE simulation procedure used in their previous works related to the breathing crack and disbonding kind of damages [20,21], to carry out the present work. However, novelty of the present work lies in proving the robustness and genericness of the SDI and introducing the new spectral-temporal hybrid method to locate a delamination. The content of the paper is divided into four sections. Details and basic results of the experimental work are given in Section 2. FE simulation is discussed in Section 3, where the contact nonlinearity is modelled using the contact elements and Augmented Lagrangian (AL) algorithm. In the simulation, coupled field elements are used to model the PW transducers. Section 4 deals with the SDI, and spectral-temporal hybrid method used for locating a delamination, is discussed in Section 5.

2. Experimental study

2.1. Specimen preparation

In this study, woven fibre composite (WFC) laminates are analysed for the detection of delamination. Three sets of laminates are made with and without delamination, in the laboratory. The laminates are made at the ambient temperature using E-glass woven fabric, Araldite® LY556 epoxy resin, and Aradur® HY951 hardener. A WFC laminate is composed of 6 layers, with total thickness being 2.1 mm and plan form dimensions of 425 mm × 265 mm. The delamination in the laminate is formed using a thin Teflon sheet. Teflon sheet is adequately thinner with a thickness of 20 μm which does not alter the properties of the host material significantly while being effective in separating two mating surfaces. For these reasons, the Teflon sheet has been widely used in the literature [24–28] for the purpose of creating artificial delamination. Authors have also carried out extensive experiments in their earlier work wherein the Teflon sheet is used to create breathing damages such as crack, disbond, and delamination [20,21,29,30]. Specimens of the laminates are made with 5 mm, 10 mm, and 15 mm delamination. The delamination is placed between the second and third layers. A WFC laminate with delamination is shown in Fig. 1. A few samples are also made with no delamination.

It is important here to make the specimens with the same dimensions and same structural properties so that the results obtained from different specimens of the WFC laminates can be correlated. To achieve this same quantity of fibres, epoxy, and hardener is used; same weight is put on the mould, and laminates are cut with the same dimensions. The WFC laminates are found to have following average properties: fibre volume fraction 0.55, in-plane modulus of elasticity 32 GPa, modulus of elasticity in the thickness direction 15 GPa, in-plane shear modulus 1.7 GPa, shear modulus in the thickness direction 1.7 GPa, and density 1850 kg/m^3.

2.2. Experimentation

The Lamb wave actuation and sensing in the WFC laminates is carried out using piezoelectric wafer (PW) transducers. The size of the PW transducers used is 10 mm × 7 mm × 0.5 mm and material type is SP-5H. A WFC laminate with the bonded PW transducers is shown in Fig. 1. The PW transducers are portable, compact, cost effective, and have wider frequency bandwidth. The experimental setup consists of Tektronix made 3021B arbitrary function generator and 1002B digital storage oscilloscope, NF made BA4825 high speed bipolar amplifier, and a computer as shown schematically in Fig. 2. A Gaussian windowed 8.5 cycle sine wave tone burst is generated in MATLAB© and stored in the arbitrary function generator. The Gaussian window gives a tone burst with less spectral leakage compared to other windowing functions. The selection of number of cycles in the tone burst is based on the trade-off between the spectral and temporal bandwidths. The tone burst is amplified using an amplifier from 10 Vpp to 300 Vpp and the signal is then given to the PW actuator. This high amplification is required to pump more power in the tone burst so that it can sufficiently excite the delamination to produce considerable contact nonlinearity.

2.3. Selection of the frequency

The range for selection of the frequency is quite liberal when one deals with the damages characterized by the contact nonlinearity such as delamination unlike the classical nonlinearity. This is mainly because, the contact nonlinearity in this case arises as a result of relatively larger stiffness changes at the contact interfaces. The authors carried out the experiments at various frequencies ranging from 68 kHz to 136 kHz and at all the frequencies considered only higher harmonics are observed. In the paper, the results at the excitation frequency of 76.5 kHz are given for the purpose of illustration.

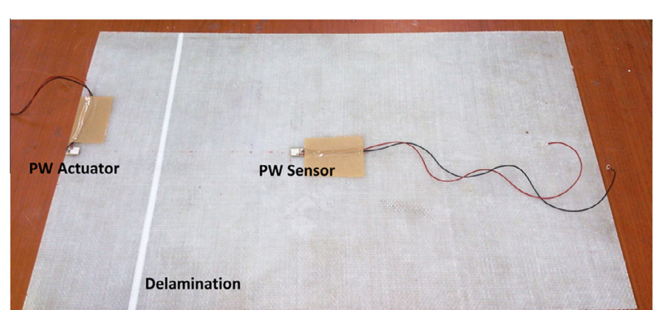

Fig. 1. WFC laminate with delamination.