NDT&E International 63 (2014) 21–27

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Higher harmonics induced in lamb wave due to partial debonding of piezoelectric wafer transducers

Nitesh P. Yelve*, Mira Mitra, P.M. Mujumdar

Department of Aerospace Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India

ARTICLE INFO

Article history:
Received 1 July 2013
Received in revised form
28 November 2013
Accepted 21 January 2014
Available online 29 January 2014

Keywords:
Piezoelectric wafer transducer debonding
Contact nonlinearity
Lamb wave
Higher harmonics
Morlet wavelet transform
Spectral damage index

ABSTRACT

Piezoelectric wafer (PW) transducers used for Lamb wave actuation may get partially debonded from the host structure, because of their prolonged use, excessive voltage supply, or improper bonding onto the host structure. In this paper, higher harmonics induced in Lamb wave because of such debonding of the PW actuator are studied both experimentally and through finite element simulation. In experiments, an artificial partial debond is created while bonding the actuator patch onto a pristine aluminium plate. Lamb wave transduced by this actuator in the plate is picked up by a PW sensor which does not have any debonding. In FE simulation, Augmented Lagrangian algorithm is used to solve the contact problem at the breathing debond. Three higher harmonics are observed in the experiments and also in the FE simulation. To ensure that the generated higher harmonics correspond to Lamb wave, time–frequency analysis is carried out using Morlet wavelet transform, and the results are reported in the paper. Spectral damage index (SDI), obtained from spectral attributes of first four harmonics in experiments and simulation, is found to be decreasing with an increase in debonding area. This shows that actuator debonding introduces contact nonlinearity which induces higher harmonics in Lamb wave. Therefore, in damage detection using Lamb wave based nonlinear techniques, the higher harmonics produced may get influenced by the false higher harmonics produced by actuator debonding, leading to incorrect results, if bonding of the actuator is not taken care of properly.

1. Introduction

In material characterization [1,2] or damage detection [3–6], using Lamb wave based nonlinear techniques, the presence of higher harmonics is used as a measure of evaluation of the material or damage state. Nonlinear elasticity spread in the material continuum and local contact nonlinearity are the two mechanisms, which give rise to higher harmonics in Lamb wave [7]. The stronger the nonlinearity, the larger is the energy transferred from the fundamental harmonic to the higher harmonics and therefore an increase in the number and amplitude of higher harmonics is observed. In such nonlinear techniques used for material characterization or damage detection, piezoelectric wafer (PW) transducer is a good candidate for actuating Lamb wave in the structure because of its portability, small size and cost effectiveness. These characteristics of PW transducer make it suitable for *in situ* applications.

Higher harmonics generation, in the PW transduced Lamb wave, in an aluminium plate with a breathing crack is studied in Reference [6]. Three higher harmonics are observed in this study and time–frequency analysis using Morlet wavelet transform showed that these higher harmonics do lie on the dispersion curves and hence correspond to Lamb wave. The PW transducer excites both symmetric and anti-symmetric modes of Lamb wave and therefore it is able to generate both odd and even higher harmonics. This is shown both analytically and experimentally in Reference [8], in a quasi-statically loaded aluminium plate, with the aid of macro-fiber composite (MFC) piezoelectric patches.

An important issue with PW transducer is its debonding from the host structure because of prolonged use, excessive deformation caused by high voltage supply, or improper bonding. Contact nonlinearity may prevail in this case, leading to higher harmonics in the Lamb wave response. This may show illusory presence of defect in a pristine material. This is proved both experimentally and through finite element (FE) simulation in the present paper. In experiments, an artificial partial debond is created in a PW actuator while bonding it onto a thin aluminium plate. In the simulation, partial breathing debonding is modelled between patch and plate by assigning contact attributes to the contacting faces [6]. Augmented Lagrangian algorithm [9] is used to implement contacting conditions at the meeting faces. The wave generated by such a debonded PW actuator, in both experiments and simulation, is picked up by the perfectly bonded PW sensor. The signal shows the presence of three higher harmonics. To

* Corresponding author.
E-mail address: nitesh@aero.iitb.ac.in (N.P. Yelve).

0963-8695/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ndteint.2014.01.004

ensure that the generated higher harmonics belong to Lamb wave, time–frequency analysis of both experimental and simulation results is carried out using Morlet wavelet transform and the results of this analysis are reported in the paper. Further, a spectral damage index (SDI) [6] is extracted from spectral attributes of higher harmonics for various debonding sizes. Variation of this SDI with increasing debonding size is found to be decreasing in experimental as well as simulation studies. This indicates that PW actuator debonding is very much susceptible to induce higher harmonics in Lamb wave which may lead to show illusory presence of defect in a pristine material. Therefore good care should be taken while bonding the PW transducers, and bonding should be always checked using some appropriate techniques. Patches may even be replaced after their use over a certain duration.

2. Experimental work

The experiments are performed on a pristine aluminium plate, with the objective of studying higher harmonics induced in Lamb wave as a result of debonding in PW transducer. The size of PW transducers used here is 10 mm × 7 mm × 0.5 mm and material type is SP-5H. Properties given by the manufacturer [10] for these transducers are mentioned in Table 1. The material of the plate used here is aluminium (grade 5052-H32) with modulus of elasticity 70.3 GPa, Poisson's ratio 0.33, and density 2680 kg/m^3 [11] and its size is 1200 mm × 1200 mm × 1.6 mm. Cyanoacrylate adhesive is used for bonding PW transducer onto the plate. The sensor patch is bonded completely whereas actuator patch is partially bonded so as to introduce artificial debonding in it, as shown in Fig. 1. Three such actuator-sensor sets are experimented with different debondings of the actuators. In these three sets, the actuators are debonded over their entire width, and 10%, 20%, and 30% of their lengths at the centre as shown in Fig. 1. Therefore, the debonded area of three actuators is 10%, 20%, and 30% of total actuator area available for bonding.

Cyanoacrylate adhesive is a fast solidifying adhesive, therefore its curing time is very less. Because of this, the chances of spreading the adhesive beyond the required bonding area of the PW transducer are very less. Also, the limiting ink lines made on the bonding side of the PW transducer further prohibits the spreading of the adhesive. The size of debonding in the transducers is checked by removing them after completing the experiments. The debonding is found to be in close limits of accuracy.

Table 1
Properties of SP-5H piezo wafers [10].

Properties	Values
Piezoelectric coupling coefficients	
k_p	0.63
k_{33}	0.73
Piezoelectric charge constants	
$d_{33} \times 10^{-12}$ C/N	550
$d_{31} \times 10^{-12}$ C/N	−265
Piezoelectric voltage constants	
$g_{33} \times 10^{-3}$ V m/N	19
$g_{31} \times 10^{-3}$ V m/N	−9
Relative dielectric constant	
k_3^T	3100
Density	
ρ kg/m^3	7500
Elastic constants	
$S_{11}^E \times 10^{-12}$ m^2/N	21
$S_{33}^E \times 10^{-12}$ m^2/N	15

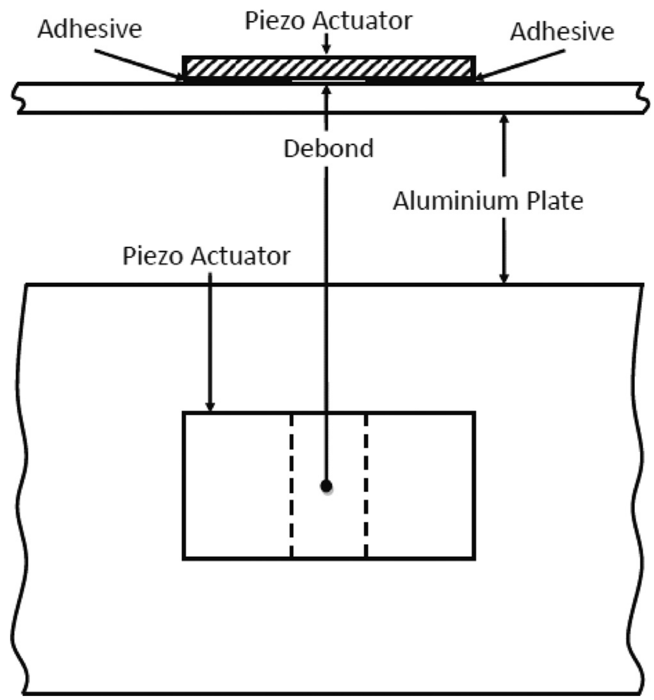

Fig. 1. Schematic of patch debonding.

The experimental setup as shown in Fig. 2 consists of arbitrary function generator (Make: Tektronix, Model: 3021B), high speed bipolar amplifier (Make: NF, Model: BA4825), digital storage oscilloscope (Make: Tektronix, Model: 1002B), and a computer. A 8.5 cycle sine wave tone burst signal windowed by Gaussian function is generated in MATLAB©. The Gaussian window of length N is defined by the equation [12]

$$\omega(n) = e^{[-(1/2)[\alpha(n/((N-1)/2))]^2]}, \tag{1}$$

where

$$-\frac{N-1}{2} \le n \le \frac{N-1}{2}, \tag{2}$$

and α is inversely proportional to the standard deviation of Gaussian random variable. In the present case $N=251$ and $\alpha=2.5$. This tone burst is then input to the function generator with a resolution of 40,000 points as shown in Fig. 3a, and set at frequency 170 kHz (Fig. 3b). Using the amplifier, this tone burst is magnified to ±100 V and given to the debonded PW actuator. The received Lamb wave at the PW sensor is shown by the oscilloscope and the corresponding data are sent to the computer for further signal processing. Fig. 4a–c shows the input signal and the output signals in time domain corresponding to the case of the perfectly bonded and the 30% debonded PW actuator. The received time domain data is cluttered and it is difficult to make any clear interpretation from it. Frequency domain analysis is useful to get the information about the nonlinearity induced in Lamb wave, in terms of higher harmonics. Here, the output time domain data is converted into the frequency domain using the discrete Fourier transform (DFT) given as [13]

$$X(k) = \sum_{q=0}^{M-1} x[q] e^{[-j2\pi qk/M]} \tag{3}$$

where

$$k = 0 : M-1, \tag{4}$$

and M is the number of data points, which is 2048 in the present case. For this purpose the Fast Fourier Transform (FFT) algorithm is