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Finite Element Simulation of Lamb wave with Piezoelectric Transducers for Composite Plate Damage Detection

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Abstract: Structural health monitoring (SHM) is an emerging research area with multiple applications. Lamb waves are ultrasonic elastic waves that travel inside and along thin plates and is frequently used as diagnostic tools to detect damage in plate-like structures. In this paper, a transient dynamic finite element simulation of Lamb wave with piezoelectric transducers for damage detection in a composite plate is carried out. The embedded cross-shaped piezoelectric active sensor arrays were used to generate and receive guided Lamb waves propagating in the plate structure. A full-scale FEM model for the laminate was created using three-dimensional eight-node layered structural solid element and piezoelectric active sensors were created using coupled field elements on the commercial finite element code ANSYS platform. The beam forming technique of Lamb waves is used to locate damage in the plate .The results of the numerical simulation demonstrate the effectiveness of the approach.

Introduction

Composites are nowadays used in most industries because of their light weight and good mechanical performance. Nevertheless, there are certain disadvantages in using composites, such as their weakness to low-velocity impacts. The idea of Structural Health Monitoring (SHM), wherein sensors/actuators are integrated with the structure itself, has therefore become of increasing interest. A promising damage detection method is the active system based on the propagation of Lamb waves [1]. A network of embedded piezoelectric transducers is used in pitch-catch. In recent years, a significant amount of research on the modeling and analysis has been carried out to further understand the properties of Lamb waves excited by piezoelectric transducers [2].

The beamforming algorithm or phased arrays are a method of creating a virtual beam that sweeps the plate-liked structures. The beam steering effect is attained through controlled delays of the signals going to the various array sensors for structural defect detection in [3, 4].

In this paper, a full-scale transient dynamic finite element simulation of Lamb wave with piezoelectric transducers for damage detection in a composite plate is carried out. The embedded cross-shaped piezoelectric active sensor arrays were used to generate and receive guided Lamb waves propagating in the laminate. The beam forming technique of Lamb waves is used to locate damage in the plate.

2. Lamb waves and beamforming algorithm

Lamb wave based damage detection with piezoelectric active sensors provides the possibility to inspect large and complex structures in service. However, the receiver signals of a Lamb wave based inspection system are complex because of the existence of two dispersive modes in minimum, the reflections from borders and structural changes and of the mode conversions at defects. Therefore the strategy of monitoring is extremely important for successful damage detection [5].

In this paper, we will consider a PZT patch polarized across the thickness. For PZT4 material, poled in the 3-direction, we express the relations between stress T, strain S, electric field E, and electric displacement D by

$$\begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ T_{23} \\ T_{13} \\ T_{12} \end{pmatrix} = \begin{pmatrix} 13.2 & 7.1 & 7.3 & 0 & 0 & 0 \\ 7.1 & 13.2 & 7.3 & 0 & 0 & 0 \\ 7.3 & 7.3 & 11.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.6 \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_{23} \\ S_{13} \\ S_{12} \end{pmatrix} \cdot 10^{10} - \begin{pmatrix} 0 & 0 & -4.1 \\ 0 & 0 & -4.1 \\ 0 & 0 & 14.1 \\ 0 & 10.5 & 0 \\ 10.5 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} \tag{1}$$

and

$$\begin{pmatrix} D_1 \\ D_2 \\ D_3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 10.5 & 0 \\ 0 & 0 & 0 & 10.5 & 0 & 0 \\ -4.1 & -4.1 & 14.1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_{23} \\ S_{13} \\ S_{12} \end{pmatrix} - \begin{pmatrix} 804.6 & 0 & 0 \\ 0 & 804.6 & 0 \\ 0 & 0 & 659.7 \end{pmatrix} \varepsilon_0 \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} \tag{2}$$

where stress has units of Pa, electric field has units of V/m, electric displacement has units of C/m^2, and ε_0 is the dielectric permittivity of free space.

Linear phased arrays are made of a number of piezoelectric transducers placed along a line. Waves generated by the transducers have an Omni-directional character and create a pattern, which is a result of the superposition of the waves generated by each transducer individually. A sweep beam, which can be steered, is created if each transducer from the set excites waves with an individually adjusted time delay. Changing the steering angle from 0 to 180^0 and calculating the time delay for each transducer, an area of the structure around the array of transducers can be interrogated. In order to focus the total signal in the direction indicated by the angle θ, the i-th array element should excite a wave with an individual time delay δ_i relative to the 1st PZT sensor given by the formula:

$$\delta_i = \frac{d_i \cos(\theta)}{c} \tag{3}$$

where d_i is the distance between the i-th and the 1st transducer and c is the wave group velocity. Focusing procedure is realized by a computer algorithm written by MATLAB program in this paper (all transducer excite waves individually and signal processing procedures based on time shifting are applied to the gathered signals).

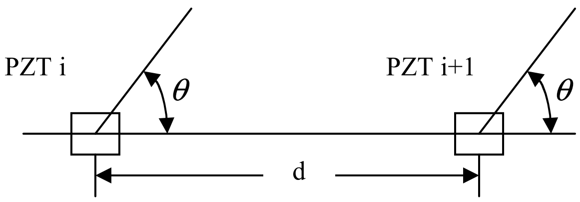


Fig.1 Array of two identical Omni-directional PZT sensors

The signals are then transformed from the time domain into the physical domain of the structure. The x- and y-axes indicate the coordinates of the investigated surface area as follows:

$$x = R\cos\theta$$
$$y = R\sin\theta \tag{4}$$

where R=ct/2 is the distance propagated by the wave packet traveling with the velocity c, and t is the time. In effect it gives a damage zone map of the plate structure.

3. **Damage Detection and Localization in composite plate**

In this paper, a transient dynamic finite element simulation of Lamb wave with piezoelectric transducers for damage detection in a composite plate is carried out. The composite plate shaped at 684mm*720mm*1mm and two array of piezoelectric transducers are surface bonded. The embedded cross-shaped piezoelectric active sensor arrays (horizon array and vertical array) were used to generate and receive guided Lamb waves propagating in the plate structure. The center PZT patches are actuators. Numerical simulations of the wave propagation process were performed using the commercially available finite element code, ANSYS. The composite plate specimen was modeled using three-dimensional eight-node layered structural solid element (SOLID46) and the three-dimensional coupled element (SOLID5) of ANSYS was used for modeling the piezoelectric sensors. Voltages DOFs were coupled for the nodes of PZT sensors at top and bottom surface to simulate the electrodes. A $[90/\pm45/0]_s$ quasi-isotropic laminate was selected for the simulation. The laminate material properties are presented in Table 1. The plate is free-free. The discretization process of composite plate specimen used 13698 elements. The FEM mesh was particularly densified in the plate, where more than 6 FEM nodes per Lamb wavelength were guaranteed to exist, and ensuring simulation precision. Note that this formulation is essentially used to obtain the voltage-time domain data of the excited plate through the sensors attached to it.

Table 1 Material properties of laminate

E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	G_{12} (GPa)	G_{23} (GPa)	G_{13} (GPa)	υ_{12}	υ_{23}	υ_{13}	ρ (kg/m^3)
168	9.31	9.31	5.17	3.45	5.17	0.33	0.4	0.33	1610

The local distributed damage as 90% stiffness reduction in sixteen elements was considered. This represents a square of the size 24mm*24 mm, which is about 0.1% of the total plate surface.

The composite plate was instrumented with two arrays of eighteen 6*6*0.2mm^3 piezoelectric transducers with cross shape configuration. The finite element model of composite plate and the locations of damage zone and the eighteen PZT sensors are illustrated in Fig. 2.

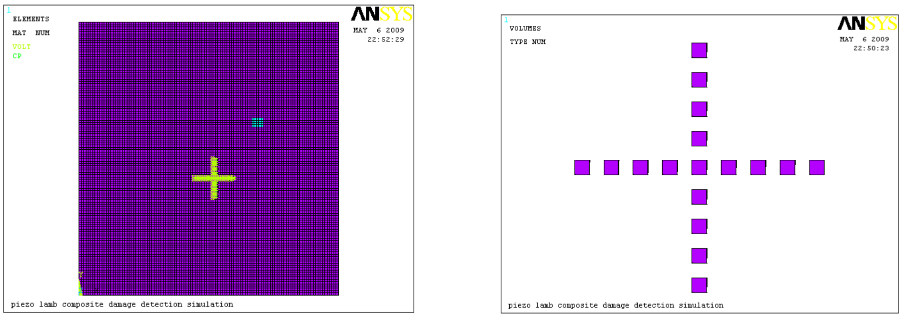


Fig. 2 Finite element model and cross shape configuration PZT sensors

The Lamb waves are excited by applying voltage to the top nodes of the actuator simulating the operation as in real applications. The applied excitation is in the form of a wave packet (5-cycle sine modulated by the Hanning window) with 10 v p-p. The main frequency of this packet is 100 kHz. Since pure S0 or A0 mode excitation cannot be achieved by a single actuator, in this particular discussion we use two actuators attached on the top and bottom surfaces of the plate and the two actuators generate a pure A0 mode.

Examples of the corresponding time domain signals of active PZT sensors (including intact plate signals, damaged plate signals and damage reflection signals) are shown in Figures 3. Based on the beamforming algorithm, the resulting data file is a collection of signals that represent the structure response at different angles from 0º to 180º. The reconstructed damage reflection signal from all sensors of the horizon PZT array base on beamforming algorithm is shown in Figure 4. It can be seen that the reconstructed damage reflection signal is obviously stronger than the damage reflection signal of single sensor. In order to illustrate the properties of two PZT arrays, polar plots of the reconstructed damage reflection signal using beamforming algorithm versus angle of arrival are created. The local damage zone angle relative to the center of the two arrays is shown in Fig. 5(a), 5(b), respectively. For the horizon PZT array, the damage zone angle is at angles of approximately 60 deg; for the vertical PZT array, the damage zone angle is at angles of approximately147 deg. It can be clearly seen that for two PZT arrays the defect direction is correctly localized.

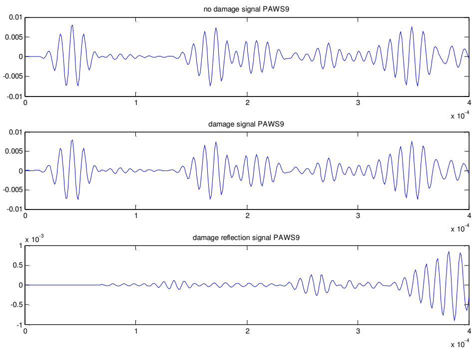


Fig. 3 Active PZT sensors signals

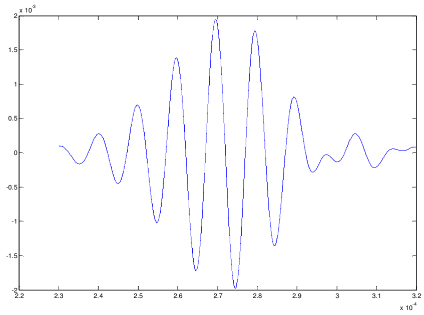
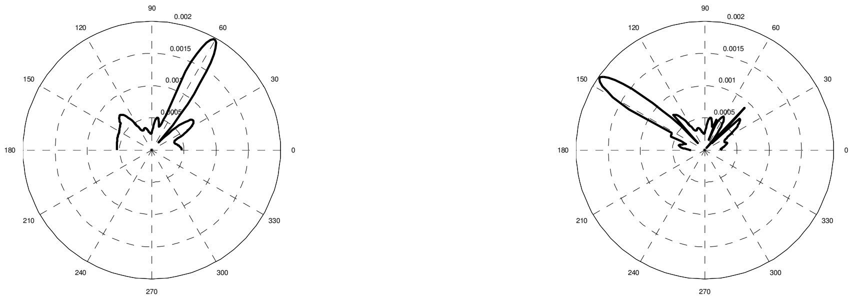


Fig. 4 Damage reflection reconstructed signal



(a) Horizon PZT array (b) Vertical PZT array

Fig.5 Polar plots of damage zone angle

These results suggest that the cross-shaped configuration with the beam-forming procedure is able to detect the distributed damage, modeled by stiffness reduction. With advanced signal processing techniques, these damage reflection data could be transformed to a 2-D plane domain to locate the damage in the plate.

Summary

In this research, we developed a full multiphysics finite element simulation using coupled field elements for the analysis of Lamb-wave-based damage detection of composite material structure using piezoelectric transducers. The beam forming technique of Lamb waves is used to locate damage in the plate. This method of this study can be easily extended to practical geometries such as stiffened composite material structures.

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